The Spatial Ecology and Conservation of Seagrasses of the Gulf of Kachchh, Gujarat

A thesis submitted for the award of the degree of
Doctor of Philosophy
in
WILDLIFE SCIENCE

by
Sameeha Vahedkhan Pathan
to
Saurashtra University
Rajkot- 360005 (Gujarat)

Under the supervision of
Dr. K. Sivakumar

भारतीय वन्यजीव संस्थान
Wildlife Institute of India

April - 2024

DECLARATION

I hereby declare that the work conducted under the thesis entitled **"The spatial ecology and conservation of seagrasses of the Gulf of Kachchh, Gujarat"**, is a record of original research work, done by me and subsequently submitted for the award of the degree of doctor of Philosophy in Wildlife Science to Saurashtra University, Rajkot. This research work has been carried out under the guidance and supervision of Prof. K. Sivakumar,Department of Ecology and Environmental Sciences, School of Life Sciences, Pondicherry University, Puducherry. The work has not formed the basis for the award of any other degree, diploma or any other qualification. I also declare that the thesis embodies my own work, analysis, observation and understanding and the particulars given in it are true to the best of my knowledge.

(Sameeha Vahedkhan Pathan)
Place: Dehradun
Date: 31st March, 2024

(Dr. K. Sivakumar)
Supervisor

Prof. K. SIVAKUMAR, Ph.D.,
DEPT. OF ECOLOGY & ENVIRONMENTAL SCIENCES
School of Life Sciences
Pondicherry University
Puducherry - 605 014. India

भारतीय वन्यजीव संस्थान
Wildlife Institute of India

Prof. K. Sivakumar

Date 18th March, 2024

CERTIFICATE

This is to certify that the thesis by **Ms Sameeha Vahedkhan Pathan** entitled "**The spatial ecology and conservation of seagrasses of the Gulf of Kachchh, Gujarat**" is an original and independent research work submitted to the **Saurashtra University, Rajkot (Gujarat)**, for the award of the degree of **Doctor of Philosophy in Wildlife Science**.

Ms. Sameeha Vahedkhan Pathan has put more than six semesters of research work embodied in this thesis under my guidance and supervision. The work presented in this thesis has not been submitted to any other University or Institute for the award of any degree, diploma or distinction.

K. Sivakumar

(Dr. K. Sivakumar)
Supervisor

Prof. K. SIVAKUMAR, Ph.D.,
DEPT. OF ECOLOGY & ENVIRONMENTAL SCIENCES
School of Life Sciences
Pondicherry University
Puducherry - 605 014. India

Ruchi

(Dr. Ruchi Badola)
Dean
Faculty of Wildlife Science

संकायाध्यक्ष / Dean
भारतीय वन्यजीव संस्थान
WILDLIFE INSTITUTE OF INDIA
देहरादून / Dehradun

Post Box No.18, Chandrabani, Dehradun - 248001. India
EPABX: +91-135 - 640111 to 640115 640990; **FAX:** 640117; **GRAM:** WILDLIFE
E-Mail: wii@wii.gov.in

SAURASHTRA UNIVERSITY
P.G.T.R Section
Main Office, First Floor
University Road
Rajkot - 360 005 (Gujarat)
Phone No. : 2578501
Fax : (0281)2856983
www.saurashtrauniversity.edu

Accredited Grade 'A' by NAAC

CERTIFICATE FOR PRE-Ph.D. PRESENTATION

This is to certify that **Ms. Sameeha Vahedkhan Pathan**has made Pre-Ph.D. Presentation as per UGC Guideline "University Grant Commission (Minimum Standard and Procedure for award of Ph.D. Degree) Regulation-2016" and Saurashtra University Ordinance for Ph.D. Programme (O.Ph.D. 8.3), on her research work entitled "**The spatial ecology and conservation of seagrasses of the Gulf of Kachchh, Gujarat**" at Wildlife Institute of India, Dehradun, Research Centre of Saurashtra University, Rajkot on **8th September 2023** before all the faculty members and students of the Department for getting feedback and comments.

I certify that the research work was appreciated by all who were present, and the comments made by the faculty and researchers have been appropriately included in the thesis.

Ruchi

(Dr. Ruchi Badola)
Dean
Faculty of Wildlife Science

संकायाध्यक्ष / Dean
भारतीय वन्यजीव संस्थान
WILDLIFE INSTITUTE OF INDIA
देहरादून / Dehradun

(Dr. K. Sivakumar)
Supervisor

Prof. K. SIVAKUMAR, Ph.D.,
DEPT. OF ECOLOGY & ENVIRONMENTAL SCIENCES
School of Life Sciences
Pondicherry University
Puducherry - 605 014. India

भारतीय वन्यजीव संस्थान
Wildlife Institute of India
(An Autonomous Institute under Ministry of Environment, Forest & Climate Change, Govt. of India)
पत्रपेटी सं0/Post Box No. 18, चन्द्रबनी, देहरादून/Chandrabani, Dehradun - 248001, उत्तराखण्ड, भारत/ Uttarakhand, INDIA

Azadi Ka Amrit Mahotsav

CERTIFICATE OF PLAGIARISM CHECK

It is certified that the Ph.D. thesis entitled **"The Spatial Ecology and Conservation of Seagrasses of Gulf of Kachchh, Gujarat"** submitted by Ms. **Sameeha Vahedkhan Pathan** has been examined by us for plagiarism check as per UGC (Promotion of Academic Integrity and Prevention of Plagiarism in Higher Educational Institutions) Regulations. The following inferences are drawn from this check:

a) Thesis has significant new work/knowledge as compared to already published work or work under consideration for publication elsewhere.

b) No sentence, equation, diagram, table, paragraph or section is found to have been copied verbatim from previous work unless it was placed under quotation marks and the source was duly cited.

c) The work presented is original work of the author (i.e., there is no plagiarism) and there is no fabrication of data or result by manipulating research materials, equipment or processes, or by changing or by omitting data or results such that the research is not accurately represented.

The report is as follows:

Software used	Date	Total world count	iThenticate® similarity index
iThenticate®	05.03.2024	23322	2%

*One paper already published from this thesis by Sameeha Pathan as first author have been excluded from plagiarism check.

The similarity index came as 2%. The report from the plagiarism check is attached with the certificate.

5/3/24
(Mr. Manohar Pathak)
Librarian
पुस्तकालयाध्यक्ष
Librarian
भारतीय वन्यजीव संस्थान, देहरादून
[illegible]

(Dr. K. Sivakumar)
Supervisor
Prof. K. SIVAKUMAR, Ph.D.,
DEPT. OF ECOLOGY & ENVIRONMENTAL SCIENCES
School of Life Sciences
Pondicherry University
Puducherry - 605 014. India

(Dr. Ruchi Badola)
Dean
Faculty of Wildlife Science

संकायाध्यक्ष / Dean
भारतीय वन्यजीव संस्थान
WILDLIFE INSTITUTE OF INDIA
देहरादून / Dehradun

Acknowledgement

Constructing an ecological baseline is never easy; I would like to express my sincere gratitude to those who have supported me throughout my PhD journey. Without their help, this thesis would have been possible, but with greater difficulty and sadness.

Firstly, I thank my supervisor, Dr. K. Sivakumar, for his guidance and for being unproblematic and approachable. He trusted me throughout these years and always had a kind word to say. I am also grateful to my project supervisor, Dr. J.A. Johnson, for his support throughout these years. I want to acknowledge the Gujarat Forest Department's Marine National Park staff for trusting and permitting me to study protected habitats. I want to acknowledge the financial support provided by CAMPA, which has enabled me to pursue my research. Their investment in my education and training has been instrumental in my success.

I am indebted to all my colleagues at the CAMPA-Dugong Recovery Project, because of whom I painstakingly learned the value of holding onto my kindness in academia. I thank the Director WII, Dean, Registrar, Research coordinator, and Nodal officer for their support.

A handful of researchers have ever dedicatedly worked at the unforgiving reefs of the Gulf. Naturally, very few people would know about the tenacity and commitment required to work there for years. I thank everyone; volunteers, field assistants and project fellows for showing up.

I would like to express my gratitude to my colleagues, Prachi Hatkar and Shivani Patel, for being great team players, leaders, and managers. To the lab team Rashmi Semval, Garima Dhiman, Rajat, Arun, staff of ICAR-Indian Soil and Water Conservation, and Sophisticated Industrial Analytical Labs (SIMA labs) for analyzing soil texture and seagrass nutrient data.

It did take a village to start and finish this study. I am honored and humbled to have the support of the whole fishing community of Beyt village. I will always be in debt to Junus Babbar and his whole family. His kindness, wisdom, and matching tenacity on-field has forever changed my life. I thank Sattar Nagiya and Razak for letting me rent, paint, sleep, and sail their boats; *Molvisa* and *Dinghy*.

This project required enormous courage to map undescribed habitats that no researcher had walked before. I thank Gem Christian, my motivation coach, my therapist, my deeply insightful researcher, and my dear friend, for not leaving my side even on the worst days of data collection at all the drowning mud-flats. For the same reasons, I have deep respect and gratitude for Diksha Dikshit, Bhargav Bhadreshwara, Fatema Hirkani, and Pradyuman Sindha for being a relentless star ecologist for doing the most mundane work even on the hottest days and roughest seas.

To Musa Chana, Karim Babbar, Ehsan Babbar, Musa, Isa, Asgar, Iliyas, Rasid Sangar, Sultan and Hashim for their on-field support during data collection, for fish rice, and light-hearted banter on the boat, all essential ingredients for a good day.

My research involved topographical assessments of habitats that had never been reported or assessed. I will always be indebted to Amir Lone for his enthusiasm and unending patience in teaching me the craft of spatial analytical tools in ArcGIS. My research ideas went from scribbles on blank pages to sophisticated topographical and bathymetric maps because of him.

Special thanks my close friends Niazul Hassan Khan, Subhashree Sahoo, Bhim Singh, Kumudani Bala Gautam, Kulsum Pathan, Sohini Dudhat, Devanshi Kukadia, Pallabi Das Rukmini Shekar, Hima and Bilkish Patel. God made me a perfect set of the most reliable and protective friends.

Finally, my mummy, Swaliha, Sabeeha, Abdulla, and Kulsum, nephews and nieces, I thank you for patiently waiting a very long time for me to come home. Their softness, innocence, and amazing courage kept me from becoming an apathetic robot had I not them in my life. This thesis is dedicated to my parents and grandparents. To my late father, who I started this journey with, who drove for sixteen hours to get me to day one in the field. This thesis would’ve made him proud beyond measure; he would have been video-calling all his friends by now to show off.

Table of content

List of figures

List of tables

List of publications and conferences

This thesis has resulted into one research paper and five oral, and three poster presentations

- Pathan Sameeha, K. Sivakumar, J.A. Johnson (2018). Dugong conservation in the Gulf of Kachchh, Challenges and opportunities. Oral e-poster presentation at the 14th Annual research seminar at Wildlife Institute of India, Dehradun, India
- Pathan Sameeha, K. Sivakumar, J.A. Johnson (2018). Dugong conservation in the Gulf of Kachchh, Challenges and opportunities. Oral poster presentation at the International Biodiversity Congress 2018, Dehradun, India
- Pathan, S., Dikshit. D, Saini. H, Rajpurkar. S, Hatkar. P, Pande, A., Sivakumar, K., & Johnson, J. A. (2019). Understanding Dugong foraging patterns in the Gulf of Kachchh, India. Oral presentation at the 15th Annual research seminar at Wildlife Institute of India, Dehradun, India
- 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, 40*(5), 499-507.
- Pathan, S., Cristian Gem, Johnson, J. A., and Sivakumar, K (2023). Studying the unseen; Foraging behavior of remnant population of dugongs in the Gulf of Kachchh, Gujarat, India. Oral presentation at the 59th Annual meeting of the Association for the Tropical biology and Conservation
- Pathan, S., Cristian Gem, Johnson, J. A., and Sivakumar, K (2023). Studying the unseen; Foraging behavior of remnant population of dugongs in the Gulf of Kachchh, Gujarat, India. Oral presentation at the 59th Annual meeting of the Association for the Tropical biology and Conservation
- Pathan, S., Cristian Gem, Johnson, J. A., and Sivakumar, K (2023). Tidally locked foraging grounds of small population of dugong in Gulf of Kachchh. Oral presentation at the 14th Students Conference on Conservation Science, 2023
- Pathan, S., Cristian Gem, Johnson, J. A., and Sivakumar, K (2023). Unveiling dugongs' culinary choreography; foraging strategies in the ever-shifting seas of the Gulf of Kachchh, poster presentation at the 16th Annual research seminar at Wildlife Institute of India, Dehradun, India.

Summary

Seagrass ecosystems provide ecosystem services that rank among the highest in economic valuation worldwide. They also provide a range of economic, social, and environmental goods and services, which greatly increase coastal communities' resilience to the impacts of climate change. As unique marine habitats, seagrass ecosystems provide shelter and food for marine species during different life stages and contribute to sediment accretion and primary production. The high diversity of marine plant and animal life supports tourism activities and provides the raw materials for medicinal, agricultural, and structural applications. Furthermore, the physical structure of seagrass ecosystems attenuates wave height and speed, protecting coastlines from erosion and storm surges.

Threats to seagrass ecosystems in the coastal areas of the Gulf of Kachchh include pollution, rising sea levels, eutrophication, reduction of light intensity and die-back. These all negatively impact seagrass ecosystems, such as increasing growth of epiphytes, sediment anoxia, or increased prevalence of diseases. Further, the effects of climate change on seagrass ecosystems will be additional stressors. The underlying factors affecting seagrass ecosystems are direct human pressures such as pollution, disturbances, and eutrophication. The combined stressors – human pressures and climate change impacts – are likely to exceed the thresholds for seagrasses, leading to, among other things, i) redistribution (reduction and coastal migration) of existing habitats and ii) widespread seagrass ecosystem die-off.

In this context, this study was conducted between January 2018- March 2022 and aimed to understand the phenology, biomass and spatial distribution patterns of seagrasses of the GoK, using which I attempted to understand the foraging behaviour, habitat use and movement ecology of dugongs in the Gulf of Kachchh. The major objectives of the study include a) Mapping the distributional characteristics and patterns of seagrass meadows in the southwestern GoK, b) understanding the seasonal variations in the abundance of seagrasses on topographically distinct meadows, c) investigating fine-scale and topographical determinants of dugong habitat preferences and d) to assess the role of semi-diurnal tides' influence on dugong foraging habitats.

Chapter 1 is an introductory chapter summarising the global and regional importance of healthy seagrass communities. Further, the importance of field-based intensive seagrass mapping surveys was discussed. Finally, a brief distribution and conservation status of dugong populations, extinct and extant (Arabian sea and Indian subcontinent populations), were discussed.

Chapter 2- Fine-scale spatial patterns in the distribution and extent of seagrass beds were mapped for the first time in the Gulf of Kachchh, India. My study provides fine-scale baseline maps of spatial patterns and distribution of seagrass beds in SW-GoK. Intensive ground-truthed methods combined with the complemented aid of hydrographic charts and statistical interpolation methods IDW in ArcGIS were used to construct seagrass distribution and extent maps. Relative wave exposure, low tide exposure, depth, and differences in inter/within reef settlement were used as factors to identify and chart patterns in seagrass species' presence, abundance, and depth profile. First, fine-scale distributional maps of extensive seagrass meadows in the southwestern Gulf of Kachchh (GoK) that colonise intertidal, mid-intertidal and subtidal zones were prepared. Results revealed an estimated total area of 20.35 km2 of seagrass meadows present in the SW-GoK. All four species, *Halophila ovalis, Halophila beccarii, Halophila decipiens, and Halodule uninervis*, have a varying colonisation depth (Dc) ranging from 2- 12 mts MHWS. *Halophila decipiens* is a new distributional record for the GoK. Meadows were characterised based on their elevation/depth relative to Mean-sea level (MSL), topographical and edaphic factors; High elevation, intertidal Reef-top meadows (RTM), Mid-intertidal tidal creek meadows (TCM), and subtidal meadows. A vast network of tidal channels and creeks were mapped, too. These were found to interconnect the spatially distant meadows across the reef complexes.

Chapter 3 I present the baseline data on the effects of temperature and light intensities on topographically distinct seagrass meadows. This chapter summarises seagrass species-specific (i) low-tide desiccation tolerance, (ii) low-light threshold, and (iii) temperature threshold for winter and summer seasons. At a regional scale, the growth phases of each species of a topographically different population (RTM, TCM) differ in their response to available light and temperature. With the use of multivariate and bivariate regression models, it was elucidated that proximate elements like temperature and light intensity assert a significant yet differential influence on the early stages (Germination, initial rhizome expansions) and late growth stages (morphometric growth, shoot multiplication, flowering/fruiting, dehiscence) of all seagrass population in the Gulf. Mann-Kendall trend tests were used to analyse the presence of seasonal growth trends in meadows. Through this study, I also present the first species-specific threshold range for temperature light intensity, within which initial emergent period and peak growth are facilitated. I further describe the reproductive phases of seagrass communities in the study area. The inception of peak phases of the flowering and fruiting period was elucidated for each seagrass species and was observed to also be regulated by increments in temperature and light intensities.

Chapter 4 presents the first fine-scale habitat selection strategies of dugongs in GoK. It describes the topographical variations within the foraging sites, habitat quality and factors that control the selection and preference of foraging habitats in the Gulf of Kachchh. I propose the use of foraging trails as a sighting substitute to analyse dugongs' relative use/preference in a complex shallow-water reef system functions as a cost-effective tool. Foraging trails and sighting data can only account for the foraging ecology of dugongs and approximate foraging movements. I used descriptive statistical analytical tools like t-test, F-test, and One way-ANOVA to test inter-site differences in edaphic, nutritive (%N), fibre (acid and neutral detergent), and foraging intensity (dugong foraging trail counts per area) among dugong foraging areas. Spatial analytical tools like near distance, contour, and Inverse Distance Weights (IDW) were used to construct tide-specific bathymetric maps for reef-top and tidal creek and subtidal meadows foraging areas. This raster layer was used as a base layer to study the foraging trail distribution and direct sighting records. The model analysed the role of foraging trail counts, forage biomass (in dry weight), and trail length (independent variables) as an effect of proximity of foraging ground to refugia distance (dependent variable) was estimated (table1). It was observed that forage biomass and distance of the foraging ground from the refugia contributed majorly to the total trail numbers and lengths. Tidal creek networks were used as movement corridors by dugongs, foraging in close proximity, which aided safety from low-tide stranding while foraging. Similarly, adjacent to foraging areas, deep-water coves served as a refuge from low-tide stranding at reef-top meadows (RTM). RTM naturally lack any tidal creek intrusion, unlike TCM.

The **synthesis** of my thesis includes the post-mortem results from two stranded dead dugongs, which confirmed the existence of a sexually active dugong population in the GoK. Through the post-mortem analysis, I have drawn inferences regarding their probable foraging grounds based on the seagrass composition in their gut contents.

Key findings:

- A total of 15 intertidal seagrass meadows and 12 minor and major subtidal meadows were identified and mapped for the first time in the southwestern part of the Gulf of Kachchh (GoK).
- All meadows mapped showed a spatial colonization pattern in which seagrass species showed spatial preferences towards certain types of sediment composition of the substratum.
- Seagrass meadows of GoK were observed with high turbidity and high-temperature tolerant species such as *Halodule uninervis, Halophila ovalis, Halophila beccarii* and *Halophila decipiens.*
- A new record of *Halophila decipiens '* distribution in the Gulf of Kachchh was reported, and its spatial patterns and morphology were studied.
- All four seagrass species found in the Southwestern Gulf of Kachchh are annual, wherein the emergence of geminates and expansion of rhizomes starts in the months of November-December. A peak growth period was observed in February-March. Dehiscence and subsequent senescent period commence after the month of March. Completion of defoliation and dehiscence of seagrasses occurred during the monsoon period.
- All species have a differential response to temperature and light exposure. Intra-species differences in these responses were also observed between topographically distinct sites.
- Dugong's habitat preferences characteristics included a relative ease of accessibility to foraging areas. They foraged on parts of meadows near a deep-sea refuge and avoided foraging further in a meadow that was away from their refugia.
- Dugong calves were often observed foraging on shallow-rooted *H. ovalis* and *H. decipiens* meadows growing on soft substratum (mud-silt) in tidal-creek meadows.
- Dugongs used the subtidal meadows for foraging during the low tide period.
- Intertidal meadows with high biomass were preferred during the high tide period.

- Unvegetated deep-sea coves were used as a refuge for resting and stop-over during the low tide period.
- Tidal creek and the channel network were observed to function as movement corridors. Tidal creeks also gave easier access to tidally affected interiors of foraging meadows.
- The percentage of Nitrogen content in the seagrasses was not found to be an essential deciding factor in dugong foraging habitat selection. All meadows had comparable percentage nitrogen values throughout the season.
- For the first time in India, the occurrences of sexual agnostic behaviours of dugongs were observed through post-mortem analysis of a few individuals.

Key Recommendations

- Topographically, discontinuous meadows are tidally interconnected via tidal channels and creeks. Since the tidal creek network is an important conduit for nutrients and oxygen, burial/sedimentation via offshore dredging can potentially impede this function. This makes tidal-creek meadows (TCM) at the Tam-Watan-Nakya belt and Patthiwadi reef especially vulnerable to the effects of sedimentation; therefore, dredging should not be allowed in these critical habitats of dugongs.
- Periodic low-tide aerial monitoring is a cost-effective method to map and monitor seagrass meadows. I recommend monitoring to be conducted at seagrass peak growth periods, i.e. late February-April.
- Post cyclone drone monitoring for possible meadow burial – TCM's Vulnerable/ Transit Creeks
- Adults of commonly found Green sea turtles can be used as a proxy subject for studying tidal/diel cycle movements and for identification of uncharted seagrass meadows in the Gulf of Kachchh.
- For decreasing anchor scars in the meadow, screw mooring anchors should replace the regular mooring anchors at Beyt Dwarka meadow, which is the only meadow closest to human inhabitation.

- Ban or regulate single-use plastic that enters the Gulf with a tourist influx. The tidal regime of the GoK meadows enhances the sedimentation of microplastics at every low tide phase, making meadows vulnerable to plastic pollution.
- Seagrass peak growth period (late February-May) is important for the identification of potential restoration areas and unhealthy meadows.
- The Dangad area of Paga reef is an important source for propagules of seagrasses that need to be included in the Protected Area for better management.
- Continuous awareness programs need to be conducted for the fishermen community who do fishing in and around critical dugong foraging habitats such as Paga, Bhaidar, Noru, and Chank reef.
- Go-slow zones (for fishing boats) must be designated for reefs of Bhaidar and Noru, as these reefs harbor the majority of the foraging areas.

My thesis provides a fine-scale ecological baseline about the spatial distributional and seasonal patterns of seagrass communities occupying topographically variant biotopes across an island-reef system in the southwestern Gulf of Kachchh (GoK), Gujarat. These ecological patterns of seagrass pastures are further used as a tool to study dugong grazing trails. Hence, the ultimate result of this thesis presented a detailed baseline description of dugong herbivory and their habitats. Specifically, the first baseline ecological description of habitat distribution, interconnectedness, seasonality and foraging movement of the last remnant population of dugongs on the western coast of the Indian subcontinent is presented.

Chapter 1- General introduction

Chapter 1- General introduction

Seagrasses

Seagrasses, marine angiosperms, are distributed vastly along the coastlines of tropical and temperate bioregions, becoming a characteristic of the coastal seascape (F. Short, M. Wycott, 2007). Seagrasses are one of the most cryptic oceanic benthophytes. These ecosystems are considered very productive and serve as nursery and breeding grounds for marine organisms (McRoy and McMillan, 1977). These plants generally prefer shallow, sheltered coastal waters with suitable bottom types and other environmental conditions for settlement and growth (Short, Coles,2001). Depending upon the species composition, seagrass meadows provide ecosystem services like protection from coastal erosion (Ondiviela et al. 2014), regulation of climate change, blue carbon storage, local food security and livelihood, and tourism.

With a coastline of 7,516.6 km bordering the mainland, India has vast, low-energy shallow waters favourable for seagrass meadow' settlement. Sixteen species out of the total of 60 global species are found in the Indian subcontinent (Thangaradjou et al., 2018). Starting from the north-western coastline of India, major seagrass meadows are found on (1) the southern coastline of the Gulf of Kachchh (Kamboj 2014, 2018), the Lakshadweep islands, Palk Bay and Gulf of Mannar on the east coast, and at the Andaman and Nicobar Islands, Understandably, due to the major differences in the bio-geographic, climatic, hydrodynamic, edaphic elements, these meadows vastly differ in species composition, spatial distribution and seasonality. The GoK experiences the highest tidal amplitude of 4-6 mts from Okha to Navlakhi (Setye et al. 1999; Unnikrishnan et al. 1999, 2003) via a mixed-semi diurnal tide. This creates a constant and lunar-variable movement of large volumes of water in and out of the Gulf. The seafloor of various reefs, creeks and islands of GoK becomes exceptionally unique in that hundreds of acres of reef area becomes completely exposed at two low tide events and submerged at the proceeding high tide periods. Irregularities in this relative submergence/emergence depend upon the elevation and w.r.t the low-tide line and lunar phase (spring/neap tides). However, resilience to tidal exposure in seagrasses is species-specific Unsworth et al., 2012; Manassa et al., 2017, and depends invariably upon seasonal changes. Understanding and assessing natural environmentally-driven change in seagrass growth requires identifying differentiation in the effects of natural turbidity (cyclones, storms, and monsoonal currents) from anthropogenic activities (dredging, mining, etc.). This baseline data is important when interpreting the results of seagrass monitoring programs.

In the Gulf, mud flats cover an area of approximately 1260 sqkm, compared to the 68 sqkm of sandy substratum. Kamboj 2018, Adhuvan et al. 2022 report, through a non-intensive survey, a total of six seagrass species from the Gulf of Kachchh: *Halophila ovalis, Halophila beccarii, Halophila ovata, Halodule uninervis, Halodule wrightii, Thallasia hemprichii* from across the southern coastline of the GoK. *Halophila sp.* and *Halodule sp.* belong to the pioneering group of seagrasses known for their fast regrowth.

Gulf of Kachchh's offshore islands are fringing type and composed of the typical mangrove-seagrass-coral reef flat triptych system. However, seagrass meadows are the understudied seascapes of the Gulf, resulting in a lack of an established ecological baseline. It, therefore, becomes imperative to map the shallow coastlines to establish a baseline for long-term monitoring of meadows. Further, seagrass potential areas must be explored and mapped accurately for possible range expansion and to understand spatial choices of seagrass species settlement. Through my thesis, I report the species distribution and range of meadows in the southwestern GoK. Spatial patterns and seasonality within meadows were also strategically studied. The results of this thesis will hence be the first comprehensive ecological baseline that can inform students, researchers and managers. Long-term monitoring of meadow hotspots about climate change can be further studied by building on this baseline.

Dugongs; a general introduction

Dugongs are fascinating marine mammals that belong to the Sirenian order, which also includes manatees. Globally, they are commonly known as "sea cows" and have a wide distributional range that spans the waters of approximately 48 countries and territories throughout the Indo-West Pacific, from the western Pacific Ocean to the eastern coast of Africa, along an estimated 140,000 kilometers (87,000 miles) of coastline between 26° and 27° to the north and south of the equator.

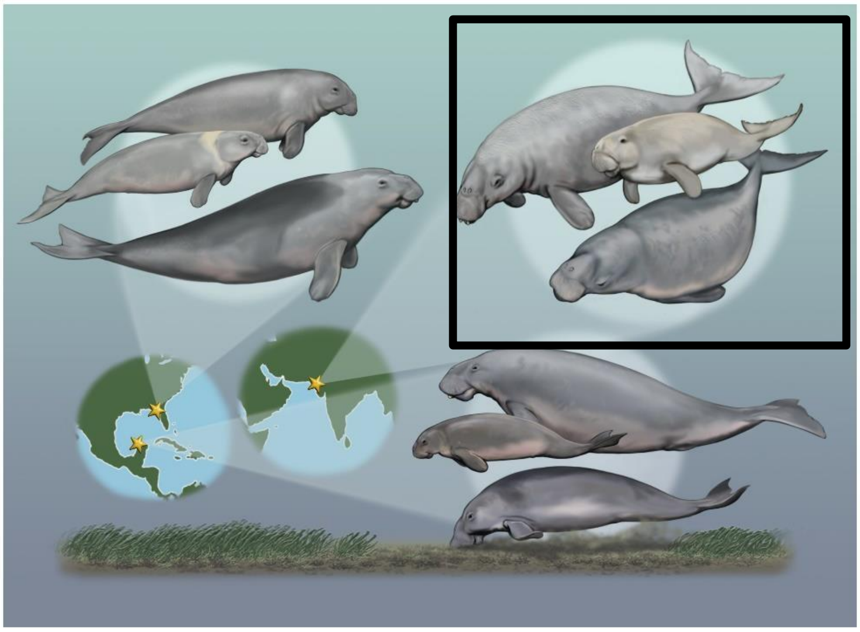
Dugongs are largely dependent on seagrass communities for subsistence and are thus restricted to the coastal habitats which support seagrass meadows, with the largest dugong concentrations typically occurring in wide, shallow, protected areas such as bays, mangrove channels, the waters of large inshore islands, and inter-reef waters. Being an exclusively marine herbivore, dugongs' populations occupying areas with vast topographical, geographical and environmental dissimilarities, have to adjust and adapt their herbivory tactics suitable to the region. In areas where there is a large tidal range, dugongs travel with the tide in order to access shallower feeding areas (Sheppard et al. 2010). Derville et al.2022 tagged 6 dugongs to understand their habitat-use patterns. They report a significant the differences in habitat-use across three eco-regions; shallow, deep-lagoonal, and for-reef shelf habitats of dugongs. Each eco-region was reported to have its unique topographical characteristics, providing a differential advantage to the resident dugong population. In my thesis, I address similar questions of relative habitat-use of resident dugongs of the GoK.

Dugongs in the Gulf of Kachchh

Sirenids of Gulf of Kachchh-

Dugongs in the Gulf of Kachchh are commonly known as *phranjara* by the local *Kachchhi* community. The vast salt pans of northern Gujarat, known as the *Rann* of Kachchh, are all underwater, forming a vast shallow sea colonised by seagrass species. This ancient sea supported dugongid megaherbivores: *Bharatisiren kachchhensis, Domningia sodhae and Kutchisiren cylindrica*, a multispecies consumer community in the geologic past Valez-Juarbe et al. 2012. The study implies the presence of tough rhizomatous seagrass species that could be uprooted by the *Domningia* species' cranial and tusk morphology. The seagrass community in the Gulf is limited to pioneering species belonging to the fast-growing *Halodule* and *Halophila* genus. This could be a gradual consequence of ancient large-scale herbivory from the multi-species community of dugongids in Gujarat.

The Gulf of Kachchh is predominated by semi-diurnal mixed tides with a tidal coefficient as high as 80-102 during spring tides. With an average tidal range of 4 mts at Okha port, it progressively increases towards the head to 6.43 m at Navlakhi from 3.02 m at the mouth near Okha. Each lunar phase brings about tidal fluctuations that cause exposure pressure on reef systems twice in a nychthemeron. Hypothesising that most of the foraging areas could be at the reef tops, the long duration of low-tide reef exposure may create a problem unique to the extant dugong populations, pauses in accessibility to the foraging areas and high risk of live stranding. My thesis has systematically addressed the stranding risk-avoidance behaviour and strategies of these reef-dwelling GoK populations.



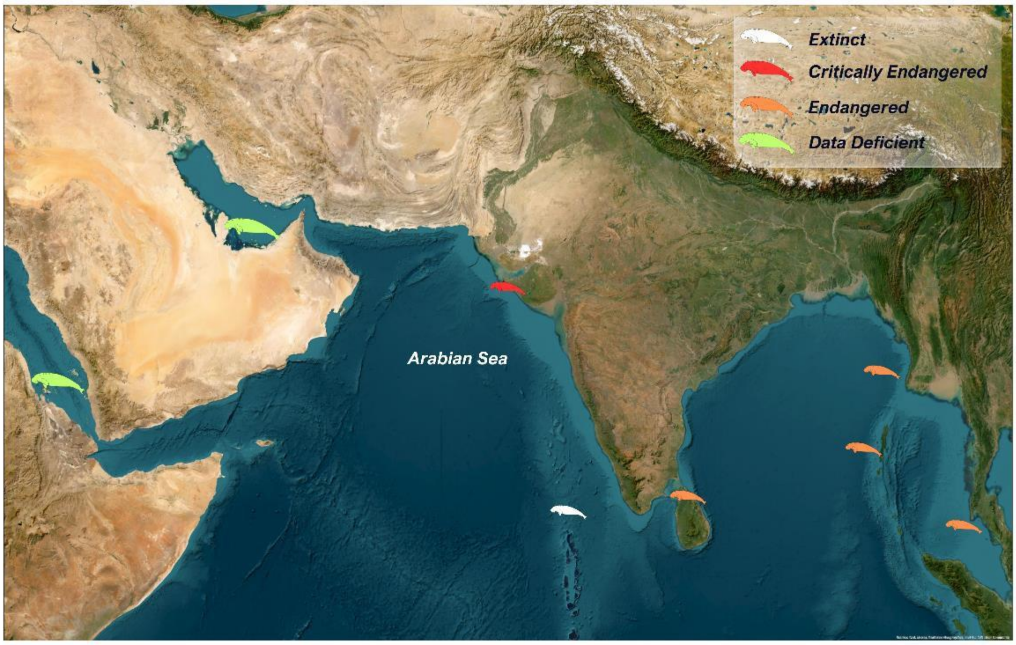
Clockwise (in the box) Bharatisiren kachchhensis, Kutchisiren cylindrica, and Domningia sodhae Valez-Juarbe et al. 2012

Predation-

Potential predators like the Pigeye shark, Pelagic thresher shark, Blacktip reef shark, and Hammerhead shark are among the large sharks that inhabit the GoK waters seasonally (anecdotal data). Whether dugongs are at predation risk by these migratory sharks remains uncertain; no dugong carcass retrieved have reported any shark bite marks in the Gulf. However, data acquired from interviews with fishermen suggest targeted shark fishing during the monsoon season might be a potential pressure on the survival of dugongs in the GoK. During the monsoon fishing ban period, sharks are occasionally and illegally sought after and are considered a valued catch. It has been suggested that the meat of dugongs, dolphins, and batoids is sometimes used as bait to lure commercially important sharks in the GoK waters.

Dugong distribution in the Arabian Sea-

The dugong population in the Arabian Gulf is believed to be the second largest in the world after Australia, and several areas in the region support important concentrations of dugongs year-round. The highest number of dugongs occur around Marawah Island in the UAE and between Qatar and Bahrain (Preen 2004). As per the Important Marine Mammal Areas (IMMA), after Australia, the central and western regions of Abu-Dhabi harbour a healthy population, with an estimated population of 2,682 dugongs. Large transboundary aggregations of dugongs were also reported to gather around the Hawar islands between Qatar and Bahrain Khamis et al.,2023. These massive herds are supported by an estimated 7000 km^2 of intertidal and subtidal seagrass meadows composed of *Halodule uninervis, Halophila ovalis, and Halophila stipulacea.* Apart from the Red Sea and Arabian Gulf, the dugong population in GoK is considered critically endangered, while the population in the rest of Southeast Asian ranges are considered vulnerable Panyawai et al 2022



Dugong distribution in the Arabian Sea

Chapter 2- Mapping the distributional characteristics and patterns of seagrass meadows in the south-western Gulf of Kachchh

Chapter 2- Mapping the distributional characteristics and patterns of seagrass meadows in the south-western Gulf of Kachchh

1.Introduction

Seagrass meadows are one of the world's most productive underwater ecosystems, but their ecological importance has long been overlooked. Seagrasses are vital habitats for various aquatic wildlife, and they produce large amounts of oxygen essential for fish in shallow coastal waters, blue carbon storage services, prevention from coastal erosion of sediments, nutrient cycling, eco-tourism services Mtwana. N et al. 2016, Himes-Cornell et al. 2018, Boudouresque et al. 2016. Tuya et al. (2014) reported that multispecies meadows in the Canary Islands make approximately 72000 USD/yr. from seagrass-associated commercial fishing. Seagrass meadows are considered to be indicators of coastal ocean health due to the ecosystem services they provide.

Mapping seagrass landscapes can help identify areas where seagrass meadows are thriving and areas where they are declining, which can provide valuable information for conservation efforts. However, there remained a long-term prevalence of data deficiency from the west coast of India regarding a systematic mapping of seagrass hotspots. This creates a scientific and conservation lacuna required to identify marine vegetated habitats of valuable habitat services. Secondly, the Gulf of Kachchh (GoK) is a hotspot for various chemical and infrastructure industries across the southern coastline. Moreover, the shallow water Gulf is an indispensable and one of the busiest shipping arteries in the nation (Fig 1). The cumulative impact of such persistent anthropogenic disturbances makes the mangrove-seagrass-coral reef habitats of the Gulf an eco-sensitive zone, regardless of its Marine National Park status.

Seagrass ecosystems are especially vulnerable to natural and anthropogenic threats, including impacts generated in adjacent marine and terrestrial ecosystems. Coastal reclamation, flooding events, siltation, dredging activities, and consequences of climate change are responsible for the worldwide reduction and fragmentation of these valuable habitats. Restorative efforts are still struggling to compensate for the large-scale seagrass habitat loss in England and Wales Green et al., 2021. To identify potential restoration-dependent sites and criterion type, i.e., restoring the extent or/and shoot density of an area, baseline distributional maps were long warranted for the study site in Gujarat. Therefore, this study aims to produce a fine-scale baseline map of seagrass landscapes in the Gulf of Kachchh to help identify vulnerable habitats and prioritise conservation efforts. These baseline maps will provide the species distribution patterns, meadows' extent, maximum colonisation depths, and seagrass species' sediment preference and answer questions about habitat variations within and between meadows across the GoK. To understand the effect of the tidal regime on meadows, a significant part of my study involves the construction of fine-scale local bathymetric maps to assess the relative tidal submergence/emergence of seagrass habitats.

This chapter provides spatially explicit information to answer those mentioned above, as well as largely unaddressed questions of spatial ecological patterns of seagrass habitat distribution within the GoK.

2. Methods

Sampling strategy:

A combination of intensive field-oriented ground-truthing and GIS-RS-based techniques were used to map the status and distribution of seagrasses in the Gulf of Kachchh. It was understood that meadows in the GoK experience mixed-semidiurnal tides, i.e., two high and low tides with different sizes each lunar day. Hence, exploratory surveys for seagrass mapping on reef tops were done during the low-tide period at minus to ebbing tidal phases. High-elevation reef-top meadows were accessed at days with tidal heights of 0.8mts and less, whereas mid-intertidal meadows were accessed at tidal heights of ≤ 0.4mts. However, subtidal mapping surveys were conducted during the slack phase of any receding or flooding tidal period to prevent overlapping of sampling between shallow and deep-water meadows.

Sampling locations

Potential meadows for ground truthing were identified by site triangulation that was done via analysis of a combination of low-tide satellite images and hydrographic charts. Nautical charts were also used to find the safest course for sampling at deep and asymmetric coves. For locating potential sites for sub-tidal meadows, hydrographic charts from software Navionics were used to identify sheltered areas near coves, bays, sand bars, spits, inter-reef regions, and other leeward areas.

Analysis of high-resolution low-tide satellite images of intertidal seagrass meadows was done using their spectral distinctiveness to identify potential intertidal survey sites**.**

Survey time

Reconnaissance surveys were made to study the spatial distribution of subtidal meadows from October 2019 to January 2020, during which intensive sampling was avoided due to winter sparseness in seagrass abundance. Pre-analysis of the seasonal surveys dataset and aforementioned habitat surveys revealed all the seagrass species in the majority of the habitats in the GoK undergo a seasonal dieback during monsoon (Chapter 3); hence, post-monsoon to pre-winters i.e., September to December were discluded from the study due to seasonal low-abundance. Surveys efforts were only restricted to seagrass' peak growth months i.e. February to April, during the entire study period (2020-2023). However, seagrass meadows characterisation, presence/absence and abundance estimate within the growth period began in 2018 (Jan-April)

Data collection strategy

Intertidal meadow mapping:

Intertidal meadows were assessed during the low-tide height of <0.5 m. Techniques like meadow-perimeter walking and range estimation using a Laser 50 Rangefinder were employed. Tracks waypoints (n~4000) were fixed using Garmin eTrex30 to characterise each seagrass-associated edaphic feature, such as rocks, rubbles, channels, sand, mud, seagrass, etc. During high tide, parallel transects were run over a meadow and physical parameters ***such as salinity*** depth via handheld depth Sounder HawkEye Dt1H. Since the intertidal meadows had homogenous coverage, a random stratified quadrat-based sampling method was used to estimate ecological parameters: seagrass point location, presence-absence data, species composition, shoot density, algal presence, and sediment composition.

GPS waypoints of marine algae data points, dead reef flats, and rocks (n~3025) were used to distinguish reef features at each site's low-tide Sentinel 2A (10 mts resolution) image.

Subtidal meadow mapping:

Depending upon the cove's size, sampling points were randomly marked in the navigation application. These were equally distributed along the depth gradient (leeward to shoreward) and within the confinements of the predicted perimeter of the area of interest (inter-reef/bay) area. These points were then navigated for sampling. To measure variations within a sub-tidal meadow at every depth gradient precisely, a replicate of each sampling point was also made.

Further, to avoid overlapping subtidal with mid-intertidal and intertidal zones, mapping efforts were only made around the receding tidal phase or low-tide period, exposing the reef areas (intertidal/mid-intertidal areas). Recorded depth values were adjusted to the mean sea level reported in the Okha Port's tidal chart and time of sampling. Point locations of sediment features like Rocks, cobbles, sand, silt, mud, etc. were also recorded at each site. Ecological parameters recorded at the subtidal points were similar to those at the intertidal mapping surveys.

All sampling points were contiguously spread to cover the entirety of a meadow's spatial extent. The spread and interval of sampling points depended on the size of the sampling site. This technique ensured full coverage of the meadow without compensating for the precision of the estimation of fine-scale ecological attributes (shoot density, depth, species composition).

Data Analysis

Bathymetry maps

Navigation applications did not project depth contours in most of the study areas. Hence, bathymetry maps were developed for each meadow type to understand the species distribution pattern in different depth gradients. GPS time tag corresponding to each waypoint was recorded to estimate the tidal height during the sampling effort. Using the estimated tidal height for each real-time depth value, water depths were then adjusted to levels corresponding to the local tidal height of 3.4 mts (mean high water spring MHWS) and 0.4mts (mean low-water spring MLWS). Lastly, at the high-tide period, transect surveys were conducted for sampling additional depth measurements of meadow-associated reef areas.

Further, to resolve the problem of irregularities in bathymetric features due to the reef system complexes, multi-temporal satellite imageries of study sites aided in demarcating depressions in the reef periphery that work as tidal inlets. Such reef-top tidal inlets were then used to cross-validate and revise reef-top depth values for a hydrogeographic zone. Using the resulting data, Inverse distance weight (IDW) was then used to create a raster for predicting the bathymetric state of sites at both spring high and low tide time periods.

Vegetation density maps

Shoot density estimates, composition, and fruit/flower counts were recorded from two replicates per sampling point. A bathymetric map was used to understand the colonisation zone of a meadow, subtidal or intertidal. Shoot density values recorded from the early season and from October to January were not considered for vegetation density maps. Peak growth seasons' (Feb-May) shoot densities were only integrated instead. Seagrass presence points were used regardless of the season. To visualise patterns in meadows' spatial distribution and abundance the sampling points were interpolated between homogenously spread ground-truthed reef waypoints to visualise patterns in meadows' spatial distribution and abundance. This was done using total shoot density/m^2 and adjusted depth values using the statistical interpolation method in ArcGIS, Inverse distance weights. Best results were acquired using the quantile method for classification for grouping raster classes

.Using predicted layers of high-tide/low-tide bathymetric maps, shoot-density gradient layer, minimum and maximum colonisation depths (Dc), predicted perimeter, homogeneity, and topographical patterns were extracted for the seagrass meadow of each study site. All local sampling points specific to an intertidal/mid-intertidal/sub-tidal zone were carefully segregated to ensure the homogeneity in measurements of independent variables: wave exposure, tidal depth variations, and sediment characteristics Fonseca, Mark, et al.2002. Each meadow's shape factor or compactness index was calculated to understand the natural structural complexity of the distributional extent (Perimeter of meadow/Area of meadow).

3. Results and Discussion

Based on the topographic elevation w.r.t MSL and their relative low-tide exposure at 0.4 mts tidal height, meadows in the SW Gulf of Kachchh were categorised into three broad classes: High elevation Reef-Top Meadows (RTM), mid-intertidal Tidal Creek meadows (TCM), and subtidal meadows (fig2). Fringing reefs formed crestlines around all RTM's of the Chepri, Noru, Chank and Paga reefs of the Gulf of Kachchh (fig3). A total of eight intertidal, two mid-intertidal, and over five subtidal meadows were mapped in the southwestern GoK (table1, fig 3). A contiguous reef complex joined the Chank, Noru, Bhaidar, and Khara/Mitha Chusna pir islands (fig 4). All meadow types exhibited a unique distributional pattern concerning low-energy zones, sediment characteristics, tidal exposure, and channel proximity. Habitat segregation in seagrass species settlement at RTM, TCM and subtidal meadows differed. Habitat illustration (fig 5) gives an overview of the habitat-specific species distribution.

1 Intertidal and mid-intertidal meadows

Reef-top meadows

All Reef Top Meadows (RTM's) combined perimeter was estimated to be 40.2 km. *Halodule uninervis* and *Halophila ovalis* formed mixed species meadows at the coarse-sand dominated sheltered reef tops. A continuous RTM dominated by *H. ovalis* and *H. uninervis* colonised substratum of coarse sand, fine-sand and gravel composition. Homogenous RTMs such as these occupy only within or around sheltered, leeward parts of the reef-flat zone and shallow lagoons. Meadow thinning was observed in perimeters that corresponded to high-energy seaward areas. Coves of reef provided a uniquely sheltered area for subtidal meadows to settle (fig 5(i)). Larger sized RTM's mapped were at Paga and Chepri reefs (fig 5(ii)). The shoot density of RTMs has a spatial pattern wherein the densest shoots occupied sheltered areas.

Conversely, a lower shoot density was observed for RTM patches near dynamic topographical and hydrodynamic features; sand dunes, and tidal inlets (blue arrows, fig5 (ii)). Sediment composition at the major RTM's was dominated by coarse sand, with clay lowest in proportions. Fine sand made 30%, and silt was 10 % of the total sediment texture (fig 12). Further, Adhavan et al., 2014, 2022, both report *Thallasia hemprichii's* presence in the GoK. Hitherto, I have made no such record for the species within the SW-GoK. Dangad reef is a lagoonal meadow with the largest perimeter of 3 km.

Non-meadow forming patches (<5mts) of *H. ovalis* and *H. uninervis* settled within the immediate interiors of back-reef areas of the reef-flat of Chank reef (east, fig 5(ii)). These shallow, rooted plants grew in dense clumps on the coarse-sand vacancy within rock-dominated areas. Shoreward patches (>5 mts patch size) north of Noru reef and Ajad Is. were composed of *Halophila ovalis, H. beccari, and Halodule uninervis* grew near mangrove forest on fine-sand-silty clay substratum (fig 5(ii)).

Mid-intertidal Meadows

Mid-intertidal areas of low reefs were dominated by channels and creeks (hereby Tidal creek meadows, TCM). A total of 50.6 kms was estimated to be the perimeter of this meadow, with A total area of 10.3 km^2 (TCM). TCMs have the largest tidal creek intrusion of any meadow in the GoK. Consequently, several overlapping low-energy flanks of tidal creeks create massive mudflats. TCMs in the SW-GoK are classified into two major categories: (i) Shallow TCM, located west and northwest of Bhaidar islands (fig 6 (i)). The average width of the shallow tidal creeks was 170.2 mts (straight line), with a sinuosity ratio of <1. *Halodule uninervis* and *Halophila ovalis* dominates the shallow-TCM.

Mud islands primarily composed of clay exclusively harbour mono-specific meadows of *Halophila beccarii*. Mud mounds were formed in shallow intertidal mudflats (MHWS≤3mts) with the lowest energy gradients that increase shoreward. Bhaidar Island has the largest area of mud flats both east and westwards of its shoreline. Noru Island has relatively smaller *H. beccarii* patches in the northern region of its shoreline. These islands are surrounded by shoreward-running meandering tidal creeks with an average width of 1.8 mts. (ii) Deep TCM formed a contiguous system in the SW of Noru reef (fig 6 (ii)). *H. decipiens* and *H. ovalis* primarily dominate this meadow. These meadows form a much deeper basin with MHWS 8.5 mts. The tidal creeks here, however, had an estimated average width of 10.3 mts with varying sinuosity indexes ranging from 0.9-1.63.

By and large, TCM's sediment texture consisted of fine sand (40%) as the dominant substratum, followed by clay (25%). Coarse-sand proportions were the lowest at all TCMs (fig 10). Deep-TCMs, however, had a higher proportion of silt-clay than the shallow-TCM habitats, making their sediment composition more akin to that of the subtidal meadows.

I reported the first new distributional records for *H. decipiens* in deep-TCM, a mid-intertidal habitat and subtidal zone of the Gulf of Kachchh, the northernmost range in the Arabian Sea.

Tidal fluctuations

Tidally affected GoK has hundreds of km^2 of reef area that undergoes complete aerial exposure due to the prevalence of semi-diurnal mixed tides with high tidal amplitude (3.0 mts in Okha and 6,0 mts in Navlakhi). This level of low-tide reef exposure is not observed anywhere across the coastline of the Indian subcontinent. Bathymetric maps based on the mean high tide (3.4mts) and mean low tide (0.4 mts) heights for RTM and TCM revealed that the meadows have a differential elevation-dependent exposure (fig 7). Settled at high elevation, all RTM experiences complete exposure at ~0-0.15 mts at all low-tide periods of tidal height <0.8 mts. Mean Sea level at spring (3.4 mts) and neap high tides (~2.4 mts) can go from approximately 1-4.5 to 0.2-0.5 mts, respectively (fig 7 (i)). Depth at high tide ranges from 2.3-4.2 mts, as opposed to the shallower RTMs like northern Betiwali reef, Chepri, and Chank reef, where the average high tide depth ranges from 1.56 mts.

Tidal creeks created depressions in the mud flat with the meadow, reserving the residual low-tide water of 0.04-0.6 mts at MLWS of 0.5 mts. High-tide depth of 2.5-3.6 mts at MHWS of 3.4 mts was estimated. However, the higher relative spatial heterogeneity in the topography of TCM compared to the RTMs resulted in a complex depth contour.

Subtidal Meadows

Lastly, subtidal meadows of monospecific *Halophila decipiens* settled in sheltered island bays and reef-flanked coves (fig 8,9, 10). These areas are mud-dominated and had an MHWS-13 mts.

Bay of Beyt Dwarka Island

The surveyed area of *Halophila decipiens* was estimated to be around 3.98 km^2 inside the cove and 0.15 km^2 outside the cove (fig 8(i)), in the sheltered eastern subtidal zone of the

Dunny spit; 37% of the surveyed area of the cove. *Halophila ovalis*' and *Halophila decipiens '* stands composed the meadow, with the latter dominating the mid-intertidal and sub-tidal zones of the Beyt cove. The total area of this submerged sub-tidal meadow at Beyt Dwarka island was 0.44 sqkm, which was 51.7 % of the total surveyed area of the cove. This was the largest of all subtidal meadows in south-west (table 1). *Halophila ovalis'* occupation was limited to the intertidal zone and gets exposed at ≤0.7 mts low-tide height. Maximum depth of the cove went up to 13 mts, however maximum meadow Dc was restricted to 8.1 mts (fig 8(ii)). These plants mainly grow abundantly on clayey-mud sediment in the shallow waters, reducing in shoot-density with the increment in depth, and silt/fine sand content. *H. decipiens*' shoot-density decreases with increment in silt/fine sand near Dunny sand spit. *H. ovalis*' maximum Dc extends up to 4.5 mts (MHWS), however an estimated average Dc remains to be 2.5 mts. Minimum Dc was ~2.5 mts wherein *H. ovalis* dominated.

Vadda Kabba cove

Monospecific stands of *Halophila decipiens* occupied the Vadda Kabba cove of Paga reef (fig 9 (i). This is the largest cove of the reef. Shoots were observed to be densest near the reef edge on both sides of the N-S-oriented cove. Gradual thinning in shoot density occurred with increasing proximity to the central tidal channel. Moreover, sparseness in shoot density also occurred seaward of the cove with the threshold Dc of 9 mts (fig 9 (ii)). Depth range of residual tidal water at low tide height of 0.4 mts is predicted to be 0.5-2mts. Predicted depth range at the cove during high tide height of 3.4 mts is 4.7-14 mts. Over 98% of the Vadda Kabba meadow was observed to remain submerged in a MLW depth of 1 mts. This cove also records the deepest ~12 mts depth (MHWS) to which *Halophila decipiens* colonizes (fig 9 (ii)). Dominant meadow substratum type was clayey-mud within the confines of the cove. The sediment texture gradient gradually changes from silt-mud to pure clay-mud from shore to sea-wards.

Chepri cove

Single-species pasture of *H. decipiens* occupied the south-eastern part of the Chepri reefs cove (fig 10 (i)). From a total surveyed area of 1.93 km^{2,} a monospecific stand of *H. decipiens* meadow in Chepri cove covered an approximate area of 0.27 km^2, making it

14.2% of the total surveyed area. Dc range was 3.4-8.6 mts (SDev±1.36), whereas the non-colonization depth range varied from 1.5- 39 mts (SDev±14) at (MSL-3.4mts). The minimum depth of residual tidal water at low tide (0.4mts) was predicted to be 0.6-1 mts. Maximum Dc was 8.9 mts. Within the perimeter of Chepri meadow, a monospecific stand of *H. decipiens* occupied regions of varying habitable depths: 1.2-7.8 mts (fig 10 (ii)). Non-habitable areas for the species also shared the same depth range within the surveyed area.

An illustrative summary of all seagrass species' colonisation depths within the waters of SW-GoK is shown in fig 11. These are average spring high-water depth ranges for each seagrass species, homogenised for all meadow populations within the region.

Sediment texture proportions of subtidal meadows depended upon the regional depth profiles of the cove. However, on an average, a higher estimate of silt was made at all meadows. Coarse-sand proportions were the lowest at subtidal meadows (fig 12)

4.0 Low energy zones and meadow' self-organisation

The reef system of southwest GoK provides a characteristic assortment of topographic and, consequently, benthic variations that result in a hierarchy of structural organisation.

The interaction of tidal currents with different areas of the reef system creates zones of low-energy waters. Murphy et al. 1995 methodically identified these high and low-energy zones, reporting that coarse sediment, low organic carbon and high seagrass coverage correspond to areas of high-energy zones within Zostera species' seagrass beds. In contrast, the opposite collates to areas of low-energy zones. Although conceptually true, the presence of morphologically smaller (than Zostera) *Halodule uninervis* and *Halophila ovalis* and a higher proportion of silt mud on reef-top beds signify that these areas receive relatively low tidal energy. This energy gradient must decline in the low-coastal mid-intertidal and lowest fore-reef subtidal meadows, as in Tam, Watan, and Nakya's mid-intertidal TCM.

Reef characteristics such as rocks and coral intrusion limit the extent of most meadows in the intertidal zone. Factors like light limitations and high current velocity of inter-reef tidal channels contributed to the constriction of subtidal meadows. Chepri meadow (fig 10), Dc and non-habitable depths fall within the same range, indicating that the prevalence of high-velocity tidal stream creates a barren central area. Meadow organisation here occurs on the low-energy flanks of the subtidal tidal stream.

I report that identifying low-energy areas across reefs is one of the elemental pre-requisite conditions for meadow settlement in a reef complex with the likeness of the Gulf's tidal regime. Further, the identification of such areas within a reef complex is a time-efficient step prior to meadow mapping.

4.0.1 Topographical configuration of seagrass meadows

Lastly, an estimated high perimeter and low area characteristic was observed for all the meadows (Table 1). This anomaly was due to the fact that the topographical configuration of the meadows is complex. This complexity was reflected in the shape index factor for each meadow. The results conclude the presence of complex perimeter convolutions, which causes perimeter increment without increasing the area. The higher the perimeter: area ratio, the higher was the shape factor/compactness. Tam-Watan-Nakya, the largest of all TCM, had the highest estimated area and perimeter, but lower topographical shape compactness when compared to most RTMs.

Further, smaller subtidal meadows (Table1- 11, 13, 14) had the highest estimated shape factor. This is due to the restrictions observed in the meadow occupancy, actuated by the lack of habitable space offered by smaller coves. For a larger subtidal cove like that of Beyt-Dwarka Islands and Chepri, a wider cover area caused a greater prevalence of seagrass habitable area, reducing the shape factor. Larger RTM (Table 1- 1 and 4, Fig 5 (ii) lower panel), had a large contiguous coverage with relatively less coral/rock intrusion at the perimeter, thus lowering the shape compactness. Low-tide image analysis of other major RTM (Table 1- 2-3, 5-7), with higher shape factor/compactness value indicated it to be the causal effect of perimeter intrusions and complete breaks by reef/rock coalescence, tidal streams, and barren sand dunes. The latter two largely observed in high-energy, tide dominated zones of reef-flats.

Limitations of spectral distinctiveness of meadows of SW- GoK

Studying the spectral distinctiveness of seagrass meadows is a cost-effective method to evaluate spatial and temporal changes (Ivajnšič, et al., 2022; Ferguson et al., 1997). Moreover, Ballard et al 2020 utilized innovative methods of mapping meadows of Thallasia sp. remotely via assessment of bubbles produced as photosynthetic by-product. Most of such remote mapping efforts are made to chart morphologically larger, and hence spectrally distinctive seagrass species such as Zostera, Posidonia, Thallasia, Enhalus etc. (Appolloni et al 2020, Fornes et al 2006) and areas of high spectral reflectance (coarse-fine sand).

Cross-validation of ground truthed presence/absence points (n=~800), perimeter tracks (n=18), shoot-density values(n=242), and species composition with Sentinel 2A (10 mts resolution) revealed that the significance of two major dense and continuous reef-top meadows of *Halodule uninervis* and *Halophila ovalis* at Paga and Chepri reefs. These RTM's show a spectral distinctiveness in low-tide satellite images taken during minus tides**.**

I report that the application of such methods is limited to visualise/map only a few reef-top meadows in the GoK, with a pre-condition of contiguous cover (~70%), high density (*Halodule* sp. dominant meadows), no coral/rock intrusion, and effective low-tide exposure. Results of post-visual analysis of low-tide satellite images (Sentinel 2A 10 mts resolution) of exposed RTM indicate that only Paga reef meadows' extent and density gradients can be accurately estimated remotely (fig 13). Similar spectral reflectance in RTM was also observed at Chepri and Chank reefs. However, interference from coral/rock and dunes, along with the relatively patchy characteristic of these meadows, reduced the meadows' sharpness of extent and caused a drastic reduction in intra-meadow spectral distinctiveness. All the aforementioned meadows are *Halodule uninervis* dominant mixed meadows.

Remote sensing methods have proven to be impractical to map the true geographical extent of the *Halophila* genus (Yaakub et al. 2013) and other small seagrasses owing to their phenotypically small sizes. Consequently, GoK's mid-intertidal and subtidal meadows were impossible to visualise remotely due to the dominance of morphologically smaller, albeit less reflective, *Halophila* sp. meadows. Further, the prevalence of turbid waters, complemented by lack of spectral reflectance of muddy substratum, decimates the visual accuracy. I propose that the use of seagrass species customised ground-truthed methods integrated with GIS based models are a better fitting technique to map seagrass meadows with high benthic and topographic heterogeneity in lieu of pure remote-sensing geospatial analysis.

Geevarghese et al., 2018, relied on processed Landsat 8 OLI imageries (30 mts resolution) to map seagrass spatial distribution of India. They incorporated radiometric, atmospheric and water column attenuation correction algorithms. This technique is suitable for producing spatial distribution maps for meadows in Palk Bay, the Gulf of Mannar and Lakshadweep; however, it is incompatible with GoK. This has resulted in (i) misidentifying areas that are inhabitable for seagrass settlement, e.g., rocky reef between Bhaidar-Noru islands, (ii) Their model does not support the identification and mapping of mid-intertidal or subtidal meadows (iii) Finally the overall estimated meadow area (17kms^2 is an underestimate since my ground-truthed data conclusively estimates over 20.5km^2 meadow area just for SW-GoK. Nayak et al., 2001, also used IRS (Indian Remote Sensing) satellite data 1A, 1B (70 mts resolution) to map and monitor the coastal vegetation of GoK. They concluded that mapping seagrass species and density is beyond the capabilities of purely remote sensing techniques.

Lack of adequate integration of accurate ground-truthed data rendered seagrass meadow mis-characterization for the GoK, resulting in grossly inaccurate and misrepresented distribution maps. A study that utilised ground-truthed surveys to map seagrass meadows' distribution in GoK (Kamboj 2014) was inadequate in that Beyt-Dwarka is listed amongst areas devoid of seagrass meadows. In contrast, my study concludes the presence of one of the largest meadows occupying Beyt's subtidal zone.

Summary

Fine-scale spatial patterns in the distribution and extent of seagrass beds were mapped for the first time in the Gulf of Kachchh, India. My study provides fine-scale baseline maps of spatial patterns and distribution of seagrass beds in SW-GoK. Intensive ground truthed methods combined with complemented aid of hydrographic charts and statistical interpolation methods IDW in ArcGIS were used to construct seagrass distribution and extent maps.
Relative wave exposure, low-tide exposure, depth, and differences in inter/within reef settlement were used as factors to identify and chart patterns in seagrass species presence, abundance, and depth profile. First fine-scale distributional maps of extensive seagrass meadows in the south-western Gulf of Kachchh (GoK) that colonizes intertidal, mid-intertidal and subtidal zones were prepared. Results revealed an estimated total area of 20.35 km^2 seagrass meadows present in the SW-GoK. All four species *Halophila ovalis, Halophila beccarii, Halophila decipiens, and Halodule uninervis* have a varying colonization depth (Dc) ranging from 2- 12 mts MHWS.

Halophila decipiens is a new distributional record for the GoK. Meadows were characterized based on their elevation/depth relative to MSL, topographical and edaphic factors: High elevation, intertidal Reef-top meadows (RTM) , Mid-intertidal tidal creek meadows (TCM), and subtidal meadows. Compared to the Gulf of Mannar, Palk Bay and the Andaman and Nicobar Islands, the seagrass richness was limited in GoK due to extreme tidal aerial/inundation and low-light conditions. Further, shorter inter-meadow distances between both subtidal and intertidal meadows suggest that the GoK's south-western zone is the most contiguous seagrass hotspot in the entire western coast of the Indian sub-continent. Importantly, I report that most meadows were tidally influenced by the semi-diurnal mixed tides.

Conclusion

An average surface clarity within the meadow where the stands were densest with an average shoot density of 1350/m^2 (SD±792) was 1.95 mts. Surface clarity estimates reduced near the sparse region of the meadow to 0.4-1.3 mts. It should be noted that these estimates for clarity were made during a low-tide time of the peak growth period when turbidity due to tidal currents and seasonal wind induced sediment resuspension was at the lowest in the Gulf. All species in the study area clearly have differential tolerance to low-tide exposure; *H. beccarri>H.uninervis,> H. ovalis>H. decipiens* (see illustration 1). Evidently, depth and minimum light requirement play a major influencing role in the success of seagrass settlement to deeper waters. Outside the Gulf, light-reflective sandy substratum and relatively clear waters of Mithapur reef increase the threshold Dc for meadows up to 14 mts. Conversely, meadows inside the Gulf experience frequent sediment resuspension events induced by tidal movement, reducing the threshold Dc's of *H. decipiens* meadows to <11 mts, limiting the extent of homogenous pastures to shallower and sheltered sub-tidal zones.

H. ovalis, H. uninervis, and H. beccarii mainly colonised the upper intertidal zones and were observed to have species-specific sediment preferences. *H. decipiens*, a low-light specialist and a new record for GoK, was observed to be the most widely spread species in the mid-intertidal and subtidal zones of reefs studied. The geographic range of *H. decipiens* described in this study is the northernmost for the species in the Arabian Sea. Predictive-real extent maps also revealed a relatively small inter-meadow distance between both subtidal and intertidal meadows, suggesting that the GoK's south-western is the most contiguous seagrass hotspot in the western coast of the Indian subcontinent. Mapping seagrass landscapes can help monitor changes in seagrass meadows over time, including changes in density, coverage, and structure. This information can be useful for future monitoring of the changes in the meadows and for studies that require data on large-scale meadow structure, such as inventories of associated biota, blue carbon storage, or modeling of the local hydrodynamics. Identifying seagrass conservation and restoration priorities: Mapping seagrass landscapes can help identify seagrass conservation and restoration priorities by coupling habitat suitability and anthropogenic pressures. This can help prioritize conservation efforts and ensure that resources are allocated to areas where they are most needed.

As human populations expand and continue to live disproportionately in coastal areas, bringing new threats to seagrass habitat, a comprehensive overview of seagrass landscapes is essential for their conservation and management. The study provides spatially explicit information in shallow waters using satellite images and field data. It presents a quantitative and cost-effective alternative for intensive in situ monitoring programs. This information can be useful in coastal management and decision-making.

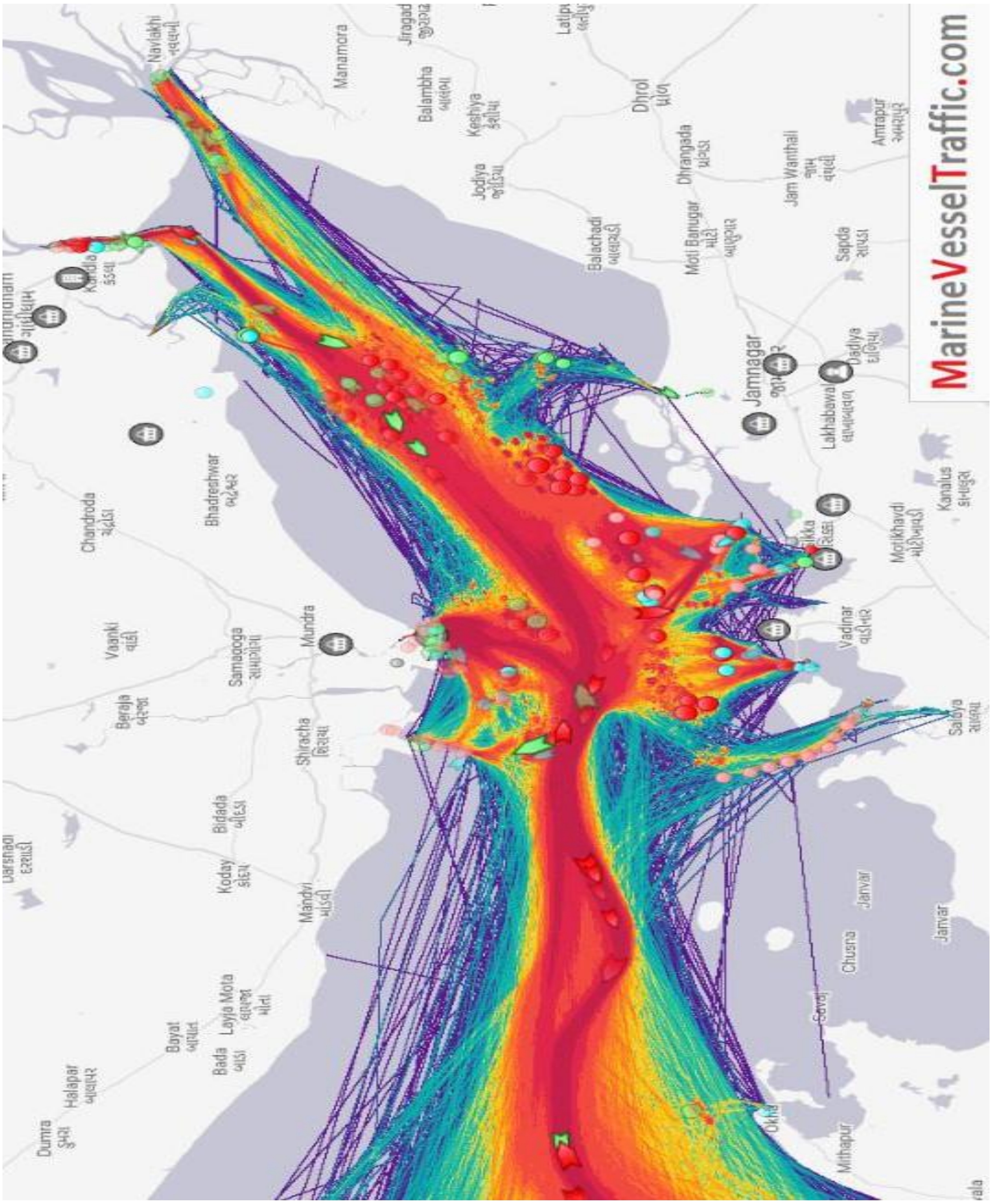


Fig 1 AIS image of shipping routes within the Gulf of Kachchh, Gujarat. The study area has minimal intrusion of heavy cargo containers. However, the shipping lanes proximity to the most offshore study area is < 6kms

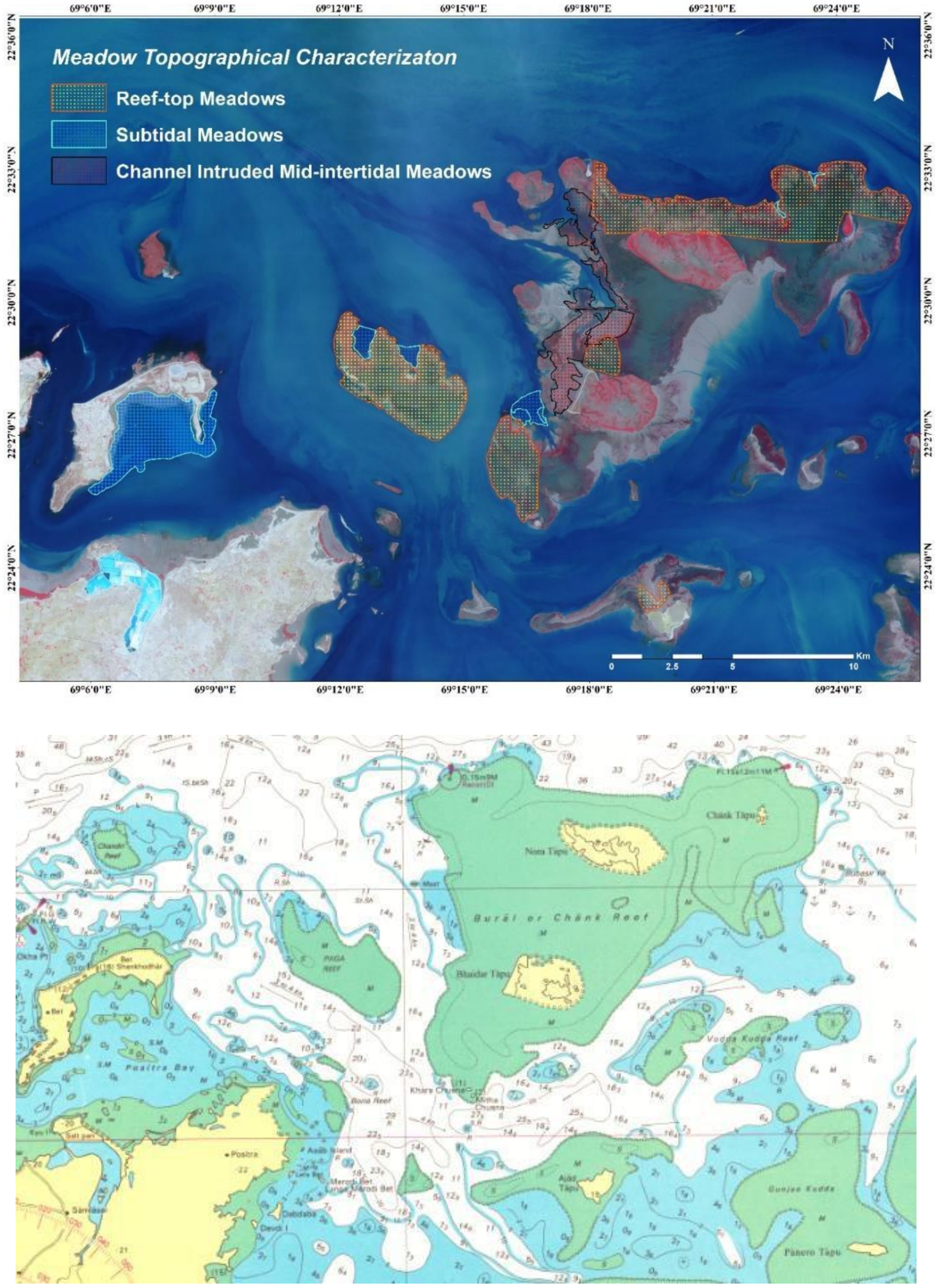


Fig 2 General categorization of seagrass meadows in the SW-GoK based on colonization depths. Fringing and Patch reefs are shown in green in the hydrographic chart below. Upper low-tide Sentinel 2A (10 mts resolution) shows the fine-scale topographical characteristics of reef-tops, mud-flats, sand dunes, channels, rocks, mangroves and islands.

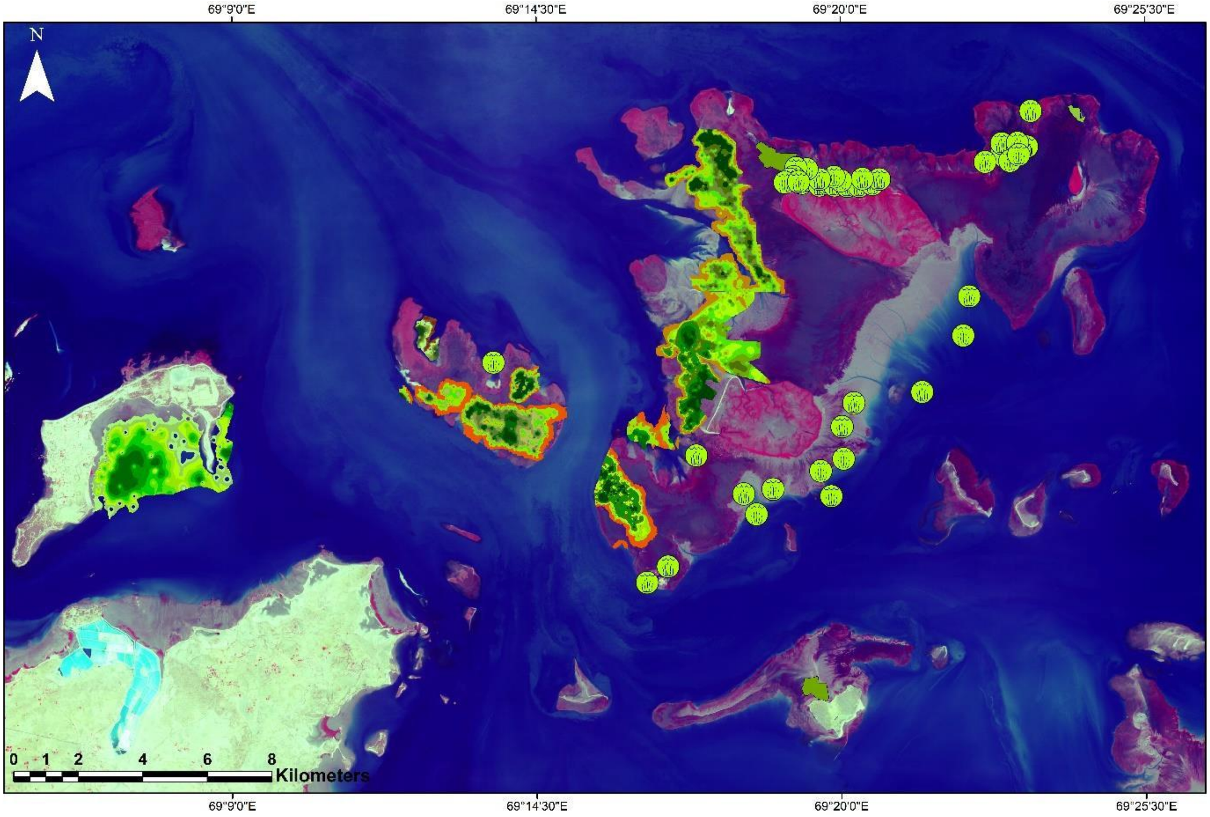


Fig 3 Spatial distribution of all seagrasss meadows in the South-western GoK. Point locations (green marks) oindicate the seagrass meadows on the eastern and northern side of the reef-complex

S. No	Site	Colonization zone	Seagrass sp. composition	Total meadow area (sqkm)	Perimeter (in kms)	Shape factor/compactness index	MSLW depth (in mts)
1	Dangad meadow (Paga reef)	Intertidal	HU, HO	2	13	6.5	0.25
2	Betiwali meadow (Paga reef)	Intertidal	HU, HO	0.21	3.3	15.71	0
3	Rumia meadow (Paga reef)	Intertidal	HU, HO	0.18	3.3	18.33	0
4	Chepri meadow	Intertidal	HU, HO	1.49	13.7	9.19	0
5	Chank meadow	Intertidal	HU, HO	0.18	2.37	13.17	0
6	Nor meadow (East)	Intertidal	HU, HO	0.26	2.2	8.46	0
7	Ajad meadow	Intertidal	HU, HO, HB	0.18	1.7	9.44	0
8	Patthiwadi meadow	Mid-intertidal	HU, HO, HB	6	19.6	3.27	0.1
9	Tam-Watan-Nakya basin	Mid-intertidal	HU, HD, HO, HB	4.13	31	7.51	0.15
10	Beyt-Dwarka	Subtidal	HD, HO	3.85	21	5.45	>1
11	Vadda Kabba	Subtidal	HD	0.44	5	11.36	~1
12	Chepri cove	Subtidal	HD	1.4	4.3	3.07	>1
13	Hankiwala cove	Subtidal	HD	0.023	1.1	47.83	>1
14	Kabdi cove	Subtidal	HD	0.012	0.76	63.33	>1

Table 1 Categorization of meadows was based on depth colonisation zone, species composition and low-tide depth MSLW(Mean Spring Low-water. Area (in sqkms), Perimeter (in kms), Shape fator shows how expansive or constricted the meadows areas

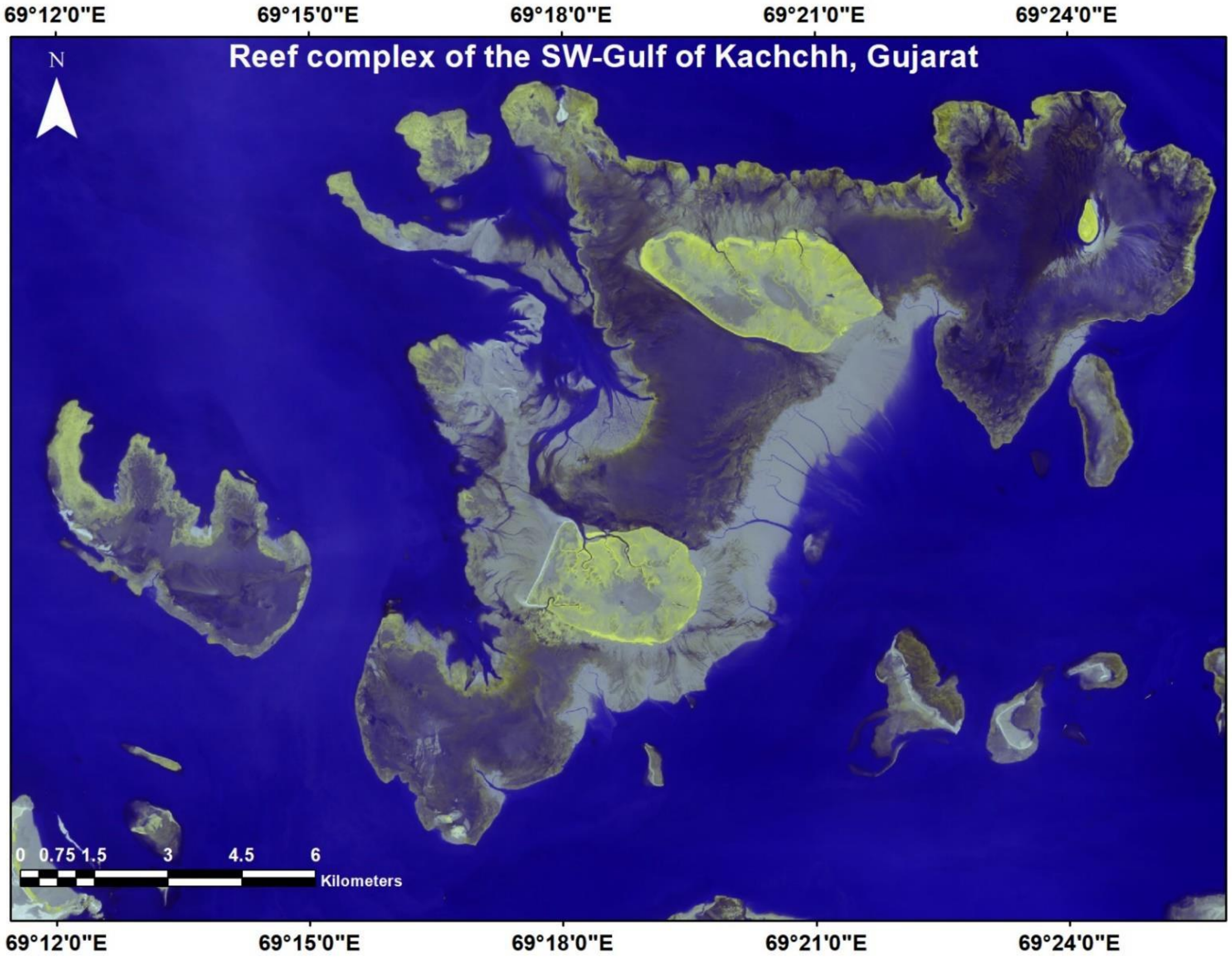


Fig 4 Sentinal 2A low-tide image (10mts resolution), showing the rocky fringing reef-flat adjoing the Bhaidar-Noru-Chank island-reef complex. Paga or Pagar, a patch reef exposed towards the west of the reef-complex. All low-tide exposures takes place twice a day, when low-tide height goes below 1.4 mts.

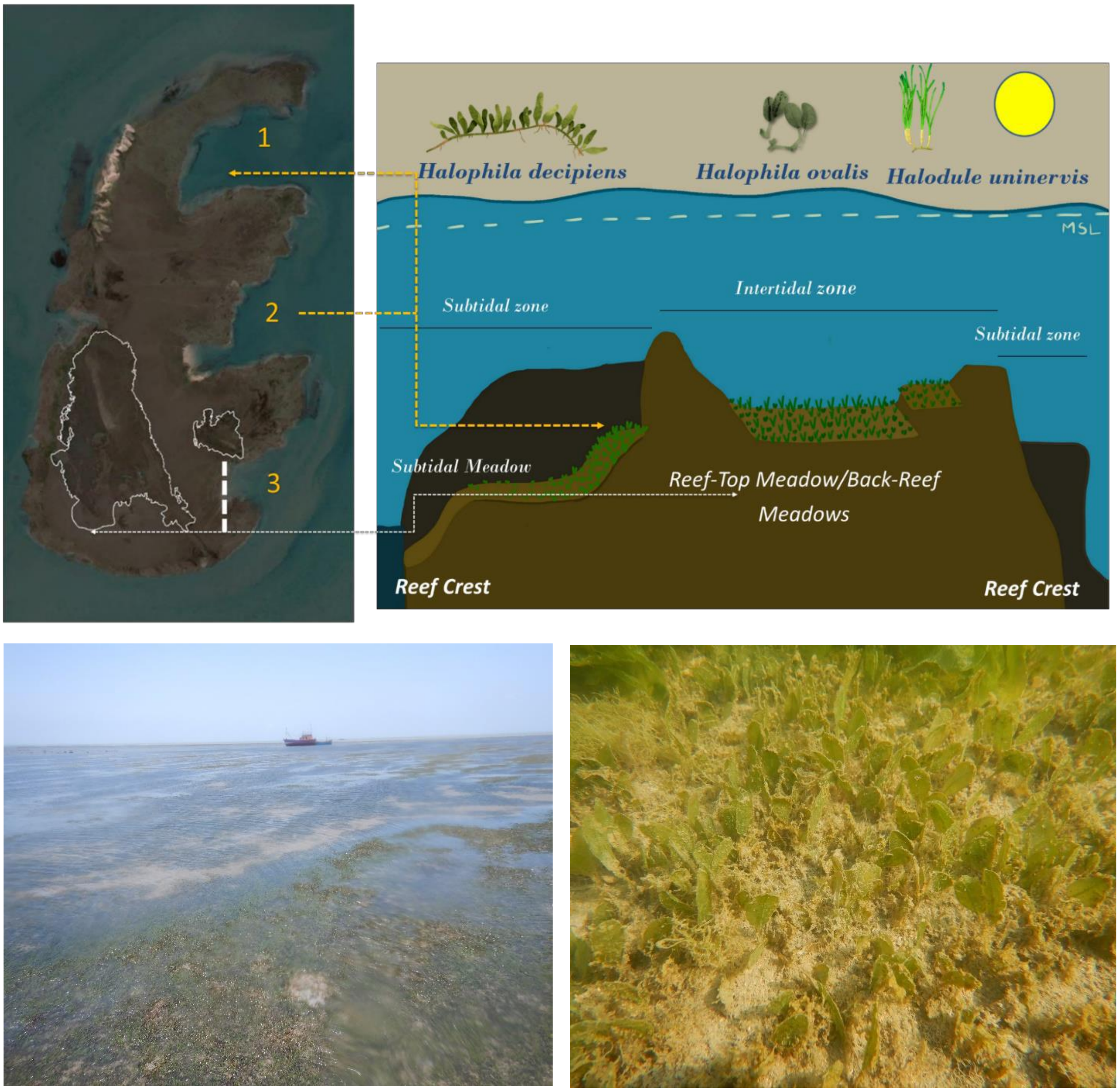


Fig 5 (i) Reef-top meadows- Topographical characteristics of a typical RTM in SW-GoK. Sattelite imaage of Paga reef (top left) has been used to represent shallow RTM- Subtidal cove meadows' association. White perimeter shows *Halophila ovalis* and *Halodule uninervis* RTM of Paga reef (excluding smaller meaodws). Bottom panel,left – Image of RTM at low-tide (<0.6mts), right- cloe-up image of *Halophila ovalis* at Chepri reefs RTM

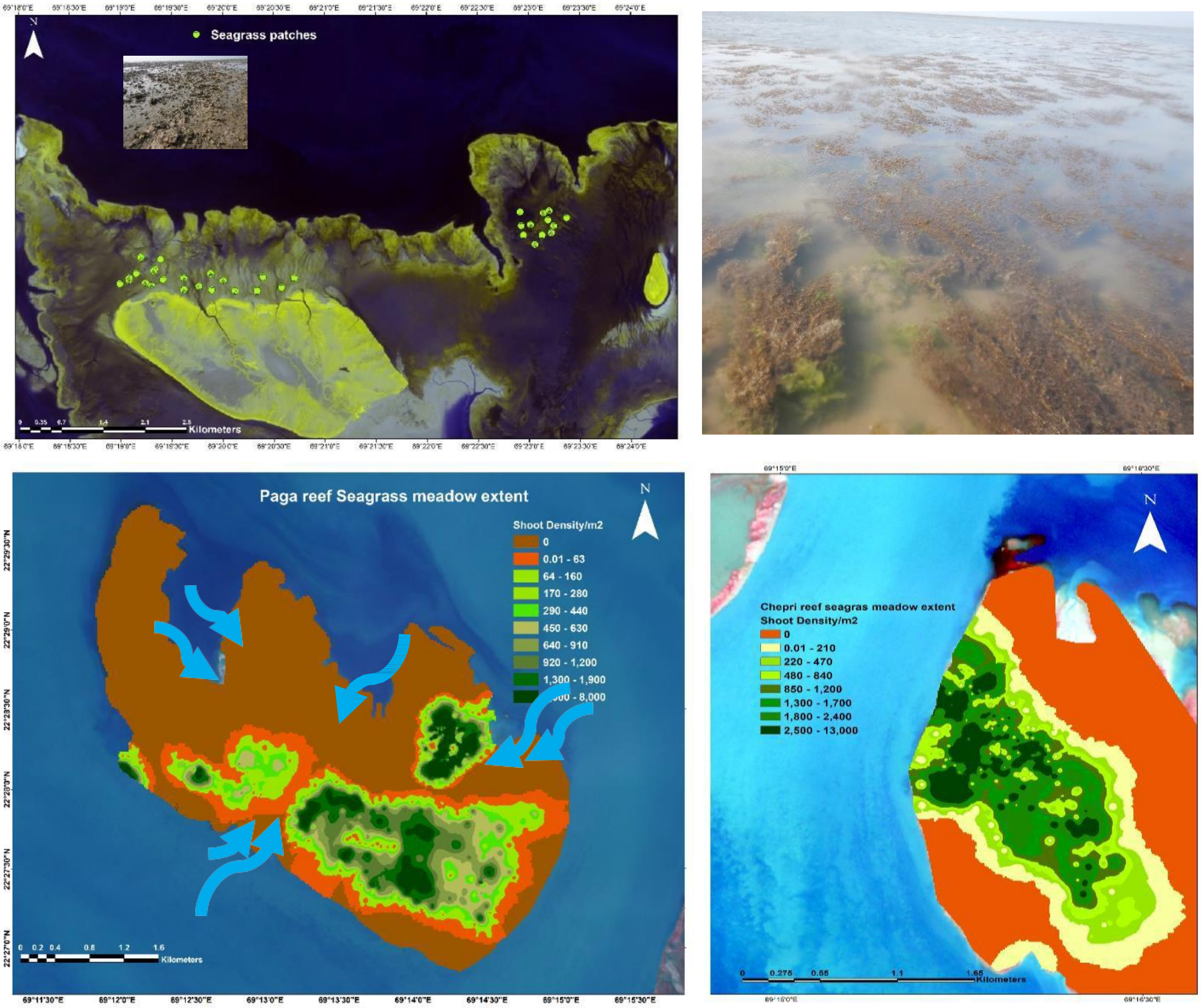


Fig 5 (ii) Reef-top meadows- Clockwise(upper panel)- Non-meadow forming seagrass patches at Nor and Chank islands' fringing reef. Lower panel- Major Contigous RTM's of the SW-GoK. Blue arrows indicate the direction of flooding tidal currents at Paga Reef

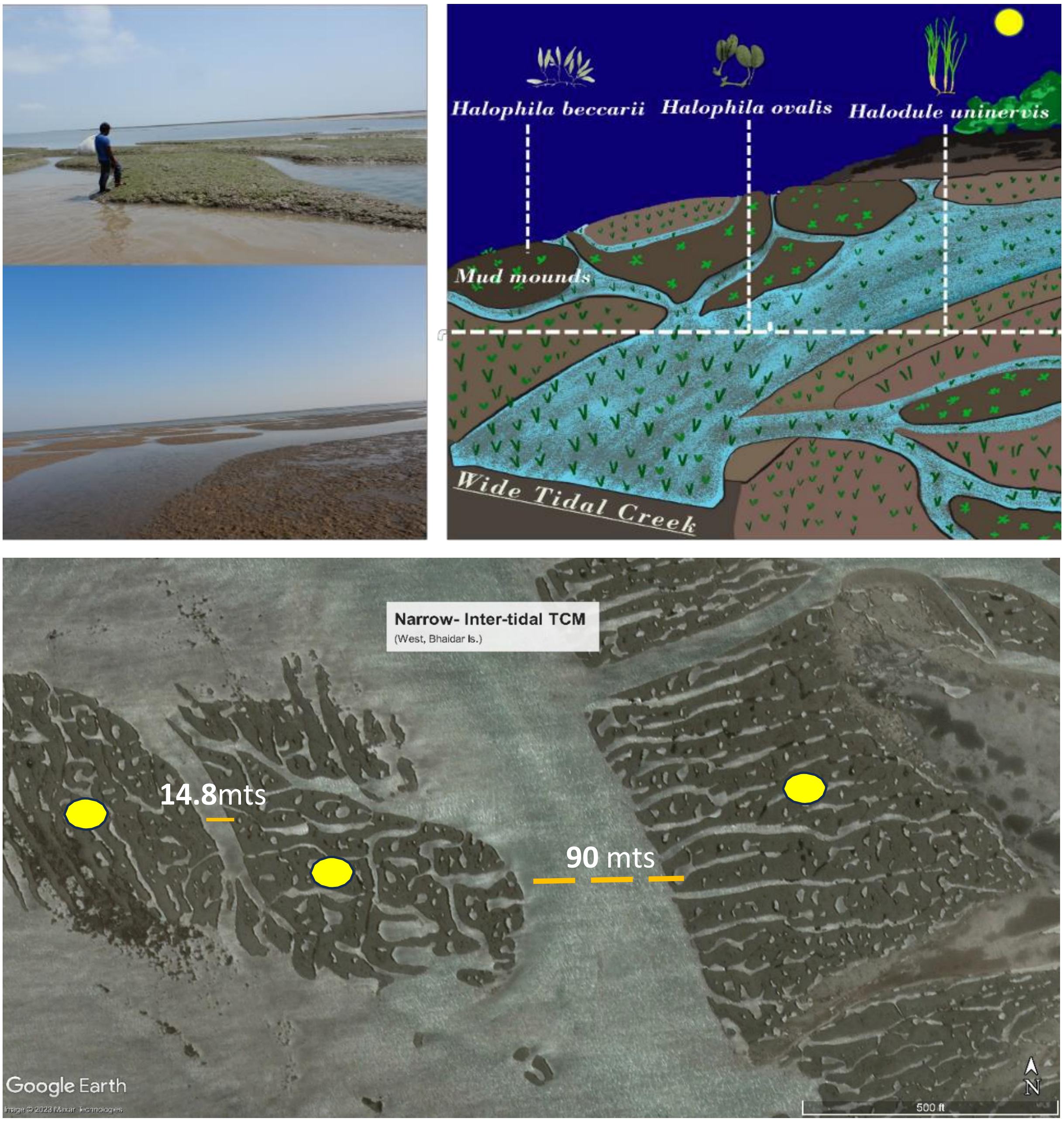


Fig 6 (i) Shallow Tidal-creek meadows were reported from SW-GoK at Bhaidar islands' Patthiwadi and Nakya reef, and at Ajad Island. Bottom picture- Satellite image (Landsat Cpoernicus, ©2023Maxar Technologies) of Bhaidar islands Shallow-TCM at 500 ft altitude. The tidal channels are flanked by mud-mounds or mud islands (yellow marks). Depth of shallow tidal creeks ranges from >0.5 mts at MLWS and 2.5-3.6 mts at MHWS.

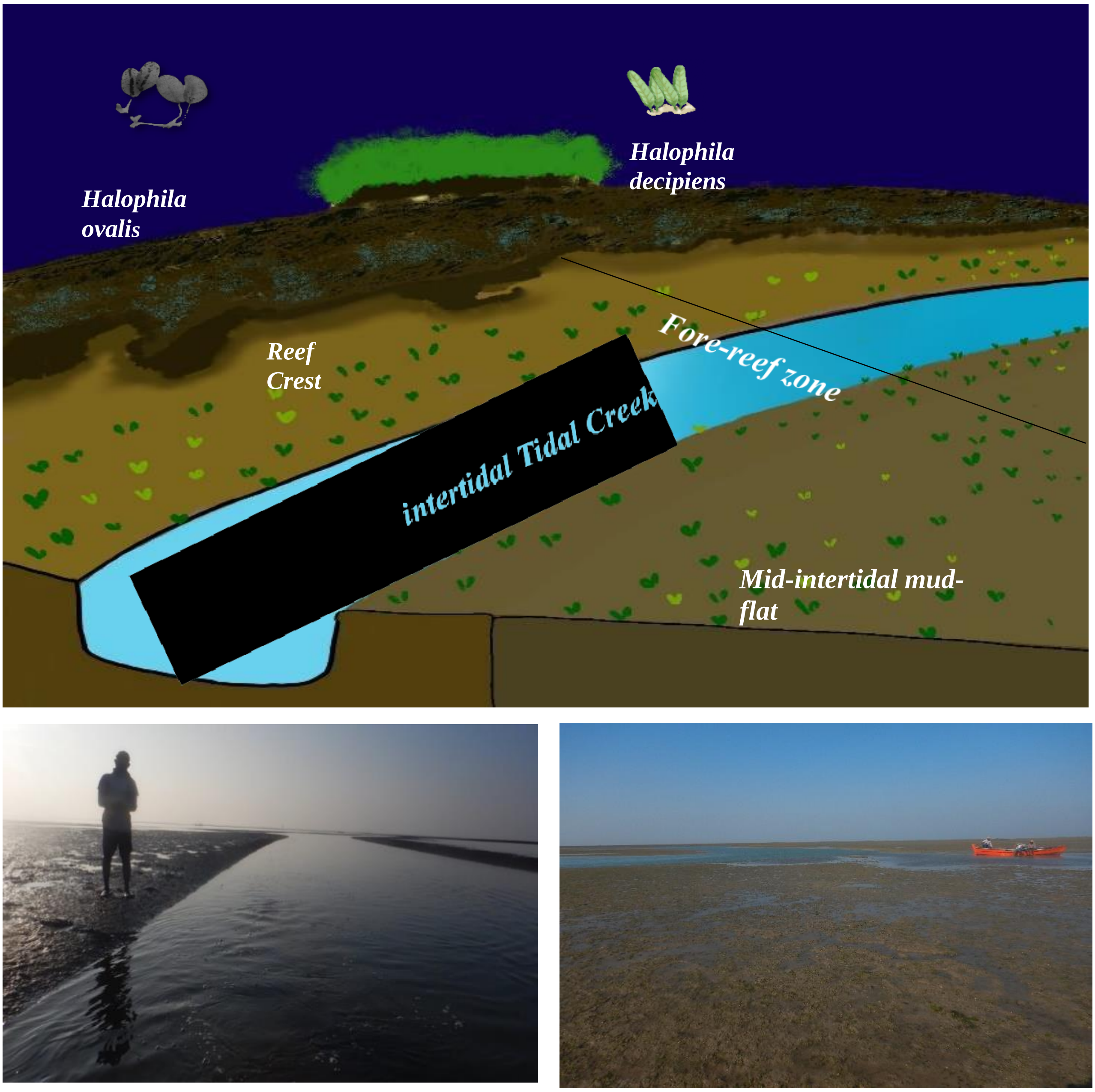


Fig 6 (ii) Deep Tidal creek meadows of mid-intertidal mud-flats, South of Noru Reef. The avergae depth of the naroow tidal-creeks may vary from 0.7 mts at MLWS and 6-12 mts in MHWS.

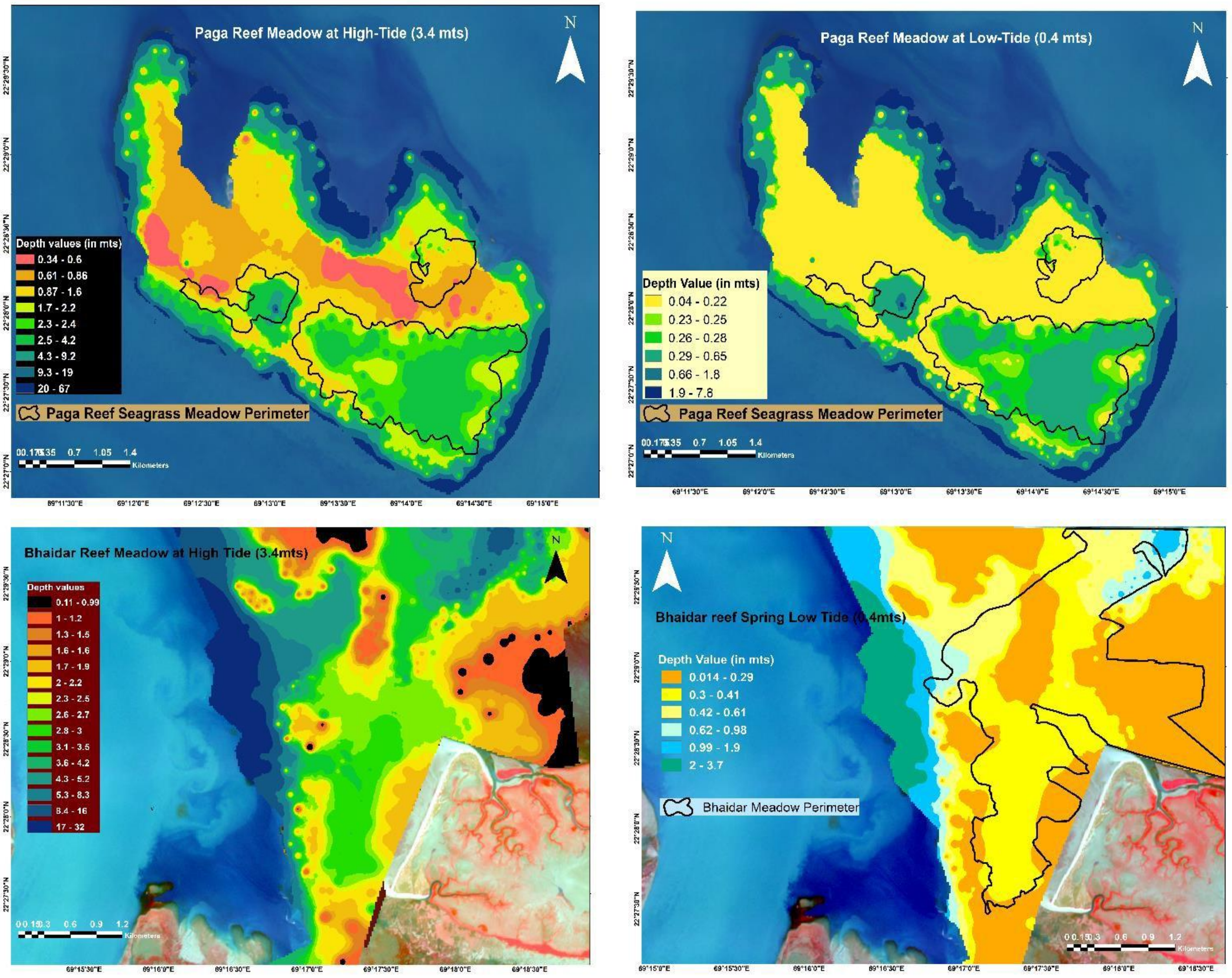


Fig 7 (i) Upper panel, Paga reef, High elevation RTM; Regional bathymetric map for high tide (left) of tidal height 3.4 mts (MHWS), and low-tide (right) at tidal height of 0.4 mts. (ii) Lower panel, Bhaidar Is., TCM; Regional bathymetric map for high tide (left) of tidal height 3.4 mts (MHWS), and low-tide (right) at tidal height of 0.4 mts.

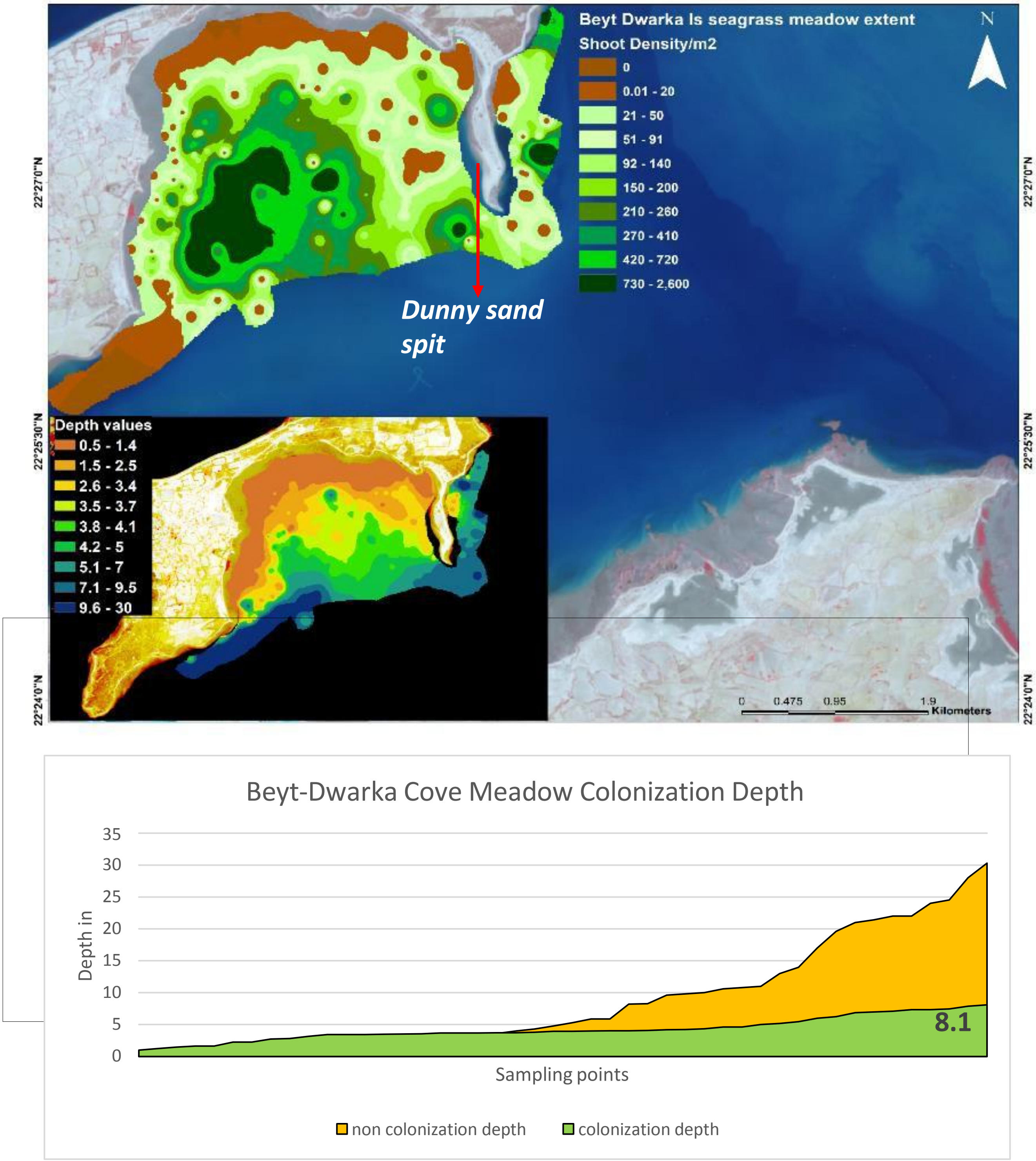


Fig 8 Subtidal meadow (i) Beyt Dwarka bay's seagrass meadows spatial extent and shoot density gradient. (inset) Local bathymetric map of Beyt-Dwarka for a tidal height of 3.4 mts (derived tidal height at MHWS). (ii) Meadow colonisation depth (n=19) (Dc) and non-colonisation depth (n=41) across the Beyt-Dwarka cove. Maximum Dc for *Halophila decipiens* at Beyt-Dwarka- 8.1 mts

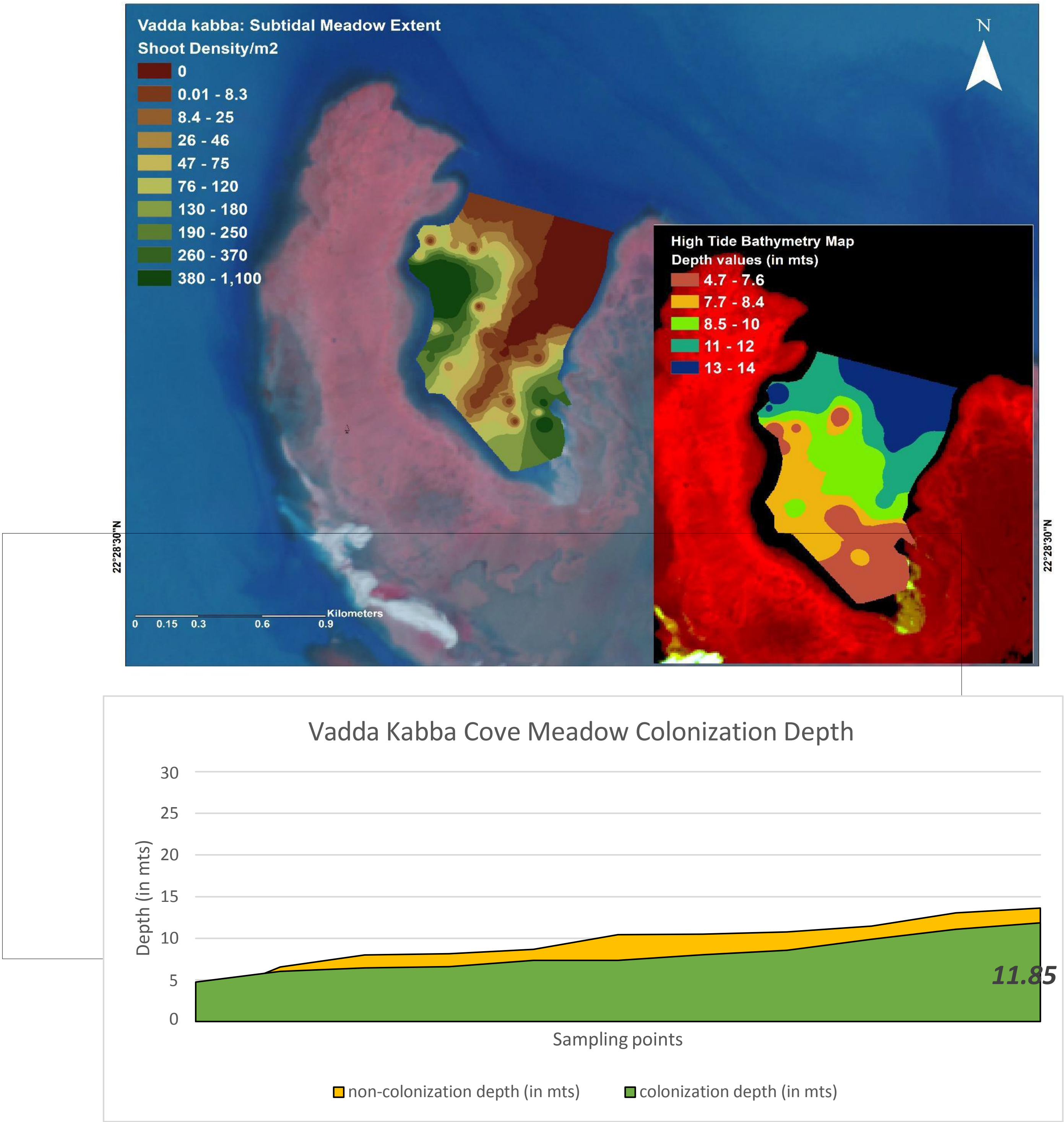


Fig 9 Subtidal meadow (i) Vadda Kabba coves (of Paga reef) seagrass meadows spatial extent and shoot density gradient. (inset) Local bathymetric map of Vadda-Kabba cove for a tidal height of 3.4 mts (derived tidal height at MHWS). (ii) Meadow colonisation depth (n=10) (Dc) and non-colonisation depth (n=7) across the Vadd Kabba cove. Maximum Dc for *Halophila decipiens* at Beyt-Dwarka- 11.85 mts

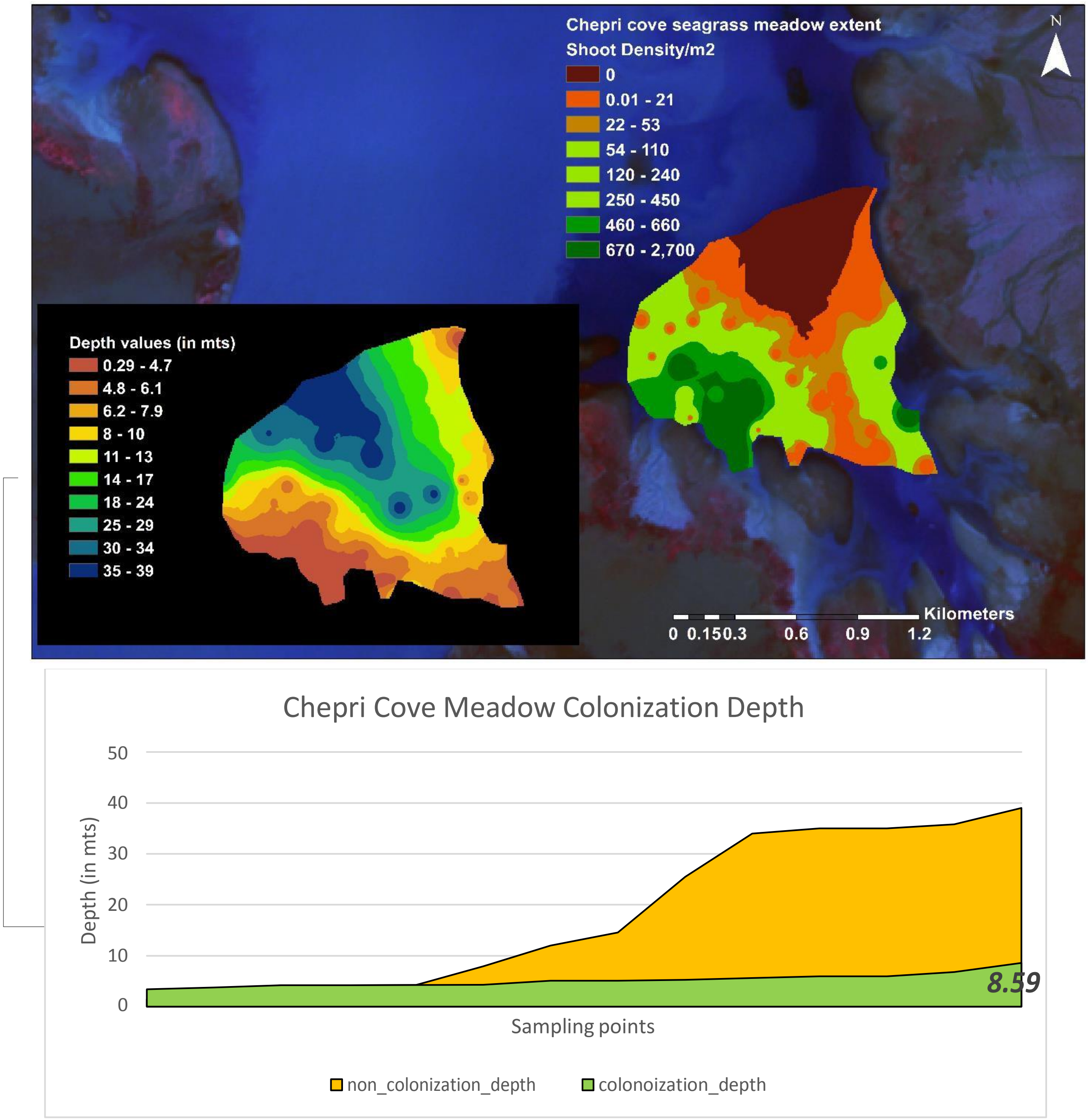


Fig 10 Subtidal meadow (i) Chepri cove's (of Paga reef) seagrass meadows spatial extent and shoot density gradient. (inset) Local bathymetric map of Chepri cove for a tidal height of 3.4 mts (derived tidal height at MHWS). (ii) Meadow colonisation depth (n=10) (Dc) and non-colonisation depth (n=7) across the Chepri cove. Maximum Dc for *Halophila decipiens* at Beyt-Dwarka- 8.59 mts

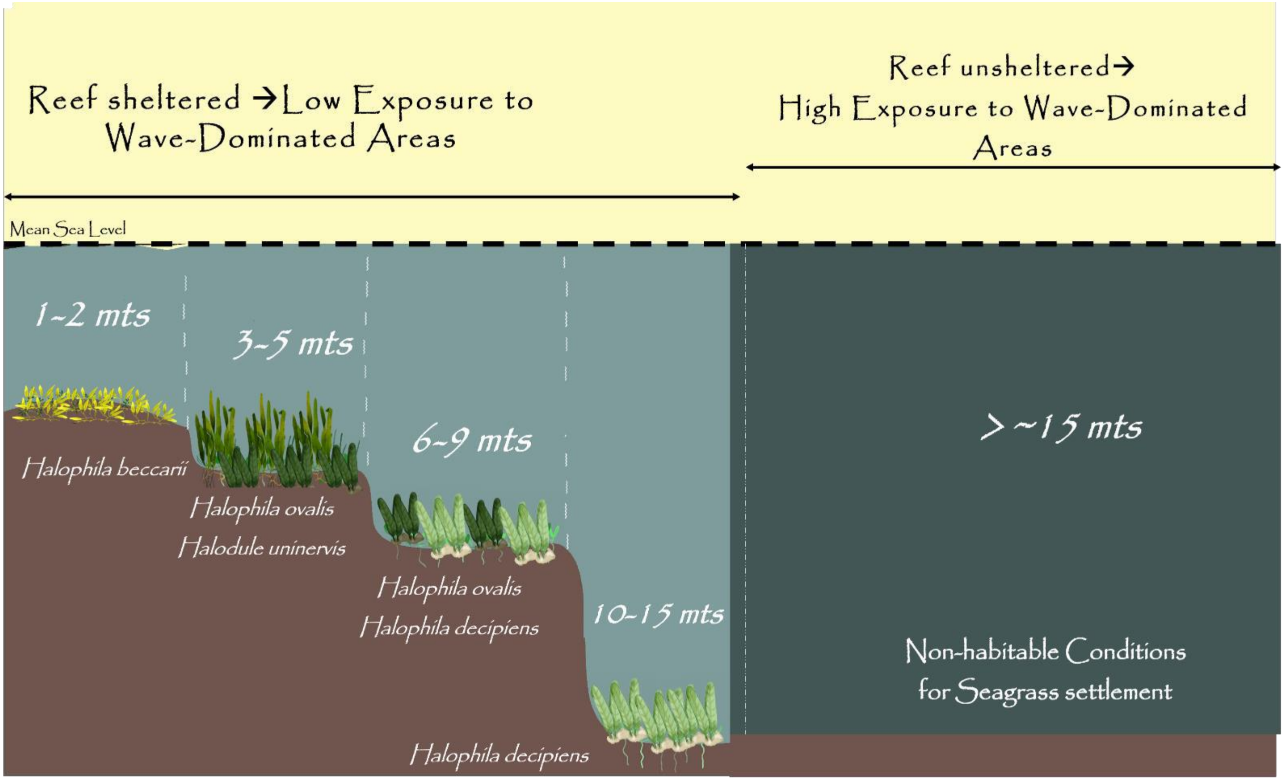


Fig 11 Illustration , Seagrass species-specific MHWS depth ranges in the SW-GoK.

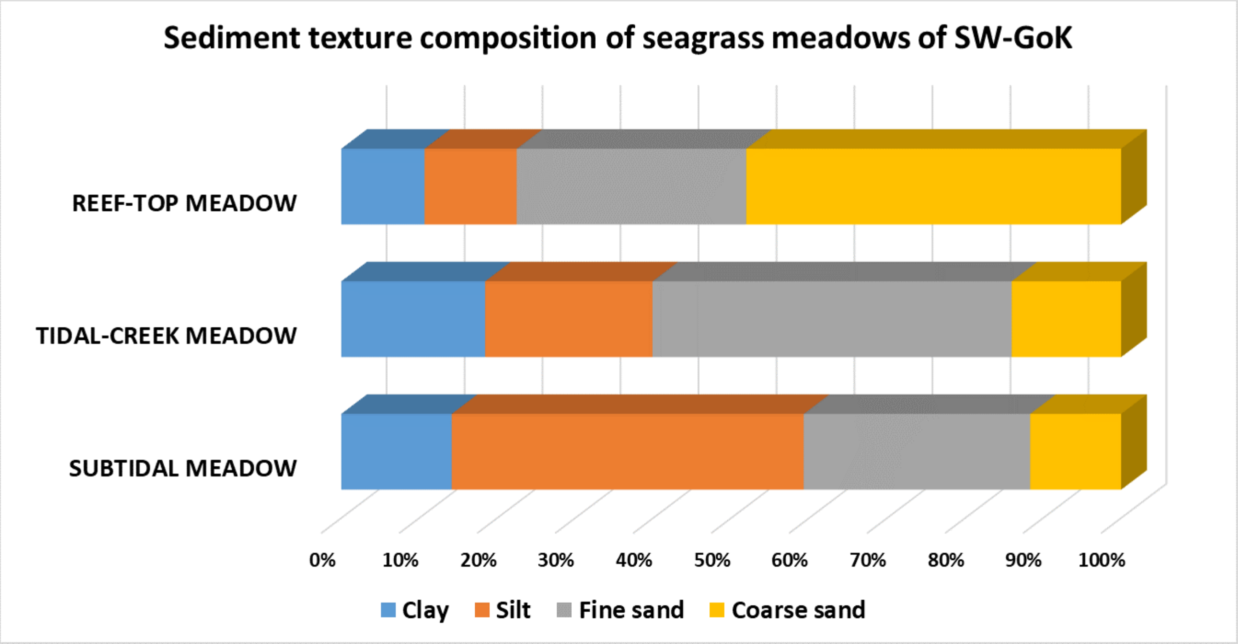


Fig 12 Sediment texture composition of each seagrass meadow type; RTM, TCM, and subtidal meadow.

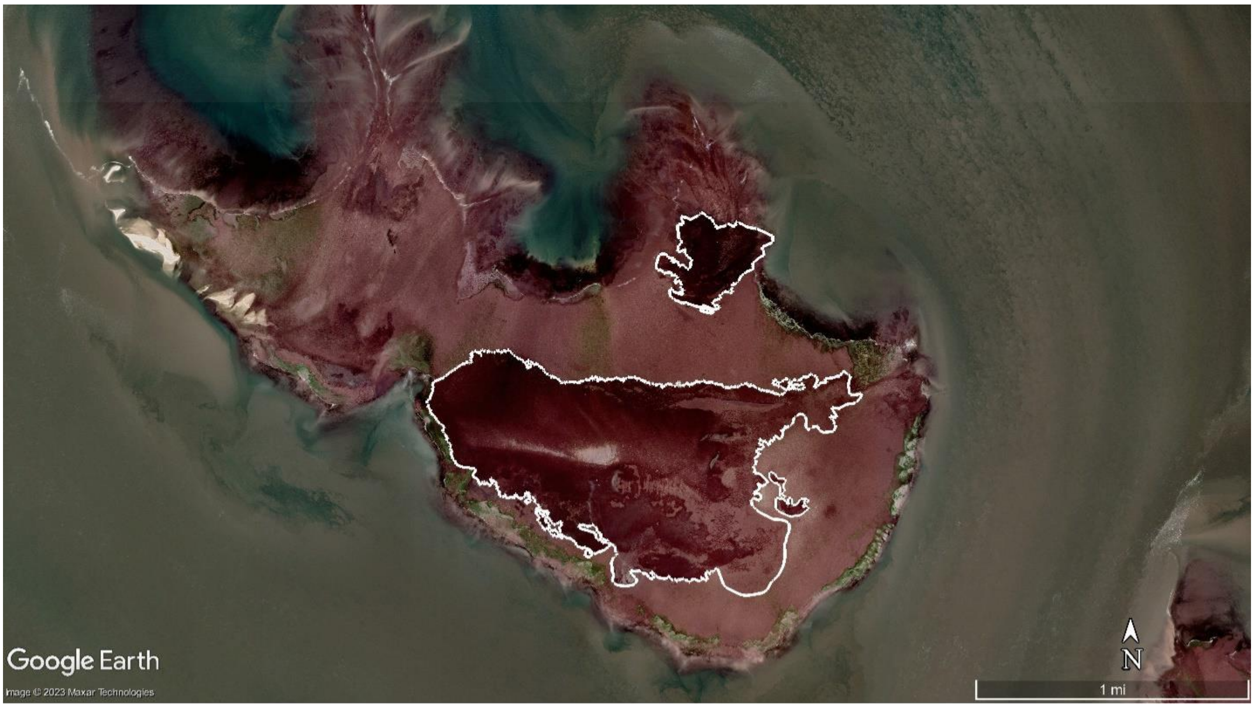


Fig 13 High-elevation dense reef-top meadow visible through both Landsat Copernicus 202 MLWS of <0.5 mts at which the reef-flat is completely exposed. Cross validation with Sent 2A imageries confirmed a total area of 0.21 km^2 of northern Betiwali reef meadows and 2 of southern Dangad meadow of the greater Paga reef.

Chapter 3- Seasonal dynamics in topographically distinct seagrass meadows of the Gulf of Kachchh

Chapter 3- Seasonal dynamics in topographically distinct seagrass meadows of the Gulf of Kachchh

1. Introduction

Seagrass meadows are submerged marine angiosperms that inhabit shallow waters across the globe. India, with a coastline of 7,516.6 km bordering the mainland, has vast, low-energy shallow waters favourable for seagrass meadows' settlement. Depending upon the species composition, seagrass meadows provide ecosystem services like protection from coastal erosion (Ondiviela et al. 2014), regulation of climate change, blue carbon storage, local food security and livelihood, and tourism.

Seagrass meadows can colonise low-energy intertidal reef tops, intertidal and mid-intertidal mud flats, and deeper submerged subtidal zones. Jagtap et al. 1991, report a total of 14 seagrass species from the Indian subcontinent out of 60 species found globally. Parthasarathy and Ramamurthy et al., 1991 both report a high species richness of 15 seagrass species from the Palk Bay and Gulf of Mannar region on the eastern coast of India. The Gulf of Kachchh is predominated by semi-diurnal mixed tides with a tidal coefficient as high as 80-102 during spring tides. Consequently, the Gulf experiences tidal fluctuations that twice cause exposure pressure on reef systems in a nychthemeron. This tidal regime becomes the major cause that restricts the species richness to environmentally tolerant species like *Halodule uninervis, Halophila ovalis, Halophila decipiens* and *Halophila beccarii.* These species are resilient to frequent low-tide desiccation stress, and turbid conditions flourish within the reef systems of the GoK, making it the taxonomically least diverse of all studied regions.

Previously, studies have emphasised studying seasonal and spatial factors that influence seagrass’ composition, abundance and seasonality in Australia (Lyon et al. 2013; Roelfsema et al. 2014), Malaysia (Rajamani et al. 2009; Ahmed Kamil et al. 2013), Indonesia (Vonk et al. 2010; Prarikeslan et al. 2019). A similar seasonal study in India is limited to Govindasamy et al. (2013), which reports the biomass changes in slow-growing species, *Cymodocea serrulata* and *Syringodium isoetifolium* in response to seasonal abiotic factors in Palk Bay, eastern coast of southern India.

There is, however, a sore lack of literature on studies that describe the vegetative and reproductive phenology of seagrasses on the western coast of India.

This was the first correlative study of seasonal abundance responses of fast-colonizing seagrass species from the Gulf of Kachchh. I studied seasonal variations in shoot density of seagrass species: *Halodule uninervis*, *Halophila ovalis*, *Halophila decipiens* and *Halophila beccarii* in response to seasonal variances in local light intensity and temperature at three topographically distinct foraging meadows. The results of this study shall further become indispensable towards predicting the effects of biomass due to climate change, the Arabian Sea's mean sea level and temperature increment, and turbidity events.

2. Methods

Data collection

Seasonal dynamics of seagrasses were studied by monitoring biological and environmental variables in the permanent grid (200 x 200 mt2) in two topographically contrasting seagrass beds in the southwestern Gulf of Kachchh from October 2020 to May 2021. Two meadow types representing topographically unique parts of the reef system were selected for the seasonal study. All the sampling grids were surveyed every month during this period.

Sites chosen (fig 1) were the Tam reef meadow, a mid-intertidal mud-flat, within which a narrow and linear tidal course dissected the meadow, and the Paga reef; a reef-top meadow (hereby RTM). The sites were surveyed and sampled every month from October to May 2020-2021. The random quadrat method was used to sample seagrass composition, shoot density, epiphytic cover, and reproductive units. A HOBO pendant light/temperature logger was mounted at each site to log temperature and light intensity readings every month from October to May 2021. The logging interval was set at 30 minutes. Loggers were wrapped with clear tape to prevent the settlement of microalgae and crustose coralline algae. Each month, loggers were inspected for probable maintenance, and data was off-loaded.

Data analysis

Data were checked for normality (Levenes test). Species-specific shoot abundance trend tests were run using the Mann-Kendall trend test for all three sites. As Tam meadows total shoot abundance did not fulfil the criterion of the Mann-Kendall test for monotonic data, I segmented the seasonal data into winters (Oct-Feb) and summers (March-May). Shoot abundance, temperature, light intensity, and sediment composition value ranges are reported as mean ±SD. Multiple linear regression models were used to analyse the differential influence of temperature and light intensity on species' shoot density flowering at each site. All descriptive analysis was done using MS Excel. Trend, normality, correlation and bi-variate, and multi-variate analysis were done using PRISM and R software.

3. Results and Discussion

Tam reef

Halophila decipiens has a life cycle span of eight months in Tam meadow, from October to May (fig 2). Post-monsoon sampling started in October 2020. The average monthly temperature in October peaked at 28.3 ˚C (fig 2 (i)), and low light conditions were prevalent in Tam reef, with an average light intensity of 65.9 µmol/m2(fig 2 (ii)).

Tam meadow comprises a mixed stand of *Halophila decipiens* and *Halophila ovalis* dominating the reef's expansive mud flat (fig 4). A small area of channel-flanking mud mounds harbours *H. beccarii*, which was not considered for seasonal study due to its relatively small coverage area. Seasonal trend results are shown in (table 1), indicating a positive trend value during winters and a strong negative trend for *H. decipiens* during the summers. This reflects the emergence period in winter and gross loss of abundance after the peak growth phase throughout the summer months, a typical unimodal growth pattern. Positive S values of both *H. ovalis* and *H. decipiens* during the winters indicate exponential increment in abundance through October-February. However, species-specific trend results indicate that *H. decipiens* increases faster in abundance during winters than *H. ovalis*. Later, during the summer months, however, there is a trend change-point in both species, with *H. ovalis* showing no statistically significant decrement in trend (S value = 4, p (no trend) = 0.2), while an abundance of *H. decipiens* experiences a drastic decrement (S value = -6, p (no trend) = 0.042)

Growth period- Tam reef

Initial annual regeneration of *H. ovalis* and *H. decipiens* meadows occurs via seed germination pathway and not asexual clonal expansion. A temperature range of 23.1 -25˚C and light intensity of 94.5- 200 lumen/ft2 is concluded to be the favourable condition for the germination and clonal expansion of *H. decipiens* at Tam reef and *H. ovalis* (fig 2)

H. decipiens emerges during the early winter months. Its germination responded well to the temperature drops and light decrements during winters at Tam TCM (R2 adj- 0.66, p-0.016). However, in singularity, the gradual abundance increment of *H. decipiens* was found to be statistically more responsive to the winter's temperature (R2 adj - 0.72, p- 0.02) than light variations (R2 adj - 0.1, p- 0.8). *H. decipiens*' plantlings germinate before November when the temperatures are between 23 ° C -25° C and increase in abundance slowly through October-January, reaching maturity from February-March end. A drop of 4 °C through November 25 ˚C -Jan 21 °C initiates clonal expansion for early-season *H. decipiens*. More importantly, *H. decipiens*' germination in winter was explained by the cumulative effect of both temperature drop and light intensity increments from 50 lumens/ ft2 to 104-164 lumens /ft2 (R2 adj - 0.66, p- 0.016). Conclusively, during the initial phases of *H. decipiens*, an effective cumulative response of both cool temperatures and light intensity in required at the species' mid-intertidal tidal-creek habitat.

H. ovalis germinates during the late phases of winter in February. Hence, with the seasonal-specific model, no detectable statistically positive response was observed for the species' negligible growth with both the winter temperature and light intensity variations (R2 adj - 0.19, p- 0.21). A species-specific model was then designed to understand the relationship strength between post-germination *H. ovalis*' abundance and temperature light intensity. The results showed a very strong response to the cumulative effects of warmer (~23° C) temperatures and higher light requirements: 150-90 lumens/ft2 (R2 adj - 0.74, p- 0.078).

Dehiscence period- Tam reef

A complete dehiscence was observed at the Tam reef meadow from late summer until monsoon. Both above (leaves, shoots) and below-ground biomass (rhizome and roots) are lost due to the combined effects of high temperatures and low-light intensity. Moreover, as reported by Short et al. (1996, 2011), regional loss of seagrass meadow may also be a direct result of seasonal high currents and wave action. Due to the presence of 1st order narrow channel, Tam meadow experienced pre-monsoonal wind-driven currents that enabled sloughing off of the meadow. The onset of the dehiscence phase at similar mid-intertidal TCMs is consequently earlier than the RTM.

Dehiscence starts from early March for *H. decipiens* and from April in *H. ovalis,* which thereafter exponentially decreases for both species. Shoot density of *Halophila decipiens* decreases gradually within three months in the summer period of March-May (fig 2), from M-671.88 ±490 SD during the summer onset to M-20±132SD shoots/m2 in May, peak summers. However, the decrease in shoot density of *H. ovalis* is sharp and starts later from April M- 1136.8±648 SD to M-512.5± 464 SD in May. The average monthly temperature rises by 7 °C after summer-onset till May, whereas light intensity through summers decreases from 180 to 20 lumen/ ft2 (fig 2 (ii)).

Singularly, summer high temperatures and low-light intensity accounted for 53% (p-0.05) and 62 % (p-0.7) of the monthly abundance variations in *H. decipiens*, respectively. However, the latter's effect on the decline of *H. decipiens* was non-significant. 58% of the decline of *H. decipiens*' abundance was estimated to be a result of the cumulative effects of light intensity and temperature during the summer.

More importantly, *H. decipiens*' abundance decline is strongly ascribed to consistent spatial competition by late-emerging and more thermally tolerant species *H. ovalis* and temperatures >26.5°C (R2 adj - 0.60, p-0.005). Fall in light intensity alone does not regulate the dehiscence event. This is substantiated by the fact that mono-specific stands of *H. decipiens* were still found in the subtidal zones of Paga, Bhaidar, and Nor reef till late April, when the temperature reached beyond 28°C. Seasonal models' results indicated that *H. ovalis*' abundance response to the cumulative effect of temperature and light (R2 adj - 0.47, p-0.034) is weaker than that of *H. decipiens*. This may indicate a higher thermal and low-tide desiccation tolerance of *H. ovalis* in a tidal-creek habitat, which consequently causes *H. decipiens*' to be outcompeted in summers.

A consistency in temperatures above 29 °C and unavailability of photosynthetic active radiative (PAR) ultimately causes meadow dehiscence of *H. ovalis* within the mid-intertidal population.

Paga reef

The Paga reef, a high-elevation intertidal patch reef, gets completely exposed during low tides (tidal height <1.5) twice daily. All meadows found at its reef top are not light-limited but experience complete low-tide desiccation. Mixed meadows composed of seagrass species *Halodule uninervis* and *Halophila ovalis* colonise these reef-tops. The phenological studies were limited to the northeastern exposed reef-top meadow, Betiwali reef.

The entire study plot was virtually barren (fig 4) during the early months of October-November. However, mother patches of 0.5-1 mts were heterogeneously distributed throughout the study plot from which *H. uninervis* expanded. These resilient patches withstand seasonal dehiscence and were observed to preserve the below-ground biomass at more sheltered parts of the meadow. Peak growth season for both species spanned from March and is estimated to have been carried on until June.

Emergence period- Paga reef

Emergence via germination, in the case of *H. ovalis* and initial ramet expansion, in the case of *H.uninervis*, was extremely gradual. Average light intensity did not vary much from October- January; M-168.4 lumen/ft2 and late season from February to May; M-172 lumen/ft2 (fig 3). This is due to the elevated position of the Paga reef, causing it to experience complete exposure twice a day during low-tide periods. Reef-top light limitations during high tide can be easily compensated by low-tide periods' daylight exposure.

Overall winter light intensity variations (fig3 (ii)) had extremely insignificant control over the seagrass abundance increments (Oct- Jan) in both species (Ho x R2 adj – 0.05, p-0.28), (HU x R2 adj – 0.02, p-0.69). This translates into a limited role of light-intensity increments, in singularity, at initiating growth response from either of the species.

Post-monsoon to early winter temperatures at Betiwali meadow ranged from 27-30°C. Growth of *H.uninervis* remained low throughout the post-monsoon high-temperature period. An exponential thermal decline of up to 10°C occurs as the season shifts from post-monsoon to early winters through Oct-Dec at the eastern Paga reef (fig 3 (i)). Similar to Tam reefs, *H. ovalis*' early season germinates strongly responded to this thermal drop and light-intensity increments (R2 adj - 0.74, p-0.08). In contrast, *H.uninervis*' abundance at the Paga reef showed a very weak response to the thermal drop (R2 adj – 0.40, p-0.05). Evidently, the growth response to temperature and light intensity was more prevalent for *H. ovalis*' than *H.uninervis*, indicating the latters higher relative resistance to fluctuations in PAR and seasonal temperature.

Growth Period- Paga reef

Throughout the summer period (February-May), both species, *H. ovalis*' and *Halodule uninervis*' abundance, had a statistically significant increasing growth trend. (fig3). The seasonal fall in growth trend observed at tidal-creek meadows, such as the Tam reefs, was not observed for Betiwali reef-top meadow. This was due to aforementioned consistency of favorable light intensity for growth and expansion from Oct-May. *Halodule uninervis* shoot-density variations in summer had a strong positive correlation (Spearman r- 0.6, p- 0.01) with available PAR; M-171 lumen/ft2 ±46 SD, maximum PAR- 238.9 lumen/ft2.

However, temperatures during the peak growth period increased by 6.78°C, further consolidating my results that a temperature climb elicits a significant positive abundance response in both *H. ovalis* (R2 adj – 0.50, p-0.04) and *H.uninervis* (R2 adj – 0.56, p-0.03).

4. Flowering density response temperature, light and shoot-density

Flowering season in the southwestern part of the Gulf started by mid-February, following which seeds from a vast majority of the fertilized fruits dehisce and form seed banks in the sediment. Seeds germinate the following season during winter. Only a few seedlings may germinate in the same season. Seed germination and flowering of *Halophila decipiens* occurs first, followed by *Halophila ovalis* and *Halophila beccarii* (fig 5). *Halodule* plants were not observed with any flowers or fruits, thus reproducing solely via clonal expansion within the study area.

The seasonal flowering density of *Halophila ovalis* had a statistically significant response to the seasonal shoot abundance variations at both reef-top; Paga meadow R2Adj- 0.73, p-0.03 and mid-intertidal meadow; Tam reef R2Adj- 0.92, p-0.10. Similarly, *Halophila decipiens* ' flowering density increased with shoot density R2Adj- 0.88, p-0.02, but also showed mild response to temperature increments R2Adj- 0.30, p-0.20 throughout the season (fig 6).

Seasonal light intensity changes caused very weak to no changes in flowering density for *H. decipiens* R2Adj- 0.04, p-0.46 and *H. ovalis* R2Adj- 0.31, p-0.28 at Tam meadow. This suggests that temperature and shoot density play an important regulatory role in flowering initiation and density. The high density of flowers observed in dense meadow areas of light-limited subtidal populations of *H. decipiens* substantiates these correlations.

Non-flowering *Halodule uninervis*

At Paga reef, *Halodule uninervis*' plantlings were observed to expand exclusively via asexual ramets from seasonally persistent mother patches of 0.5-2mts width from the previous season. Older mother patches of *H.uninervis* found in October indicate tolerance of this species to an extended period of monsoonal low light availability. Ramet expansion progressed faster from dense sheltered patches on the northeastern reef. This species exhibited no flowering or fruiting events throughout the GoK. Mcmillian et al.,1980 did experimental transplantation to study seagrass flowering under various temperatures and salinity. They report that environmental conditions like prolonged high temperatures, low-tide period, and hyper-salinity (induced due to low-tide) tolerance, ultimately decided the initiation and duration of flowering and fruiting. A shorter life span of *Halodule uninervis* meadows, higher temperatures, and the fact that the species is restricted to only reef-top meadows and shallow mid-intertidal meadows, habitats vulnerable to frequent desiccation, may cause a lack of reproductive phase in the species.

5. Seasonal changes in epiphytes

Epiphytes are organisms growing on seagrass leaves and can range from bacterial colonies to microalgae, hydrozoans, ascidians, etc. (Borowitzka 1989). Micro-algal epiphytes were observed on *Halodule uninervis, Halophila decipiens and Halophila ovalis* during the early winter months (Dec-Jan) with an average cover of 40-65%. During the peak summer months, the epiphytic algal colonisation was site and abundance-dependent. High density mixed meadow of Halodule-*Halophila ovalis* composition, had 60-95% of epiphytic algal cover (fig 7). Settlement of epiphytic algae was also observed to be patchy. Parts of a meadow with higher shoot density and low direct aerial exposure had a higher epiphytic cover.

Non-random colonisation of micro-algal epiphytes has been observed in Posidonia sp. Trautman et.al (1999). This colonisation is differential on morphologically distinct seagrasses. My observations also conclude that morphologically, smaller seagrass species like *Halophila beccarii* did not harbour any epiphytic cover throughout the season. This could be due to the lower content of natural fibre in the species, making the leaf area too fragile for epiphytic adhesion.

6. Seasonal variations in subtidal meadows

Seasonal study done at Chepri cove and Tam reef shows a clear change in subtidal vegetation densities throughout the season. Loss of subtidal seagrass biomass initiates in late April when temperatures rise up to 29.8°C, and < 247 lumens/m2 light intensity. Although habitat surveys were prohibited during the monsoonal months of July-September, it is understood that the completion of meadow dehiscence should coincide with the monsoonal period, as the temperatures and light intensity values cross well beyond the species' critical growth conditions (July-September Avg-T-29.7°C, L<40.1 lumen/m2).

Seasonal loss in abundance and other disturbances through burial and excavation is thought to be countered by *H. decipiens*' high colonisation capacity through seed recruitment (Cabaco et al. 2008) and clonal growth. Negatively buoyant seeds of the *Halophila g*enus are persistent and can potentially remain dormant in sediment for more than a year. The fruit count recorded in *H. decipiens* 70-120 seeds/m2 in the Gulf indicated the presence of a healthy seed bank in sediment with seeds from multiple seasons and growth stages. This ensures fast recovery of a meadow after the post-monsoonal drop in biomass. Young germinates were observed again in December after the seasonal monsoonal dehiscence of a meadow. The location of these seasonally persistent patches was more constricted to the summer high-density areas of the meadow.

Spatial distribution analysis revealed that seedling patches were confined to the lowest energy areas of the cove, making similar sheltered subtidal areas indispensable plant nurseries.

During the growth period, germinates from these plant nurseries mature and propagate vegetatively for meadow expansion.

The successful germination rate depends upon the timely synchronisation with favourable environmental variables. However, bioturbation and bio-irrigation caused by seagrass-associated fauna like shrimps, crabs, echinoderms, and stingrays (DeWitt et al. (2009)) may directly affect seagrass recruitment, growth, and survival. This is caused by the burial or uprooting of seeds, seedlings, shoots, and seagrass patches. The gross effect of such disturbances on the species' pasture remains obscure.

7. Role of Meadow exposing low-tide periods and of light availability

All seagrass species are light-limited in the GoK. Decrements in abundance values were synchronous to low-light intensity across sites. Low-tide exposures at TCM occurred only at tidal heights <0.4 mts (5-6 spring days/lunar month). The persistence of low-light conditions started in March at Tam Meadow, after which gradual seasonal dieback occurred. Temperature increments and low-light availability had a stronger regulatory role in TCM growth.

On the contrary, seasonal low-light prevalence at RTM was countered by low-tide exposure. Hence, at Paga reef, a fall in PAR occurred late in June. Consequently, no major seasonal senescence at the RTM was observed within the summer period. Definitively, tidal-creek meadows like Tam reef are more vulnerable to the prevalence of sediment resuspension events that may be caused by dredging activities and monsoonal cyclones.

At Paga reef, an intertidal seagrass bed, the duration of low water exposure showed a gradual shift from night-time (October -February) to daylight hours (March-July) (fig 8). Lastly, in August-September, meadow-exposing low-tide hours during the day were comparable and later fewer than the post-daylight low-tide hours. The temperature hiked to 26-32°C during the March-July period, coinciding with a higher daylight meadow exposing low-water events at RTM. This made the biomass at the RTM more vulnerable to burning or browning via desiccation. Due to a larger surface area, desiccation burns were profoundly manifested on leaves of *H.uninervis* as browning on foliage. Desiccation burns were minimal on any *Halophila* sp. in the Gulf. Erftemeijer et al., 1994, reported a similar loss of above-ground biomass via low-tide desiccation.

8. Effects of sea temperature and sea-level rise (SLR)

An exponential increment in temperature-shoot density trend occurred at both sites. Increment in seawater temperature in winter months may cause the late emergence of seagrasses, affect growth patterns and reproduction and potentially lead to major diebacks of all the temperature-sensitive meadows in the Gulf of Kutch. During the peak summer period, I report an average temperature threshold of ~30°C at the reef tops. Persistent increments beyond that, along with monsoonal wind-driven currents, ultimately cause species senescence. Coastal waters' of GoK show a trend in sea surface temperatures that has been positive and climbing. In the recent epoch, Arabian Sea temperatures have risen to 1.2-1.4 ˚C. Deshpande et al., 2021, report a 52% increment in Arabian Sea tropical cyclone frequency from 2001-2019. They concluded that this correlated to humidity caused by increased sea surface temperatures. Correlating this fact with the results of my study, I deduce that an area constriction of light-limited subtidal meadows may occur. Further, RTM may experience biomass thinning and unsynchronised reproductive events. Depending on local conditions, the increasing SLR will simultaneously also cause increments in already high tidal amplitudes in the Gulf basin. This shall inevitably prolong the desiccation stress of meadows, becoming a serious threat to intertidal seagrass meadows in warmer regions (Seddon et al. 2000). Conclusively, the south-western Gulf of Kachchh meadows are extremely vulnerable to climate change effects. Being highly responsive to temperature and light intensity changes, these meadows must be considered a bio-indicator subject for focused long-term climate change studies in the northern Arabian Sea.

9. Annual transfer of nutrients and trophic connectivity from shallow to deep-water zones

Unnikrishna et al., 1999, reported that a tidal residual circulation within the semi-enclosed Gulf of Kachchh has implications for the distribution of nutrients. They also reported a seasonally wind-driven tidal flux that enters into the shallow regions of the Gulf and circulates water over mudflats and through mangroves. As a result, residual currents become enriched with nutrients, sediments, and organic matter. It can be safely deduced that the annual monsoonal senescence of seagrass meadows of GoK, when exported to the deep-water zones, may most likely enhance its primary production through biomass degradation. I also report that the contribution of this energy transfer would have the following descending sequence; high-biomass intertidal RTMs > moderate-biomass mid-intertidal TCMs > low-biomass subtidal meadows. Hemminga et al., 1991 elaborated on the importance of the transport of nutrients drawn from senescent leaves of seagrasses to the from the proportion of meadow loss by different species, with <1% for Thallasia hemprichii and over 70% loss for smaller Syringodium sp. All species at the GoK belong to pioneering and fast-colonizing *Halophila* and *Halodule* genera, which undergo almost complete monsoonal sloughing off, with negligible contribution as a beach wrack. This suggests that almost ~90% (except the seasonally persistent patches) of meadows contribute to enhancing nutrient concentrations and trophic connectivity in deep-water zones via residual tidal circulations, typical in the Gulf. More focused studies are warranted to understand these nutrient dynamics within the shallow and deep-water trophic systems.

10. Conclusion

This study summarises seagrass species-specific (i) low-tide desiccation tolerance, (ii) low-light threshold, and (iii) temperature threshold for winter and summer seasons.

Ralph et al., 2007, and Dennison, 1987 addressed the spatial distribution of seagrass based on light availability and limitations. I conclude that, at a larger scale, all seagrass species in the Gulf are restricted to shallow intertidal and subtidal zones due to the limited availability of suitable low-energy areas and substratum (as discussed in Chapter 2). However, at a regional scale, the growth phases of each species of a topographically different population (RTM, TCM) differ in their response to available light and temperature.

Conclusively, temperature and light intensity elicit a significant yet differential influence on the early stages (Germination, initial rhizome expansions) and late growth stages (morphometric growth, shoot multiplication, flowering/fruiting, dehiscence) of all seagrass populations in the Gulf. Through this study, I summarise a species-specific threshold range for temperature light intensity, within which initial and peak growth is facilitated.

Temporal variations in emergence/dehiscence patterns in plants play an especially significant role in the foraging ecology of herbivores. Moreover, a better understanding of the effects of the seasonality of food sources on mega-herbivores like the green sea turtles and dugongs in the GoK s hall be achieved. Animals rationalise their activity budgets synchronously with the seasonal availability and abundance of their prey/forage (Senft, 1987). A background multi-temporal and spatial distributional datasets regarding seagrass dynamics are essential to gain insights into associated green sea turtles and dugong distribution, foraging, and movement ecology (Taquet et al. 2006 Heinsohn et al. 1977, Preen et al. 1995)

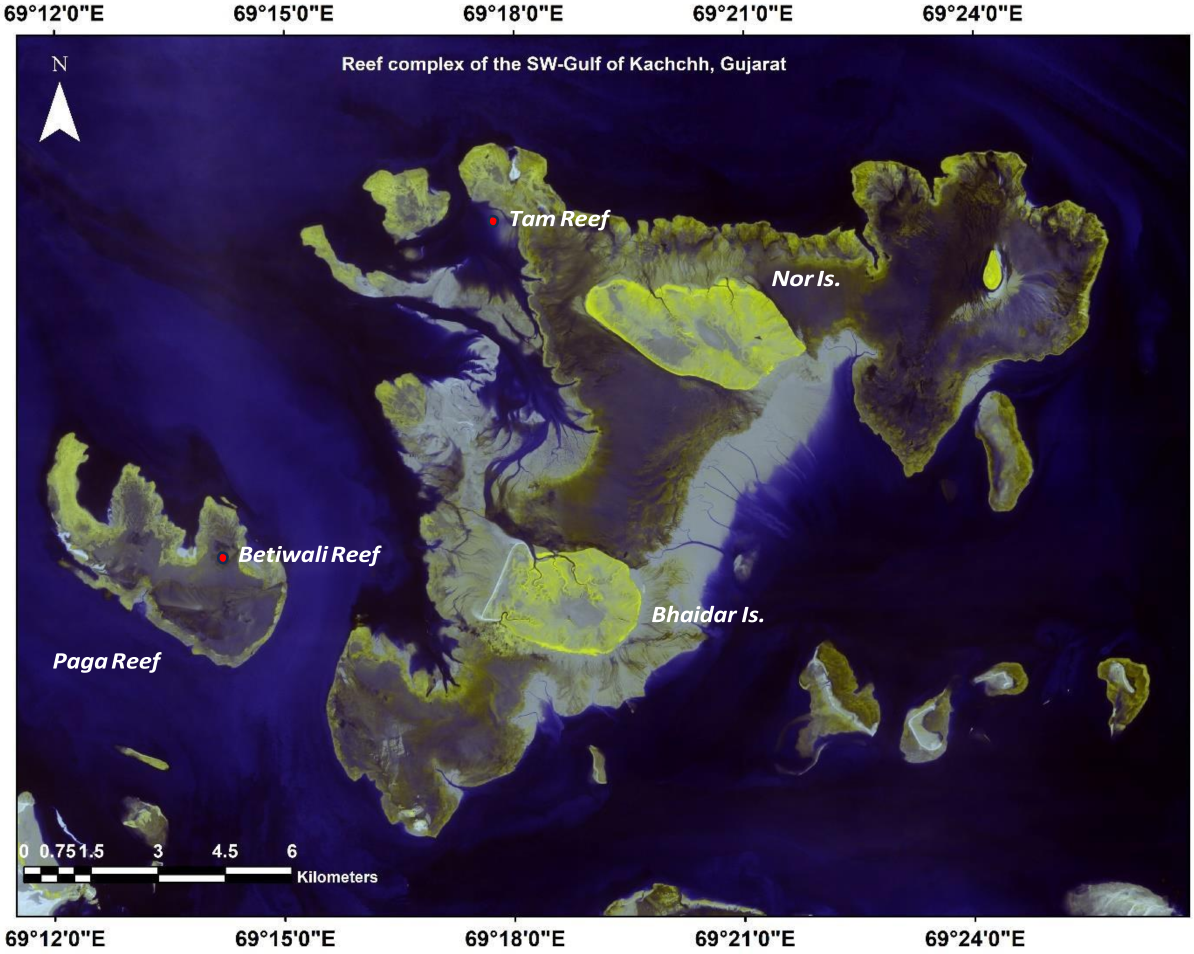
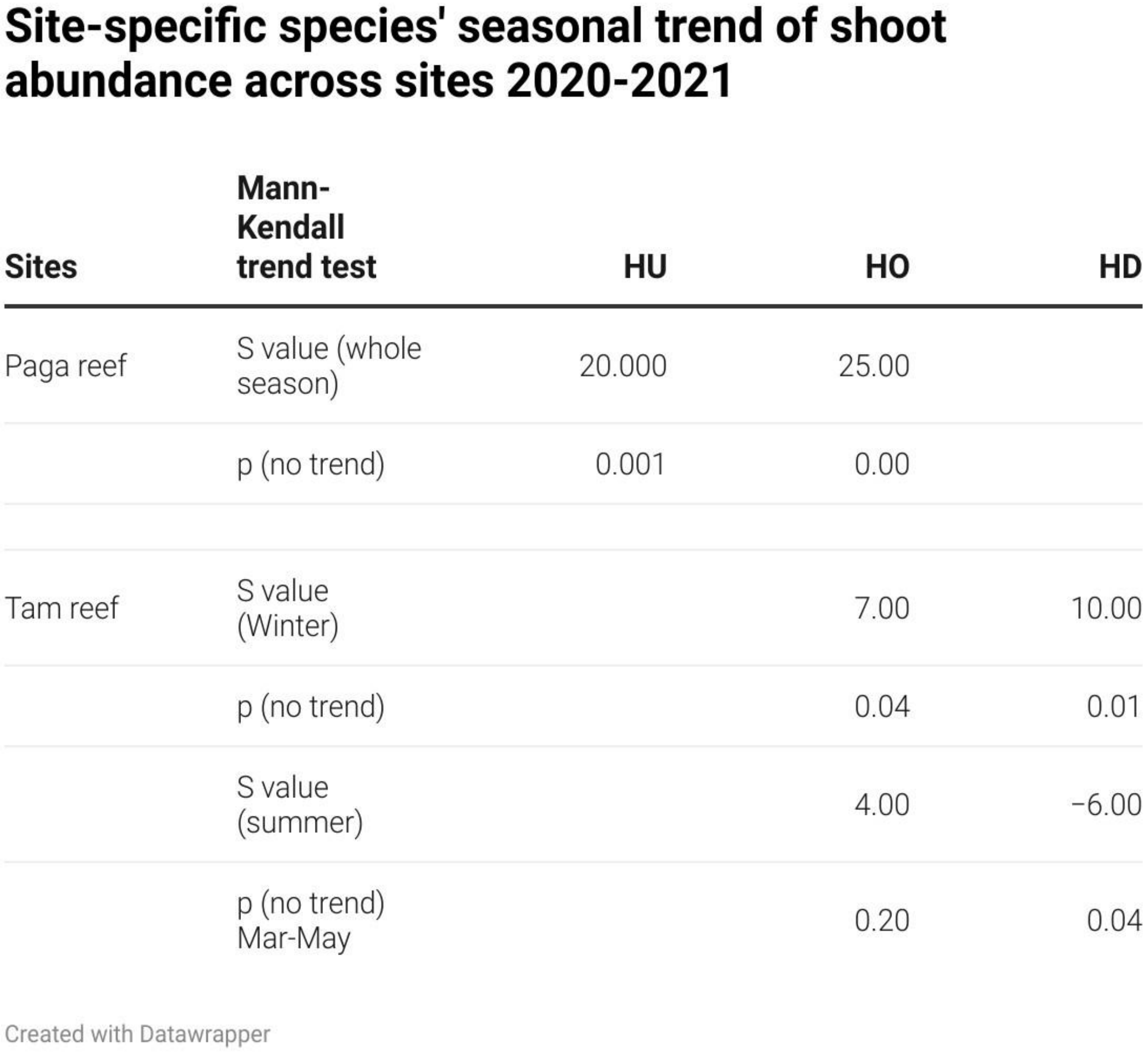


Fig 1. Site location of topographically different meadows selected for the seasonal study at the south-western reef complex of the Gulf of Kachchh. Intertidal reef-top Betiwali meadow of the Paga reef in the south-west and mid-intertidal tidal creek meadow of Tam reef towards the north-west.



Site-specific species' seasonal trend of shoot abundance across sites 2020-2021

Sites	Mann-Kendall trend test	HU	HO	HD
Paga reef	S value (whole season)	20.000	25.00	
	p (no trend)	0.001	0.00	
Tam reef	S value (Winter)		7.00	10.00
	p (no trend)		0.04	0.01
	S value (summer)		4.00	−6.00
	p (no trend) Mar-May		0.20	0.04

Created with Datawrapper

Table 1 Results for the Mann-Kendall trend test. Summer shoot-densities trend of both the species is negeative. For Tam reef, the Mann-Kendall test revealed a negative summer shoot-densities trend for *Halophila ovalis*, starting in April, and *Halophila decepiens*, starting in March, indicating declining abundance for both species during summer. Statitically significant increase in growth of both species was observed for both the species at Paga reef. HU- *Halodule uninervis*, HO- *Halophila ovalis*, HD- *Halophila decipiens*

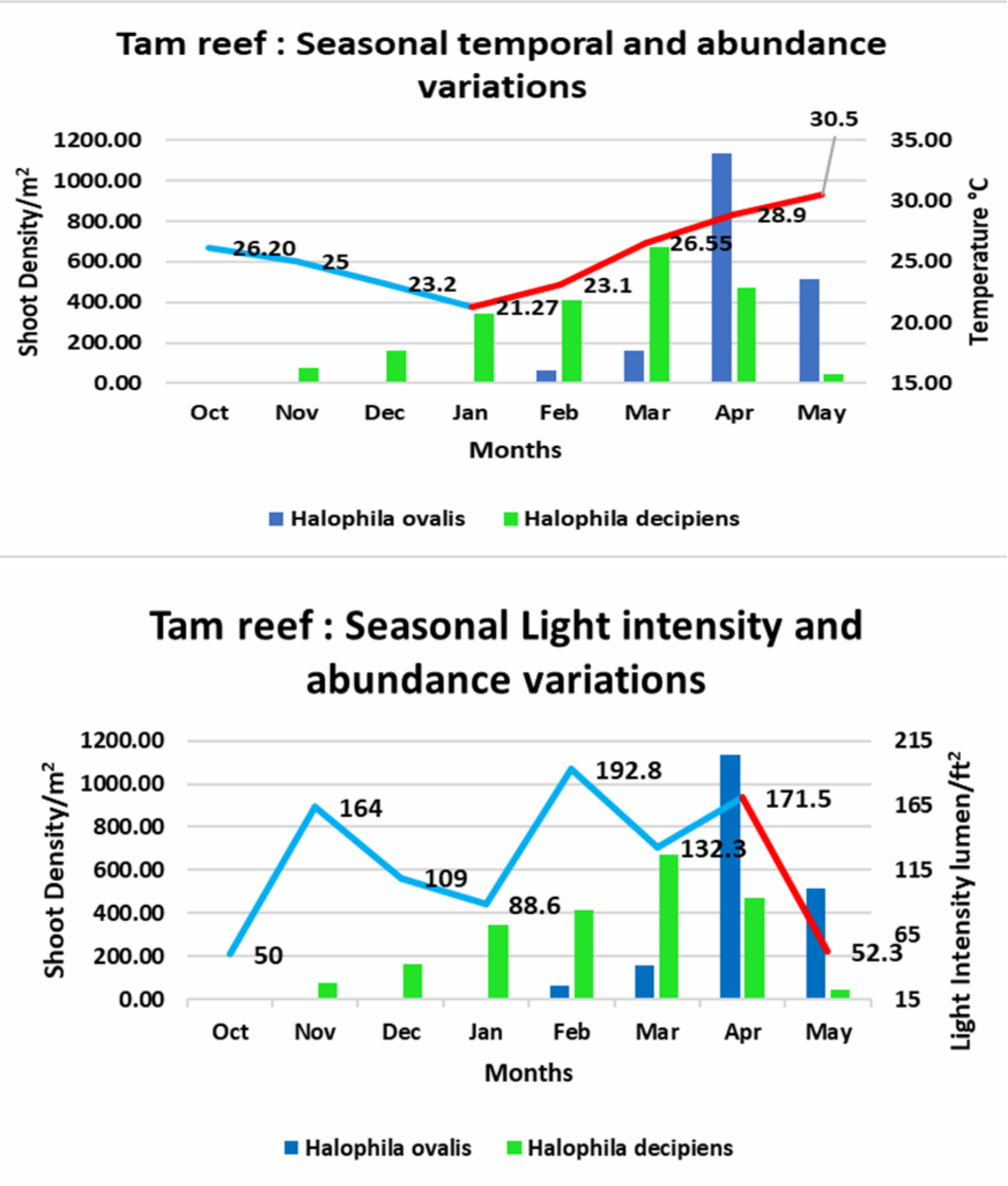


Fig 2. Graphical represention for the seasonal dynamics at Tam reef meadow. (i) Seasonal temeprature:Shoot density dynamics (ii) Seasonal light-intensity :Shoot density dynamics

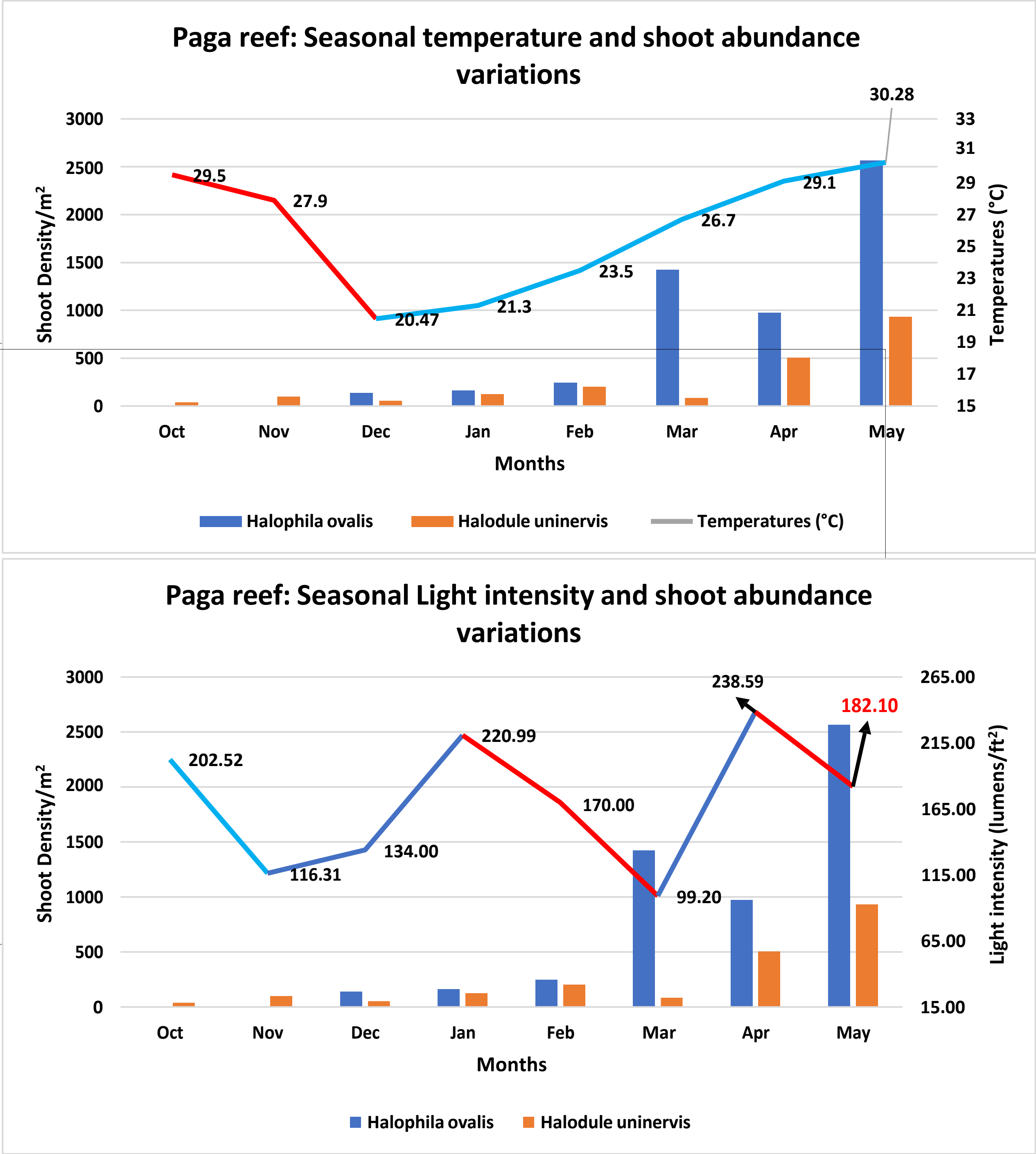


Fig 3. Graphical represention for the seasonal dynamics at Paga reef meadow. (i) Seasonal temeprature:Shoot density dynamics (ii) Seasonal light-intensity :Shoot density dynamics

Fig 4 Seasonal changes in seagrass meadow abundance. (Top panel) Low winter abundance, (Central panel) Tidal creek meadow at summer growth period with *Halophila ovalis* and *Halophila decipiens* mixed species composition, (Lower panel) Dense Reef-top meadow at summer peak growth period; mixed species composition of *Halophila ovalis* and *Halodule univervis*

Fig 5 Reproductive units observed in *Halophila spp.* (Top panel) Left- Halophila ovalis female plant, Right- Male plant, (Central panel) Left- *Halophila ovalis* ripe fruit with seeds, Right- *Halophila beccarri* ripe fruit with fewer seeds, (Lower panel)Left- *Halophila decipiens* reporductive unit and (Right)- Ripe fruits

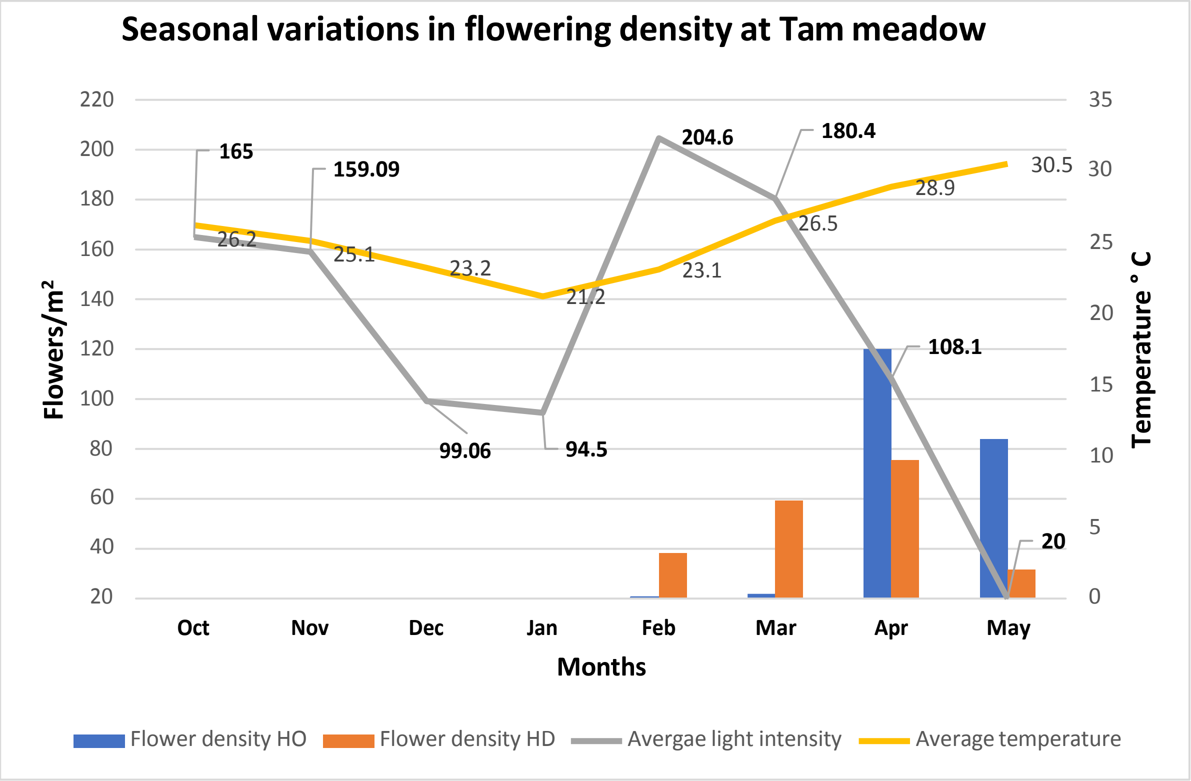


Fig 6 Graphical represention for the seasonal density variations for flowering in HO- *Halophila ovalis*, and HD- *Halophila decipiens* April-May was the peak floweing season for HO, and March-April for HD.

Fig 7 Epiphytic cover on *Halodule uninervis* and *Halophila ovalis.* (Top panel) sediment adhesion on foliar epiphtes, (Central and lower panel) Epiphytic algal variations were observed depending upon seagrass species and season.

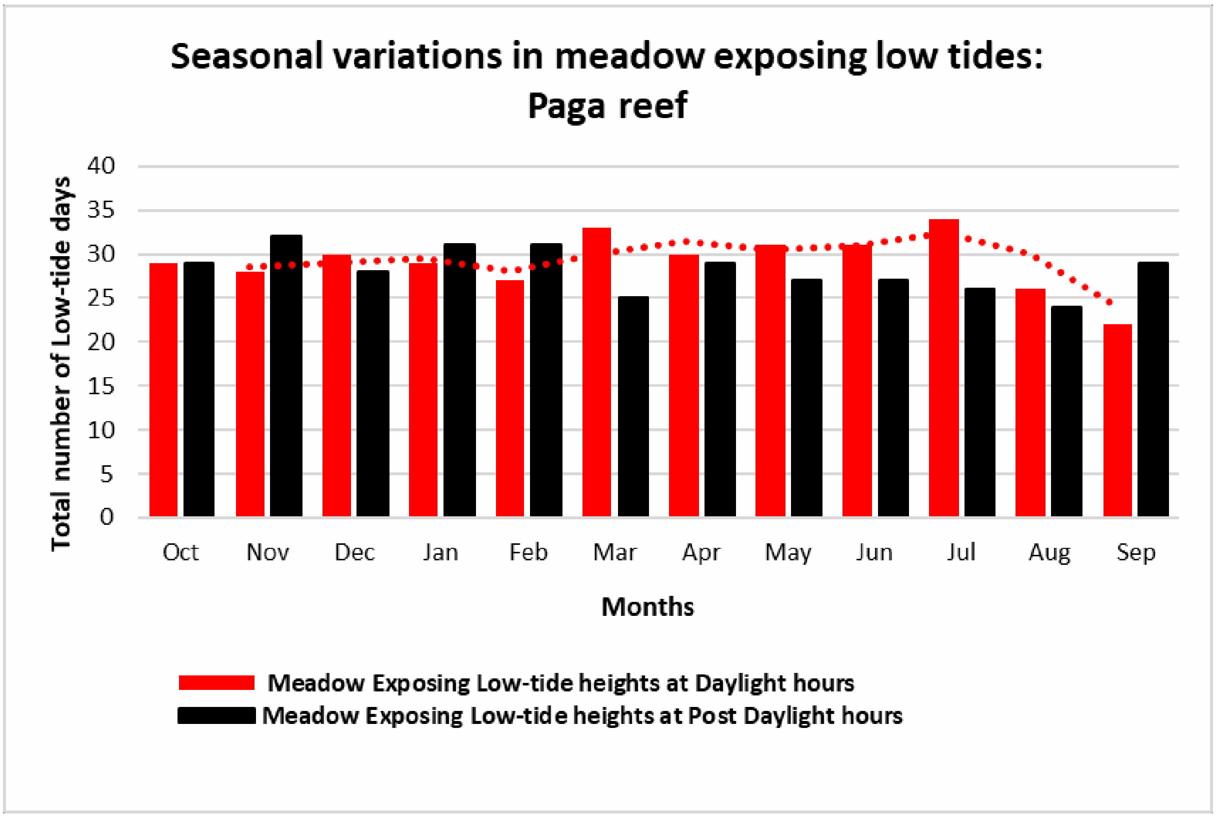


Fig 8 Graphical represention for the annual seasonal variations in Meadow exposing low-tide at Reef-top. Trend line indicates a decline in the numer of meadow exposing low-tide heights during dayliht hours.

Chapter 4-Spatial ecology of foraging habitats and their use by the remnant population of dugongs in the macro-tidal basin of the Gulf of Kachchh, India.

Chapter 4-Spatial ecology of foraging habitats and their use by the remnant population of dugongs in the macro-tidal basin of the Gulf of Kachchh, India.

1. Introduction

All ecological systems are in a state of constant natural and anthropogenic motions, the pace of which either instils and hones the adaptive capability of the species inhabiting it or inhibits their sustenance, causing local extinctions.

Regarding herbivores, foraging theory concerns all movement patterns and decisions associated with foraging. It addresses decisions regarding (i) where to search, (ii) when to feed, (iii) which forage species is optimal, and (iv) when to terminate foraging and leave patches (Schoener, 1971; Charnov et al.,1976. Applications of this theory have considered only fine-scale, over periods of minutes or hours, to large-scale movement between foraging patches and seasonal changes regarding it. However, for dugongs, or any marine nektonic animal, proximate and ultimate foraging behaviours can be expressed over a hierarchy of spatial and associated temporal scales, from choice of forage and movement route within food patches to movements generated by seasonal forage changes and tidal restrictions.

Dugongs are known for their clever selective foraging strategies. An exclusively herbivorous marine mammal, it eats approximately 35-40 kgs of wet-weight seagrasses daily (Preen, 1995, 1992). To meet this energy demand, they strategise their foraging movements between meadows (Sheppard et al. 2007, 2009, 2010). These benthic foragers select meadows which harbour the rapidly growing and early pioneering species such as *Halophila ovalis and Halodule uninervis* (Preen 1995) etc. over slower-growing fibrous seagrass species, *e.g.*, *Enhalus acoroides, Thallasia acorodoies.* Further, similar to terrestrial hind-gut fermenters, dugongs too are known to sustain low-quality forage. Dugongs' spatial ecological studies have been conducted by Sheppard et al. 2007, 2009, 2010, and reported a tidally synchronised inter-group heterogeneity in the choice of forage and associated movement. Such fine-scale tidal and diel behaviours, however, can only be studied with the aid of satellite telemetry.

Integration of seagrass meadows' spatial and temporal ecology into Dugong foraging ecology

The Gulf of Kachchh (GoK) experiences mixed-semidiurnal tides of ~4 mts to ~6 mts at Okha and Navlakhi, respectively. This puts this basin in a perpetual state of tidal motions, displacing sediment differentially across reefs and coves, homogenising salinity, temperatures and nutrients on reefs. Complex reef morphology and high inter-reef proximity in this macro-tidal system produce tidal channels of varying degrees, streams, shelter from incident waves, massive mud-flats and sandy reef platforms, creating unique and favourable spaces colonised by seagrass meadows.

Transit corridors used by herbivores in a terrestrial system are naturally stationary. Conversely, tidal channels and tidal flats are closed dynamic systems influenced by tides and other meteorological events (discussed in Chapter 2). For most marine predators, temporal and spatial use of hydrodynamic features is in concordance with the availability of mobile prey. Conversely, dugongs; a shallow water marine mega-herbivore, forages on seagrass meadows, habitats associated with perpetually varying hydrodynamic events. These events are predictable: flood, slack, and ebb tide periods. Results from previous studies of the meadows in the southwestern GoK report that seagrass meadows are unique as they are insular, truncated by topographical features and affected by mixed semi-diurnal tides. Hence, except for the subtidal meadows, all meadows are tidally affected. However, disjointed, most meadows have proximity to one another. With the use of foraging trails' spatial distribution as a tool, I address intra and inter-site habitat selection determinants in the S-W GoK. Further, I investigate the fine-scale bio-physical and coarse-scale topographical factors that may facilitate and influence dugong's selection of forage areas (hereby DFA).

The lacune for consideration of dugongs and their habitats in conservation management of Marine Protected areas of the Gulf was likely due to their small population and cryptic nature. Consequently, the difficulty in dugong core area demarcation came from a lack of necessary baseline ecological data.

Dugongs' use of space among core habitats and their movement patterns has been studied on the fine scale in Australian (Marsh et al., 1990; Holley et al., 2006, Sheppard et al, 2007, 2009, 2010) and New Caledonian waters (Cleguer et al., 2015, 2020). Replicating methodologies that used satellite telemetry to understand the spatial ecology of dugongs is a high-risk feat for a critically endangered and highly dispersed population of the Gulf. From within the Indian subcontinent, our understanding of foraging ecology within the dugong ranges, Tamil Nadu and, the Andaman and Nicobar Islands, and Gujarat is largely missing. This research vacuum is mainly due to logistical challenges that can make it difficult to access the habitats, conduct/design practical, direct observational studies, and ultimately achieve an adequate sample size to develop a suitable research model.

I, therefore, present a cost-effective and non-invasive method to construct a baseline spatial ecological study on a small population of reef-dwelling dugongs in the Gulf. Utilisation of the spatial and temporal distribution patterns of dugong foraging scars and their habitats' tidal sequences was used as an effective tool for the study. A descriptive ecological investigation on dugongs' habitat use was warranted for a population residing in a macro-tidal and constricted GoK.

2. Methods

Study of Dugong foraging areas

The extent of foraging areas, i.e., the spatial distribution of foraging trails, was mapped over 2018-2023. Perimeter tracks around foraging areas and waypoints were recorded using a handheld Garmin eTrex30 to delineate core foraging areas within meadows. Further, 30-40% of randomly sampled trails from the total core area were used to record the length and width of a trail. Point locations of proximal submerged topographical features like inter-reef channels and reef edges/perimeters were recorded for geo-referencing. These features would have been otherwise ambiguous in low-tide satellite imageries. A qualitative semi-structured dugong questionnaire surveys were undertaken to interview *on-field* local fishers regarding animal sightings on/around the reef.

Tidal channels base-map

Tidal channel morphology was studied using low-tide HR-Sentinel images-2A of 10 mts resolution and multi-temporal low-tide Google Earth imageries. Field data points and tracks were used as references to aid in tracing meandering narrow channels of width <2 mts, which were pixelated in the satellite imagery. Bathymetric points were used to follow a channel path to the highest order at the point of culmination at the tidal flat. Channels were categorised based on their ecological function and the surface area of the tidal stream bed.

Bathymetry and vegetation density base-maps

For methods to chart bathymetry and vegetation density maps, refer to Chapter 3. To understand dugongs' tidal accessibility, bathymetric and seagrass meadow layers were used as base maps to simulate the availability of different foraging meadows at varying high tide heights of 3.4 mts (Mean High Water Level; MHWL for spring), 2.8 mts (MHWL neap tide), 0.4 mts (Mean Low Water Level; MLWL at spring tide). Animal sighting' locations, tidal phase at the sighting time and foraging trail distribution and number (n=1507) were incorporated in each simulated map to understand tide-based habitat selection. The minimum depth of accessibility was decided at ~1mts (Cleguer et al., 2015, 2020). Estimation of the percentage of the area of meadow available for foraging was then calculated at (i) Spring high tide period, (ii) Neap high tide period, and (iii) Spring low tide period.

Forage quality

Two sites with relatively different foraging intensities were chosen to understand if forage intensity causes any change in nitrogen levels of the seagrasses. To test whether the forage selection in the dugong population of the Gulf is nutrient-driven, I sampled and analysed forage samples from fixed plots (200 mt^2) at foraging areas. Foraging micro-habitats with a high average (of peak seagrass growth period) feeding trail counts (n- >30) and moderate average (of peak seagrass growth period) feeding trail counts (n-15-20) were selected for this study. To assess the changes in %N throughout the season, sampling was done from each site from October-May, 2020-2021. Forage samples were analysed for % of Nitrogen (N), Acid-detergent fibres (ADF), and Neutral-detergent fibres (NDF). Kjeldahl method was used to estimate the total nitrogen concentration in the samples. Mann-Kendal time series test was first done to understand the trend in nitrogen uptake in early season (October-December) and late season (January-May) seagrass samples from both sites. Further, two sample t-tests were performed to compare differences in mean % Nitrogen. F-test was used to compare variances in %ADF- %NDF for reef-top meadows (RTM) and tidal-creek meadows (TCM). Variances have been mentioned wherever their function was appropriate.

Assessment of intra-site foraging selection-

Based on the seagrass community's seasonal data presented in Chapter 3, I categorised seagrass species as early and late foraging species. Monthly Dugong foraging trails' (DFT) counts were recorded simultaneously to seagrass abundances from Oct-April at Dugong foraging area (DFA) at TCM, Bhaidar and Tam reef, and at RTM; Betiwali reef. Early season (Oct-Jan) foraging intensity was studied at the Bhaidar and Betiwali reefs. Multiple linear regression models were used to test the combined effect of all forage species' seasonal abundance on the foraging intensity at the three sites. Further, individual species-specific response to foraging was also tested using a smaller bivariate linear regression model.

Assessment of inter-site foraging habitat-selection

A total of twenty-three separate *seagrass abundance: feeding trail days* across all DFA's were used to investigate **inter-site** habitat *selectivity* based on forage abundance. All foraging trail numbers and total seagrass shoot density values were analysed through a bivariate regression model to test foraging site *selectivity* (binary decision). Abundance values with complete feeding trail absence were not considered in this analysis to assess the *relative* relationship between feeding trails and forage abundance.

Further, forage-abundance-based categorisation into (i) low-moderately shoot abundance 260±160 shoots/m^2, and (ii) highly abundant meadow 2001±817shoots/ m^2 was done a priori to test if foraging *intensity* varies with abundance.

3 Results

Fine-scale determinants of habitat preference

(i) Forage Nitrogen and fibre

There was no significant difference in the nitrogen contents (in %) in the seagrasses eaten by the dugongs between two foraging sites, such as RTM and TCM sites; t-test (t (6) = 0.6, p=0.28). Moreover, there was no difference in the percentage of nitrogen content in the most preferred seagrass species of dugongs, such as *Halodule uninervis* and Halophila sp., in which the nitrogen contents were more or less similar (t (4) = 0.5, p=0.31). However, Acid-detergent fibres (ADF) and Neutral-detergent fibres (NDF) contents in the seagrasses of RTM and TCM sites significantly varied (F (9,8) =4.3, p=0.02, F (8,8) =7.35, p=0.005, respectively).

(ii) Forage abundance

Irrespective of seasonal abundance, inter-site bivariate analysis (between all foraging areas) showed that only 5% of variations in dugong foraging site selection could be explained by the forage abundance R^2- 0.05-F-1.12, p-value- 0.3, N(sites)-23. However, foraging intensity: abundance-based categorisation reported a statistically significant difference between trail counts from low-moderately abundant meadows and highly abundant meadows F¬ (9,11)-22.1, Fcrit – 4,2, p-value- 0.0001. Moreover, the results of multivariate regression analysis of the within-site response of dugong foraging intensity to abundance variations showed varied species-specific responses (see table 1)

Topographical-scale determinants of habitat preference

During the entire study period, I recorded 31 direct dugong sightings (active fishers and personal sightings) and 1507 foraging trail distribution in the study area, as shown in Fig 1. Consequently, the first photographic evidence of dugongs was documented from the Gulf of Kachchh region through this study. A total of six reef-top meadows (RTM), four mid-intertidal tidal-creek meadows (TCM), and four major sub-tidal foraging pastures were discovered and mapped in the southwest part of the Gulf of Kachchh. Mapped seagrass meadows have differed with respect to elevation (MSL); hence, I broadly characterised these meadows into reef-top (RTM) tidal creek meadows (hereby TCM) and subtidal meadows (chapter 2, fig 2).

(i) Tidal regime and foraging habitat selection

Spatial distribution patterns of dugong foraging trails have differed between RTM and TCM. Tidal heights were found to be one of the elemental factors required for making decisions regarding the choice of foraging meadow. Accessibility to each type of meadow (RTM, TCM, Subtidal) depended upon the minimum high and low tide depth retained at spring and neap tides.

Results of the bathymetric mapping indicated that during the spring high tide the water level was ≥ 3.4 mts, during which all DFA's had dugong accessibility depth (fig 2 (i)). Depth levels at all RTMs fell below the dugong accessibility depth during all low-tide heights of ≤0.4 mts and neap high tides ≤2.8 mts height.

During the neap tide days, the accessibility of dugongs to all foraging areas was reduced to 78.2% during the high tides. At all low-tides (neap and spring days), only subtidal meadows had accessibility depth, thereby reducing the daily total proportional accessibility of DFA's to 28.4% (fig 2(iii)). In conclusion, I found that the spring tide days were more conducive for dugongs to access major parts of the meadows than the neap tide days. However, only TCM and subtidal foraging areas remained accessible during the neap tide days. Finally, only subtidal meadows could be accessed during any low-tide period.

(ii) Deep-water refugia

The spatial extent of the foraging trails within each DFA's was strongly correlated with proximity to deep-water or tidal refuges, coves or creeks (Fig. 3). Tidal refugia for dugongs were categorised into two major kinds that distinctly differed between RTM's and TCM's. At RTMs, total foraging trails were clustered close to coves (Fig 3(i)). But, at TCM, the foraging trails' density consistently remained either within, in the case of shallow vegetated tidal creeks (fig 3(ii)) and around in the case of narrow-unvegetated tidal creeks (fig 3(iii)). Hence, creeks functioned as tidal refugia at TCM. Maximum distance foraged from the refugia differed at RTM and TCM (fig 3 (iv)). Distance from the refugia did not determine the foraging effort (table 1, (5)). However, forage biomass, trail lengths (ease of forage removal), and foraging intensity were statistically significant determinants for the distance the animals chose to forage away from the refugia (table 1). This foraging strategy was the same for both tidal creeks and reef-top meadows.

(iii) Transit-only tidal channels (${}_{TO}$TC)

I observed that dugongs have utilised the differential depths of channels and creeks in the Gulf of Kachchh for their ease of movement, gaining accessibility to the interiors of tide-influenced meadows from refugia. The order of these open-water tidal channels to inshore tidal creeks is illustrated in Fig (4). Low order- deep water tidal channels that run alongside reefs connect the foraging meadows and hence became important for mega-fauna navigation; hereby referred to as transit-only tidal channels (${}_{TO}$TC). ${}_{TO}$TC culminated/dissected deep tidal-creek meadows discussed in Chapter 2. Inter reef deep-water transit channel had higher velocity with a mid-line and a width of 1.5-3.5 kms, with an average depth of ~15 mts. The width of ${}_{TO}$TC depended upon its placement within the reef patches. For example, ${}_{TO}$TC that flows between Paga and Bhaidar reefs was wider with ~1.5 kms width.

However, high order-tidal creeks have had a high stream bed area to depth ratio and are essentially the culmination of deep-water channels and ${}_{TO}$TC that ascend towards tidal mud flats. Creeks dissecting shallow mid-intertidal TCM (Low elevation tidal creek, hereby ${}_{LE}$TC) have a low-tide depth of 30-150 cms and a width range of 5-20 High elevation tidal creek ${}_{HE}$TC have a low-tide depth of 2-15 cms and a width of 2-40 mts. ${}_{LE}$TC and ${}_{HE}$TC's differential functions are discussed

Moreover, no foraging trails were recorded on the sub-tidal meadows due to a lack of photographic evidence caused by high turbid and turbulent waters. However, direct observational records (n-15) of foraging (confirmed by the presence of turbid plumes formed while foraging) in the subtidal meadows of Chepri cove, Vadda Kabba cove, Hankiwala cove, and at Beyt-Dwarka's bay were observed (fig 6).

(iv) Assessment of dugong site-specific foraging strategy

Longer foraging trail lengths were observed in DFA at TCM; $\bar{x}$ = 9.5 ± 3.8m (n=159), compared to DFA at RTM's where $\bar{x}$= 3.5 ±0.88 m (n=189) was observed. A multivariate regression model was finally designed to assess the best-fit determinants for the foraging intensity at TCM and RTMs. The model analysed the role of foraging trail counts, forage biomass (in dry weight), and trail lengths (independent variables) as an effect of proximity of foraging ground to refugia distance (dependent variable) was estimated (table1). It was observed that forage biomass and distance of the foraging ground from the refugia contributed majorly to the total trail numbers and lengths. The advantage of such a foraging strategy observed is discussed later.

(iv) Forage's ease of removal

The composition of the substratum of different meadows was studied and found a difference in the variances of substratum composition between RTM (σ^2- 206.2) and TCM (σ2- 310.3). Non-foraging meadows had the lowest variance in the sediment texture (σ2- 52.2). This correlated with foraging trail length, i.e. ease of removal of forage. At TCM, silt, clay, and fine sand dominated the sediment composition, with coarse-sand constituting the lowest proportion. Conversely, coarse and fine sand comprise most of the total sediment composition of the reef-top meadows' substratum. Subtidal meadows' substratum was primarily composed of clay and silt. Largest foraging cold spots were found at *H. beccarii* meadows, which occupied clayey mud mounds at TCM (fig 5).

4. Discussion

Investigation of fine-scale habitat preferences

(i) Habitat preference based on forage quality; % Nitrogen and Fiber

However, abundance-based foraging strategies in dugongs differed in Northern Australian meadows and Queensland's meadows (Tol et al., 2016). Tol et al. 2016 also reported that dugongs prefer high biomass meadows at one foraging area and preferred low nutrient low biomass meadows at another. % Nitrogen content was not found to be an essential deciding factor in dugong habitat selection. However, to test the effect of foraging intensity on the total %Nitrogen, I compared the estimations of whole plant amongst forage of Paga reef (low habitat selectivity) and Bhaidar reef (high habitat selectivity) of *Halophila ovalis* and Halophila uninervis community. Results indicate tthere is hat no statistically significant difference between the sites t (2) =0.001, p= 0.5. However, the difference in variance values,

%N Paga reefs forage σ²- 0.01, and Bhaidar reefs forage σ²- 0.22, is evidence of the fact that a high grazing intensity can alter total foliar nitrogen concentrations. Similar results were reported by Aragones et al. (2006), where grazing by megaherbivores was found to increase the nutrient quality of the forage. A similar finding was reported for hind-gut fermenters, such as Cape Mount zebras, which exhibited no nutritionally driven habitat selection (Forbes et al., 2022). Their choice for a foraging ground depended upon forage abundance. Evidences from experimental grazing effect on the seagrass meadows are warranted to understand the direction of the effect foraging has on the % nitrogen content of the forage.

Post grazing, a drop in nitrogen concentrations occurs. Seagrasses invest nitrogen in regrowth after every grazing event and other similar disturbances (Perry and Dennison et al., 1999). This is observed in fig 7, wherein a high fluctuation in the nitrogen content could be an effect of regrowth on barren foraging trails in the meadow with young plantings. This results in the change of age structure in favour of relatively high nitrogen plantlings. A post-grazing higher proportion of new foliage growth showed high nitrogen concentrations and low fibre content.

(ii) Cultivation grazing’s effect on habitat quality

Perry et al., 1999, extended the advantage of timing the regrazing in that benefit from high foliar nitrogen could only be successfully acquired when megaherbivore grazed in moderation and only after regrowth had been established. The site-fidelity analysis consolidates this evidence. I report that dugongs actively controlled and timed their re-grazing intensity within a DFA. Re-grazing, an intensely foraged area, was either done after an interval of ~ 20-35 days or in moderation (%N dips in DFT’s). This strategic way of regrazing might ensure the consumption of a higher-quality seagrass forage.

Further, two dips in % nitrogen were observed throughout the season fig 7. The first fall in %nitrogen in forage fig 7 (B) at all three sites could be a combined effect of energy energy-consuming reproductive phase of the seagrasses (February-April) and mobilisation of energy resources towards post-grazing regrowth. Lastly, the fall observed late in summer (April to May) (fig 7 C) could be due to foliar nitrogen thinning during the pre-senescent period (Mae et al. 2004; Avila et al. 2014; Zakari et al. 2021). The inherent low foliar %N concentrations are reported to be a consequence of nitrogen-poor soil. However, Perry and Dennison et al.,1999 reported a reduced nitrogen fixation rate in ungrazed sediment.

(iii) Role of fibre content in foraging ground selection

Fiber plays a vital role in making decisions regarding forage habitat selection. ADF values measure lignin and cellulose and are indicators of the forage's digestibility. To contextualise, a high ADF value decreases forage digestibility and its net energy gain. A nutritious forage with low digestibility will be essentially unavailable to the animal. NDF measures hemicellulose, cellulose, and lignin. NDF is inversely related to animal forage intake. A high NDF shall mean a lower consumption of forage. Forage NDF and ADF have been used extensively to understand its digestibility; an elemental criterion for deciding feed quality (Hansen et al., 2017).

Annual seagrass species that colonise the Gulf of Kachchh are classed as fast-growing, low-fiber species (Preen et al., 1991). I report no differences in overall ADF/NDF of forage from the RTM and TCM, but estimated a high inter-genus difference in variances. Fibre content of forage with pure stands or dominant mixed stands of *Halodule* ranged between 23% - 44% ADF and 28% -56% NDF, whereas Halophila ranged from 28%-34% ADF, 30%-38% NDF. Complemented with the nitrogen fluctuations (implications of young plant re-growth after grazing), a higher % NDF/ADF further explains low foraging intensity at RTMs as dugongs attain the net energy required from uprooting fewer high-fibre swards.

Lastly, calf trails identified with a width range of 10-12 cms were largely observed at TCMs and at RTMs only when the forage was composed of young plants. A high NDF forage may not be suitable for young dugong calves, hence increasing their dependence on TCM's low NDF forage. Based on the digestibility element alone, all low ADF/NDF meadows (primarily TCM with low-fiber Halophila sp) should be ideal foraging grounds for dugong calves.

To conclude, although the % nitrogen is a weak determining factor for habitat selection, a rotational re-grazing strategy should ensure the maintenance of higher habitat quality via young pasture. Fiber concentrations differed slightly and only between foraging habitats at RTM and TCM.

Habitat preference based on seasonality of seagrass species and abundance

(i) Effect of seasonal forage on foraging home range

The foraging home range differed due to seasonal forage availability (fig 8). During the early growth period of (September-December), dugongs foraged on sparse, young plants of *H.uninervis* meadows. Early season meadows are characterised by their sparsely abundant M-208±122.1 shoots/m^2 young shoots of *Halodule uninervis*. High dependence on the presence of early-season low-fibre forage increases the conservation importance of the foraging grounds that harbour winter forage. These are all reef-top meadows: the southern meadow of Paga reef, Bhaidar, Chank, and Nor Island meadows. Early-season foraging grounds are the only areas available for the small population of dugongs from post-monsoon till the onset of winter (September- December). Collating this with the fact that the forage abundance throughout the winters is thin, also attributed to the fact that to meet up with the net energy gain via foraging during the early season (September- December), animals will have to increase their foraging range (DFA's at RTM have high inter-meadow distance).

Further, during the seagrass peak growth season (Feb-May), homogenous meadows of Halophila sp. dominated DFA's at the Tam-Watan reef. Meadows of the mid-intertidal (TCM's) and subtidal zones cause contiguity between the RTM's. TCMs and subtidal meadows were selected for foraging simultaneously as the *Halodule uninervis* dominated RTMs; i.e. site-fidelity was observed at all types of meadows. Conclusively, a high summer abundance of forage at all sites may constrict the populations' home range during this period, minimalising the need for wide-range movement patterns like those during winters.

(ii) Forage abundance as foraging habitat determinant

Results indicated that the selection of meadows for foraging purposes was regardless of their abundance; however, the intensity of foraging differed invariably between high and low-moderately abundant seagrass meadows (table 1, (1)). The lowest grazing intensity of 10-20 trail counts (fig 9) was observed in areas with higher shoot abundance. Conversely, a higher count of foraging trails of the range 65-295 was found in habitats with a low-moderate category of forage abundance (fig 9). The latter was the predominant scenario at tidal creek meadows or RTMs that have multiple channel inlets, e.g. Nor Islands RTM. Meadows where foraging intensity/efforts, i.e., trail counts were high, harboured morphometrically smaller seagrass species and/or meadows growing on the soft substratum, which provides ease of forage removal. Variations in DFT counts suggest that to achieve a high net rate of energy intake, and dugongs increased their foraging efforts in sparse meadows. At abundant meadows, foraging by uprooting fewer seagrass swards lowered foraging effort, thus saving more net energy.

(iii) Dugong foraging intensity to intra-site variations in shoot abundance

I studied seasonal variations of dugong foraging efforts from three DFA: Tam, Bhaidar reef and Betiwali meadow (of Paga reef), the latter of which are RTM and former both TCM’s. All sites differed in seagrass composition (see Chapter 1 for details). Further, all dugong foraging areas (DFA) studied had variable foraging onset and regrazing intensity across the season (fig 10). This indicates a foraging strategy involving variations in temporal usage of these core foraging areas.

The earliest foraging in the season was observed at Bhaidar reef (R^2Adj- 0.98, p-0.01) (fig 10 (iii)) in November. Foraging at the rest of the DFA’s studied started later with the emergence of forage. This could be explained by the presence of a seasonally persistent high ratio of below-ground: above-ground biomass of *Halodule uninervis*, a foraging advantage that the other sites lacked.

Early season response of foraging intensity to total species abundance at Betiwali (R^2Adj- 0.98, p-0.11) and Bhaidar meadow (R^2Adj- 0.72, p-0.02) showed a strong positive correlation (see table 2). Fast colonising *Halophila ovalis*' emergence and expansion were evidently essential to the increments in early season foraging intensity, making the species the most preferred forage.

A range of 11-104, 23-55, and 16-27 foraging trails were observed throughout the season at Bhaidar, Tam, and Betiwali reefs respectively; indicating lowest foraging degree of the Betiwali reef forage (fig 10 (i)). No consistent seasonal correlation was observed between overall seasonal foraging intensity and species abundance across the sites, except at Tam reef (table 2). At Tam reefs DFA, the increase in the foraging efforts was partly explained by the increments of shoot density of *Halophila ovalis* and *Halophila decipiens* (R^2Adj- 0.52, p-0.01).

(iv) Rotational grazing and its importance during peak forage growth period

Establishment of fast-growing species hence is elemental to support the forage requirement in forage-limited period (Oct-Jan) in the Gulf. Dugongs then move to foraging at these sites even at the specie' low-biomass, emergent periods; attributing to the fact that site-fidelity to foraging areas is a seasonal response to seagrass emergence and is independent of high-biomass. Later as seagrasses become densely abundant post-February, a shift in foraging strategy was observed, in that meadows were left ungrazed or were only mildly grazed after a high grazing event. Concomitantly, a number of other adjacent yet disjointed DFA's to which the population showed fidelity towards were found (fig 10). This suggests that the small populations foraging strategies are structured and mediated by rotationally grazing on well-connected DFA's. Such foraging strategies have also been reported by De Iongh et al., 2007 in Indonesia and in green sea turtles by Hernández et al., 2014.

Investigation of topographical-scale habitat preferences

Dugongs’ use of foraging habitat at different lunar tide days

In a system where herbivores have a small population size and availability of preferred forage throughout their range, occupation of higher quality habitats comes before the subsequent lower quality habitats. On the ground of this, selective foragers such as dugongs in the Gulf of Kachchh have an advantage as all meadows composed of the preferred fast-colonizing species of pioneer genera; *Halodule* and Halophila (Preen et al., 1995). To optimally forage the individuals within the dugong population will have to capitalize on the tidal regime of the Gulf of Kachchh by reducing energy spent in movement and accessibility to pastures. This has been achieved by dugong populations around the world.

Selection of foraging habitat and residence time of animals in it depends on seagrass coverage/biomass, reef topography, water depth, tidal and diel cycles (Chilvers et al., 2004, Sheppard et al. 2009, Sheppard et al. 2010, Derville et al. 2022). Interaction of rotatory tidal currents complemented with the clockwise-circulation of currents within the Gulfs funnel with the local reefs and islands, creates tidal-height specific seascape of submerged and aerial meadows.

In the Gulf of Kachchh, foraging accessibility to the three types of meadows; reef-top, tidal-creek meadows, and sub-tidal meadows, differ in a tidal cycle (high and low tides within 24 hrs) and tidal phase (spring tides or neap tides in a month) (fig 2). Moreover, the distribution of these DFA types form a high proximity network, the association of which is further aided by tidal, creeks and gullies channels (fig 3 (ii, iii)). This makes a greater portion of the meadows of the GoK, a dynamic interconnected foraging pasture.

Amamoto et al., 2009 reported that the dugong population at Talibong islands which has similar topographically heterogenous habitats as the Gulf of Kachchh, also made tide-specific foraging habitat decisions. My study gives conclusive evidences that dugongs sustain in a macro-tidal system by temporally synchronizing optimal foraging in each meadow type (RTM, TCM, and subtidal meadows) in the pasture-reef network with tidal cycles and phases. Such topographical and hydrodynamic characteristics of RTM, TCM, and subtidal zones are discussed.

(i) Foraging pastures at Reef-top meadows

RTM’s occupy areas at relatively high elevation patch and fringing reefs and have a higher relief than the TCM due to the presence of peripheral reef and fossilized coral complexes. Due to their elevated position, RTM’s experiences effects of the mixed tides more profoundly than other TCM (refer chapter 2). In the Gulf, RTM support highest biomass forage;1.1-2.7 DW/m^2, and %NDF followed by the light-limited TCM; 0.2-0.8 DW/m^2 and lastly meadows of the subtidal coves 0.16- 0.30 DW/m^2.

RTM meadows; Chank, Nor, Chepri and at Paga reef, along with the adjoining reefs are aerially exposed during all low tides (spring or neap) (fig 11 (i), bottom panel), hence, naturally remained inaccessible to mega-herbivore foraging. However, neap tides have a notable effect on DFA at reef-tops in that a 100% of the foraging meadows retained only <1mts water level during the high tides, rendering the meadows submerged yet inaccessible to foraging (fig 11 (i), top panel). Total monthly duration of RTM accessibility is therefore halved due to foraging unavailability at both high and low water periods of neap tide days.

Sheppard et al., 2007, 2009, 2010, reported that dugongs at complete resource availability period of high and intermediate tides, selected patchy habitats with high nitrogen and high starch concentrations, and did not necessarily select high biomass meadows to forage. Since the GoK meadows are nutritionally homogenous, foraging on high biomass pastures (like RTM’s) becomes optimal. To prevent the effects of potential nutrient reduction that comes with total plant maturation (especially for annual herbage), large herbivores restrict themselves to a grazing micro-habitat, wherein they repeatedly forage on (M.F. Wallis et al., 1996, Iongh et al., 1998).

At GoK, site-fidelity was observed at all foraging micro-habitats at the high biomass RTM’s. The function of re-grazing is especially indispensable at RTM meadows (high fiber *Halodule* dominant) for the maintenance of stable abundance of young low fiber forage. Further, close proximity of foraging micro-habitats at RTM’s, to adjacent coves becomes deep-water refugias for dugongs. This additionally explains their foraging movement patterns i.e., deep-water cove↔RTM, energetically advantageous for this reef-dwelling population.

(ii) Tidal creek meadows and Ecosystems corridors

TCM’s were estimated to occupy the largest perimeter of all meadows recorded, followed by moderately sized reef-top and subtidal meadows (chapter 2). Network of transit and foraging channels, locally enhances the functionality of the tidally influenced areas as ecosystem corridors for a variety of nektonic animals. However, accessibility to the elevated reef-ward region of TCM is limited to the available length of tidal creeks that anastomose within the mid-intertidal mud-flats.

Tidal waves, currents, streams and channels dominates the reef system of the Gulf and more effectively influences the seagrass and mangrove ecosystem. Tidal circulation of waters plays a major role in structuring the seagrass ecosystems architecture (Pace et al 2015), in de/stabilizing sediments, nutrient mixing, regulating seagrass composition and abundance etc. Channels are often found in association tidal sand banks, and intersecting intertidal flats and mangroves in macrotidal environments such as the Gulf. Channels and have a characteristic high velocity, which is very prominent during the flooding tide period but vary depending upon the surface area of the channels stream bed. Ascending shallow water waterways; a culmination of deep-water channels, have low-energy, narrow width and dissect the intertidal mud-flats are called tidal creeks. Their importance to dugong herbivory and accessibility to foraging ground is discussed.

Transit-only/ unvegetated tidal creeks

Boström et al., 2006 reported fish juveniles’ use of unvegetated barren strips within seagrass meadows used to tidally migrate to the deeper offshore waters in their final stage of maturation. Such usage of transit-only tidal channels (herby $_{\text{TO}}$TC); depth of >14 mts MHWL, was observed in mega-fauna like green sea turtles, Indo-pacific humpback dolphins, and dugongs within the Gulf of Kachchh.

Tidal creeks of mid-intertidal meadows

I further report two types of foraging tidal creeks based on the elevation of meadows they dissect, and consequently, their differential function. Creeks dissecting low-elevated mid-intertidal DFA (Low elevation tidal creek, hereby ${}_{\mathrm{LE}}$TC) and vegetated foraging tidal creeks (High elevation tidal creeks- ${}_{\mathrm{HE}}$TC), that dissect TCM at high-elevation mud-flats.

${}_{\mathrm{LE}}$TC have a high-tide depth of approximately 4.5-6 mts and a width range of 5-20±9.8mts. The DFA's they dissect are composed of *Halophila ovalis* and Halophila decipiens. Strong flooding currents near its stream bed prevents seagrass settlement. Therefore, ${}_{\mathrm{LE}}$TC predominantly serves the transit function during high tides. Dugongs used the length of ${}_{\mathrm{LE}}$TC to gain access to the interiors of foraging areas, accessibility of which is otherwise limited by tidal restrictions (fig 3(iii)). ${}_{\mathrm{LE}}$TC's association to pastures of lower %NDF forage (see section 4.1, (iii)) makes these areas ideal for mother-calf foraging. Gannon et al., reported that manatee mother-calf pairs were observed more often during high tides in areas minimally affected by tides. This implies the usage of tidal streams during high-tide phase by shallow-water sirenians helps conserve energy. Predominance of tidal streams refuges in TCM than RTM foraging areas, further explains mother-calf' foraging habitat choice of the former.

Similar ease of accessibility to shallow-water, and high elevated DFA's of Bhaidar and Nakya tidal flats is provided by vegetated foraging tidal creeks (High elevation tidal creeks- ${}_{\mathrm{HE}}$TC); high-tide depth of approximately 2-3.5 mts, and width of 2-170 mts. Shallows of ${}_{\mathrm{HE}}$TC become a favorable environment for settlement of *Halodule uninervis* and *Halophila ovalis* on their stream bed. ${}_{\mathrm{HE}}$TC hence serves the dual function of transit/accessibility to elevated DFA's and provision of forage within its premises. Further, ${}_{\mathrm{HE}}$TC interconnects the foraging areas of reef-top, facilitating these reef-dwelling herbivores a shorter and easier route between core foraging areas (fig 3 (ii), fig 11)

Tidally mediated and synchronized foraging strategies are not unique to dugongs. Mendes et al., 2002 and Scott et al., 1990 reported bottlenose dolphins' pods swimming with the tidal high water to access bays wherein prey accumulation occurs at the tidal front. At the Narrows of the Irish seas, pinnipeds were observed to preferably forage at the edges of channels, utilizing the low-energy channel flanks for hunting the benthos. Unless travelling actively to forage, they chose to passively swim in the mid-channel area to reduce metabolic costs of travelling Lieber et al., 2018. To actively hunt benthic prey, pinnipeds in their study occupied, akin to dugongs of Kachchh, optimum foraging areas that provided both fastmoving surface waters (for pinniped transit) and slower stream-bed flows (for prey accumulation).

(iii) Subtidal foraging areas

An estimated proportion of all foraging meadows available at mean low-water level (MLWL) of ≤0.4mts (Chapter 2, table 1), conclusively states that most subtidal meadows are accessible for foraging at all low tides. In the Gulf of Kachchh, subtidal meadows are solely composed of mono-specific stands of *Halophila decipiens* . This asserts the importance of the forage species' tolerance to low-light conditions that aids in its colonization of deep waters, essentially making it a low-tide forage.

Further, dugongs were spotted by fishers at the sheltered cove area of Chepri, and Vadda Kabba during receding to slack phase of the tidal cycle. They were reported to be foraging at these sub-tidal meadows during low-tide period (fig 6), when the adjoining RTM's become unavailable for foraging. Contrarily, the low-water sighting locations at Tam, Chank and Hankiwali coves (red marks fig 1) did not harbor any vegetated areas within their premises, indicating that these areas are being used as stopover sites, functioning to wait low-tide periods of inaccessibility. More importantly, barren refugias are ideal in their proximity to the expansive foraging zones of Tam and Chank reef which may be accessed during a following flooding tide.

Since, subtidal foraging areas are fewer in the south-western region of the Gulf, and the only available foraging grounds at low-tide period, directly indicates the conservation importance of these sites.

(iv) Importance of refugias in macro-tidal habitat

Dugongs' edge-association via tidal refuges of coves is stranding risk avoidance strategy. Similar deep-water refugia-association was reported in several mangrove dependent nektons by Knieb et al (1994). Hence a complex of refugias; deep-water coves, transit and foraging tidal creeks within or/and adjacent to core foraging areas, enable optimal movement by reducing the metabolic cost of time-sensitive transit in areas of high tidal fluctuations. Spatial association DFA and refugia type: RTM↔cove, subtidal meadows↔cove, and TCM↔tidal creeks are a dynamic topographical construct that dugongs utilize for increasing foraging success in tidally affected pastures of reef-complex of the Gulf. LaCommare et al., 2008, reported Antillean manatees' occupation of coves that adjoin tidal channels, along the central coast of Belize, which has vast and abundant seagrass meadows. Curiously, this area had a tidal range of <0.3 mts, and rarely suffered any low-tide exposure. Hence, function of barren cove habitats depth may not be limited as a low-tide stopover site but by extension may also provide resting habitats for dugongs in the Gulf of Kachchh. Due to reef asymmetries, GoK has abundant cove area, both barren and vegetated and alike channel areas, these refugias must be given a higher priority in dugong conservation and management decisions.

(v) Foraging cold-spots and avoidance

Inter-site differences in substratum type were found to be a fine-scale foraging habitat determinant too. High foraging intensity observed at TCM's like Tam and Watan meadows was attributed to the ease of uprooting the meadows' morphologically smaller species; *H. ovalis* and *H. decipiens* occupying a soft substratum, a characteristic of mid-intertidal seagrass meadows

However, this relationship between soft substratum and higher counts of foraging trails has a threshold. The foraging trails observed directly over *Halophila beccarii* meadows were rare (<4 in a total of five years of study period), in comparison to *Halodule uninervis*, *Halophila decipiens*, Halophila ovals meadows. Although, *H. beccarii* have been reported to be selectively foraged upon by dugongs at Talibong islands of Thailand (Nakashini et al., 2006), I report foraging cold-spots or avoidance of this species in the Gulf. Reduced utility of *H. beccarii* meadows as a foraging pasture could be attributed to the clayey consistency of the species' preferred substratum, making uprooting a difficult feat. This was assessed by comparing mean water holding capacity (MWHC) of substratum to the foraging intensity. On a highly foraged reef-top meadows' average of MWHC of composite substratum of coarse-sand and fine-sand was 40.4 ±3.7, whereas on least foraged mud-mounds; *H. beccarii*' microhabitat, the average of MWHC was 48.2 ±5.2. This suggests that the water-retention property of clayey mud may render the mud-specialist seagrass species; *Halophila beccarii* in the Gulf of Kachchh, least preferred. Consequently, *H. beccarii* meadows become foraging cold-spot with a total estimated perimeter of 36.01 km^2 in the SW-Gulf of Kachchh (fig 5 (i)).

However, Sameeha et al., 2022, reported small amounts of the species in stomach of two stranded dugongs, which implies low preference but not complete avoidance of the species. Moreover, the species' meadows were also found on mud-mounds with relatively higher proportion of silt These areas may be uprooted with ease. Such meadows are located at the Chepri reef of Bhaidar islands.

Dangad meadows' (south Paga reef, see chapter 2) relatively less foraging intensity (3-20 DFT counts), despite its high shoot density 5580/m^2(Sdev-±1199), might be attributed to the presence of biogenic sand, the accumulation of which is caused by a reduction in sediment resuspension (Fonseca et al, 1992, Binzer et al, 2005). A 25 gm (dry weight) of *Halodule uninervis* uprooted was estimated to adhere at least >8.5gm of biogenic sand intertwined in its fibrous roots.

This is a seasonally persistent meadow which consequently renders the canopy height of older plants to be naturally higher; approximate height 14-20 cms. Arguably this canopy height is not efficient enough to cause wave attenuation, but submerged dense vegetation, opportunistically may cause reasonable sedimentation by slowing water movement during the low water levels of ebbing and flooding tides periods. Consistency in the sedimentation function of Dangads' reef-top lagoonal meadow accumulates biogenic sand's entanglement in the below-ground biomass, rendering the potential RTM forage a hindrance for mastication.

Lastly, foraging cold spots also depended upon intensive intrusion of rocks and corals (fig 5 ii)). No foraging trails were found in seagrass patches growing in the midst of sheltered sediment vacancy of fossilized coral reefs at Chank and Goose reef (eastern Gulf).

Decline of the dugong population of the Gulf of Kachchh

Based on fisher community surveys of the geriatric population (age class >65-80), fidelity to these foraging meadows is not recent, and are of historic importance. Long-term site-fidelity and regrazing patterns may become a potential conservation issue in the Gulf due to the overlap of fast pace of newer maritime activities such as ship traffic, dredging channels, mineral exploration and extraction etc. Importance of group network within a healthy population size is useful to maintain the knowledge flow from older individuals to the younger age class. This diminishes gradually with the thinning of population size. Disappearance of knowledge regarding spatial and temporal use of meadows especially when most of the forage is tidally affected, may become self-deprecating to the resident population of dugongs of the GoK.

4. Conclusion

The Gulf of Kutch has temperature-cum-turbidity-sensitive meadows (Chapter 1) that are endangered due to climate change especially because of increase in seawater temperature, which may disrupt , phenology; interrupt growth patterns and reproduction of seagrasses. This will gradually reduce the extent of available pasture, which could cause local extinction of mega-herbivores especially dugongs and green sea turtles. Spatial patterns in habitat use by dugongs is largely behavioral synchronization to the tidal phases is not only an essential method to optimize foraging in a macro-tidal basin such as the GoK, but is also important to avoid low-tide stranding risk. My findings prove that dugongs have fine-scale geographic adaptations to survive in a macro-tidal habitat in that they use tidal channels for transit, foraging and accessing the interiors of meadows on tidal flats. I further deduce that they may also utilize tidal cues to pick an appropriate foraging ground and allocate foraging time on it accordingly.

Since, core foraging sites are congregated in the south-western complex of reefs, I imply that these meadow network of the south-west has a higher foraging utility due to their interconnectivity. With the aid of satellite telemetry, UAVs and other aerial survey methods, movement ecology of dugongs has been done extensively studied in Australia (Sheppard et al 2006, 2009, 2010), New Caledonia (Cleguer et al 2020). Deployment of satellite telemetry methods would not have been logistically feasible during this study. This is due to the lack of expert animal handlers and small population size of dugongs in the study area (protected by Schedule I of Wildlife Protection Act). Consequently, direct observational studies are improbable in such cases. Hence, I propose that the use of the foraging trails as a sighting substitute to analyze dugongs’ relative use/preference in a complex of shallow-water reef system functions as cost-effective tool. Foraging trails and sighting data can only account for foraging ecology of dugongs and approximate foraging movements. Consequently, non-foraging movements, and habitat use for non-foraging purposes (resting, traveling etc.) cannot be studied via this model. However, predictive elements complemented with the unpredictable meteorological events such as pulsed turbidity, storms, winds etc, with seasonal variations of pasture abundance, requires a concrete energy efficient grazing strategy.

GoK’s dugongs are the only remnant population in India that have been surviving in a tidal-influenced landscape. My study also implies that such tidally-synchronized behavior might also be used by wider variety of reef-dependent taxa, including the Green-sea turtle population; another mega-herbivore of the GoK. Habitat use of dugongs especially for foraging in a macro-tidal ecoregion requires aid of tidal channels, therefore, I propose to declare all these identified ToTC as ‘Go-Slow’ zones to avoid disturbances from recreational and fishing vessel activities. It was observed that these ToTC channels were also used by fishermen for navigation to sea that needs to be regulated with limiting the speed of the vessels. Whiting et.al.,(2008) studied that small population of dugongs in macro-tidal areas of Darwin region of northern Australia that was similar to my observations in the Gulf of Kutch. Similar to my recommendations, they too emphasized that dugong management in the Darwin region required the consideration of large spatial scales, and multiple habitat types. In Gulf of Kachchh, dugong management should not be limited to core-foraging areas. Rocky reefs, transit channels, mud-flats, and deep-water refugia habitats over the entire stretch of the southern coastline should be considered as area of equal importance.

The ultimate aim is to provide herein the scientific base-line ecological data necessary for upgrading the conservation status of the dugong hotspots and better management of their critical habitats within the Gulf of Kutch region, thereby recovering their population in the Gulf. This comprehensive ecological background of foraging ecology and habitat preference and use becomes imperative for conservation managers in decision making.

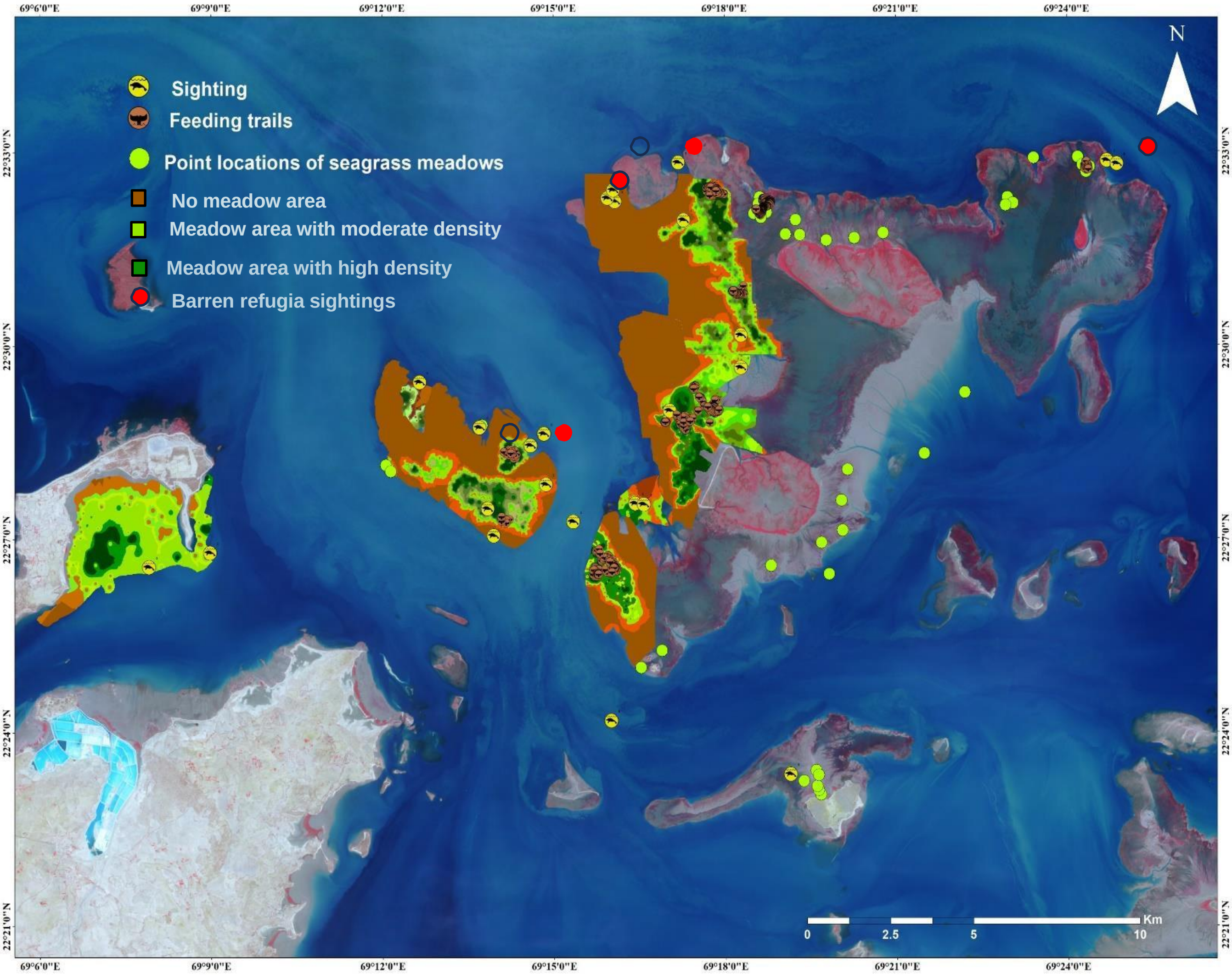


Fig 1. Spatial distribution of dugong foraging areas, sighting locations, and seagrass meadows.

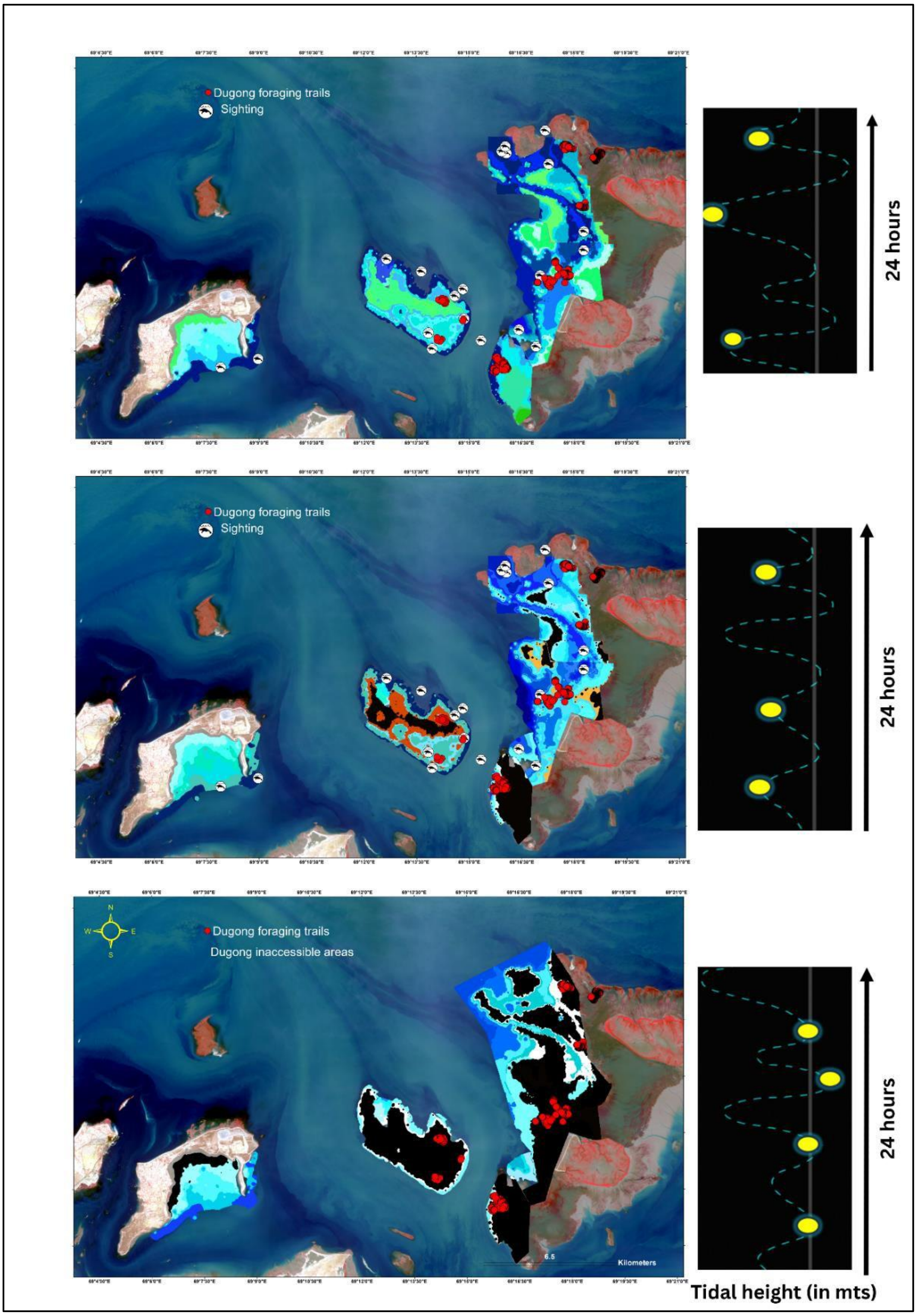


Fig 2. From top, bathymetric map for Spring (3.4mts) and Neap high tides (2.8 mts) and low tide height (0.4 mts) for topographically different dugong foraging areas. Exposed/ inaccessible for foraging areas are colored black.

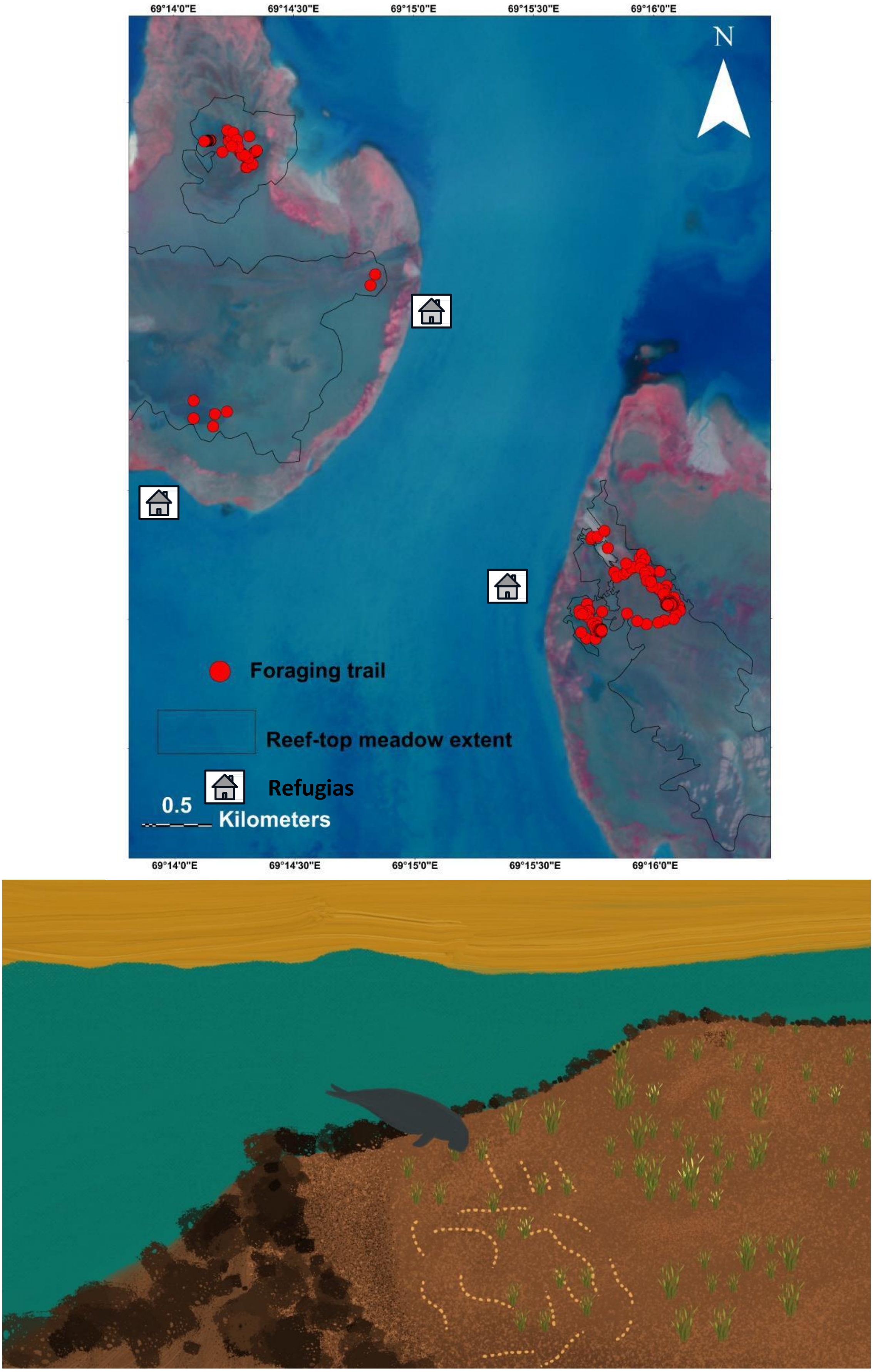


Fig 3 (i) Dugong foraging area spatial extent at reef-top meadows and deep-water refugias at adjoining coves. Bottom-illustration of dugong foraging microhabitat at reef-flat.

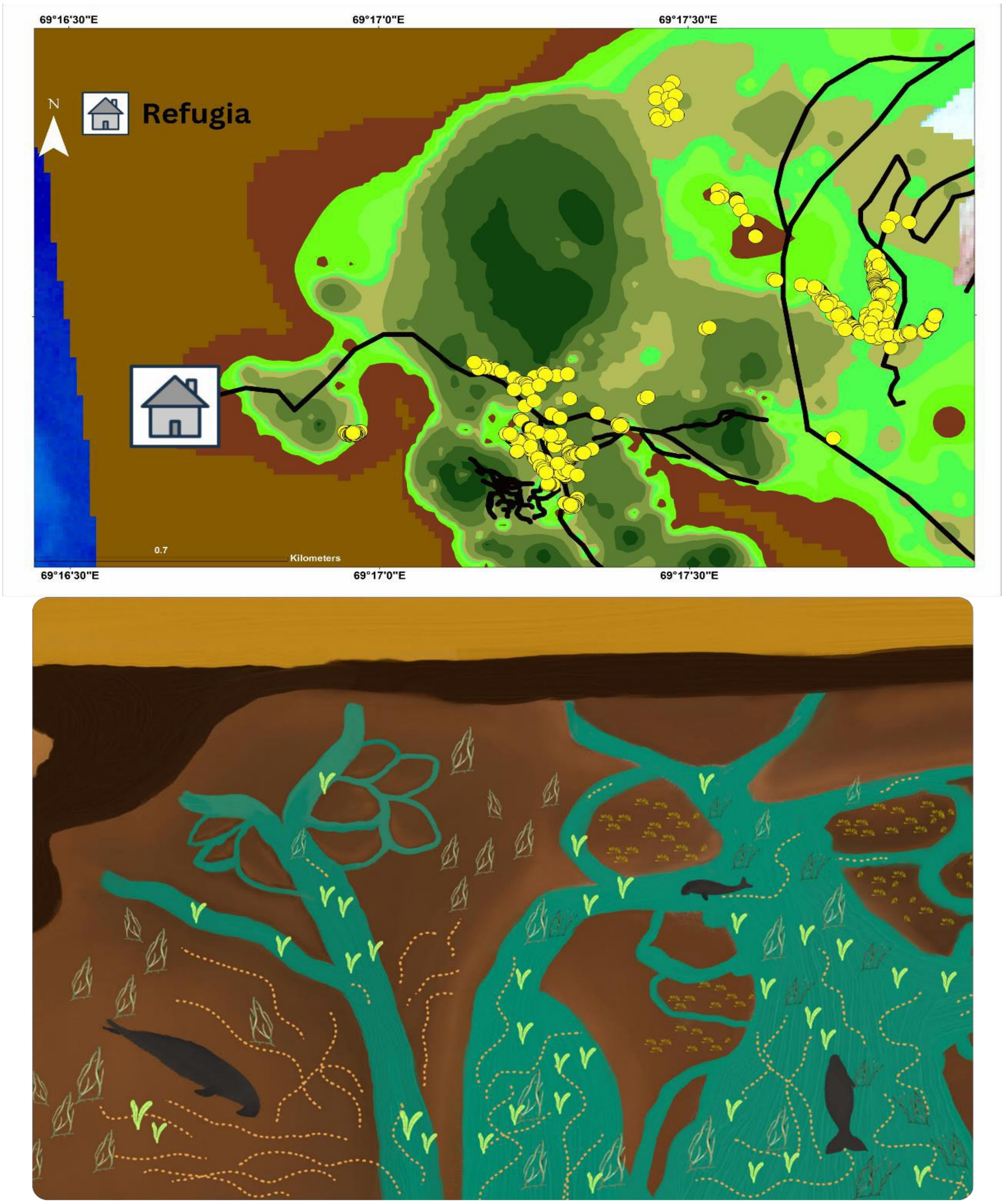


Fig 3 (ii) Dugong foraging area spatial extent at tidal creek meadow flanking high-elevation tidal creek refugias. Bottom-illustration of dugong foraging microhabitat at high-elevation tidal creek meadows Foraging trails were found both within and at flanking areas of the tidal creeks. Tidal creeks were used for both movement and foraging purposes at shallow-water habitats

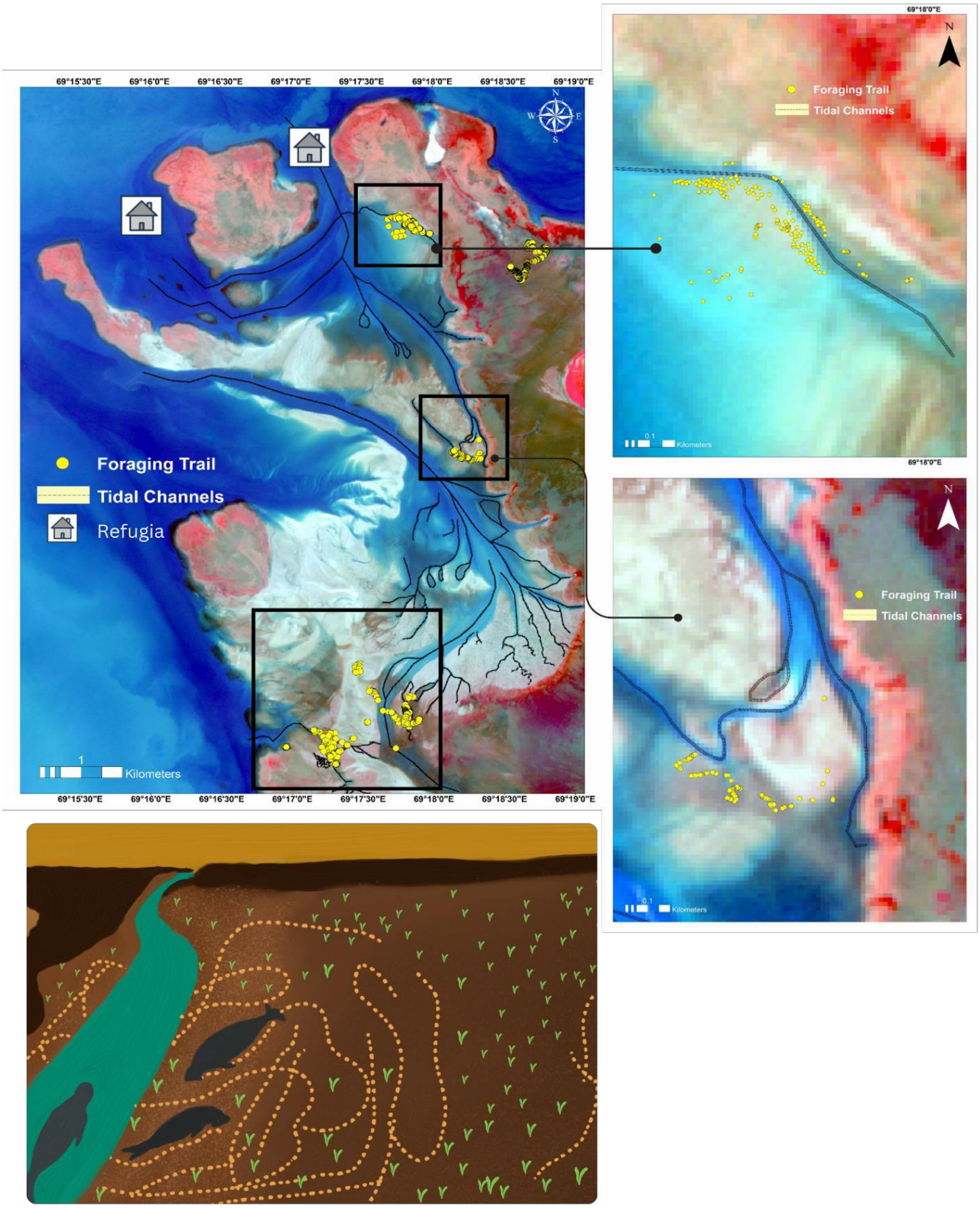


Fig 3 (iii) Dugong foraging area spatial extent at tidal creek meadow flanking low-elevation tidal creek refugias. Bottom-illustration of dugong foraging microhabitat at low-elevation tidal creek meadows. Foraging trails were found only at flanking areas of the tidal creeks. Stream bed of the low-elevation tidal creek was barren. Low-elevation tidal creeks were used primarily for movement in shallow-water habitats

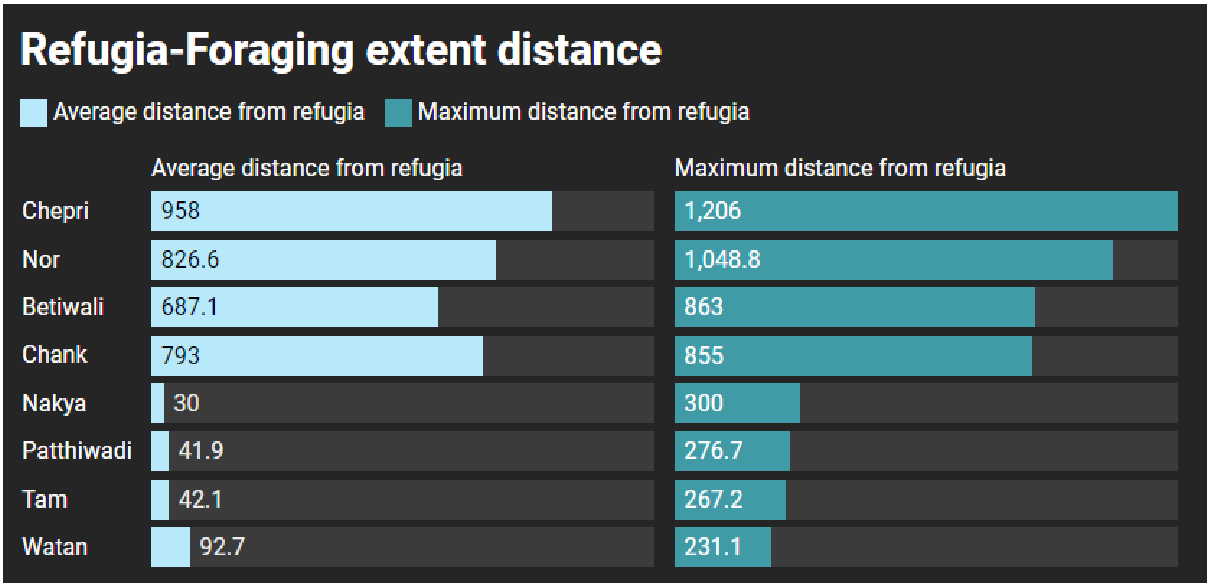


Fig 3 (iv) Near distance estimates from fixed-point closest refugia (> 3 mts MLWL) to total dugong foraging trail point locations (in mts) of Reef-top (Chepri, Nor, Betiwali, Chank) and Tidal-creek meadows (Nakya, Patthiwadi, Tam, Watan).

Multivariate regression variables	**R2 adj**	**p value**	**coeff**
1. Forage biomass ~ trail count	0.95178	0.016203	-82.998
2. Refugia distance ~ forage biomass	0.77655	0.048257	0.88122
3. Refugia distance ~ forage biomass ~ trail length	0.91651	0.041745	
4. Refugia distance ~ forage biomass ~ trail counts ~ trail length	0.94104	0.1542	
5. Refugia distance ~ trails count	0.50112	0.40507	-0.43274

Table 1 Result table for multi-variate regression to analyze the tide-mediated dugong foraging strategies at topographically distinct meadows.

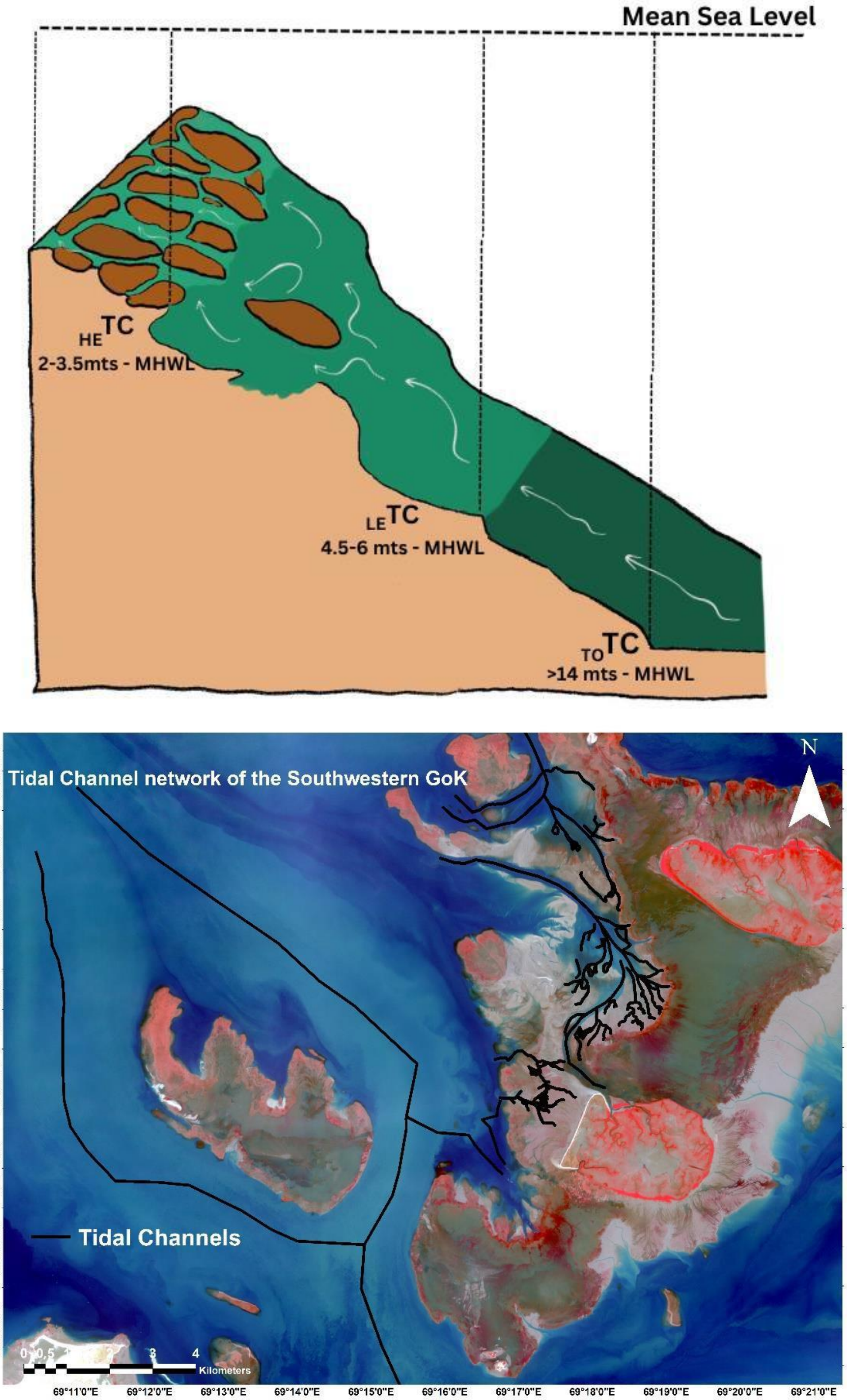


Fig 4 Type and order of tidal channels and creeks in the south-western Gulf of Kachchh reef complex. Mean sea level- 3.6 mts Okha port

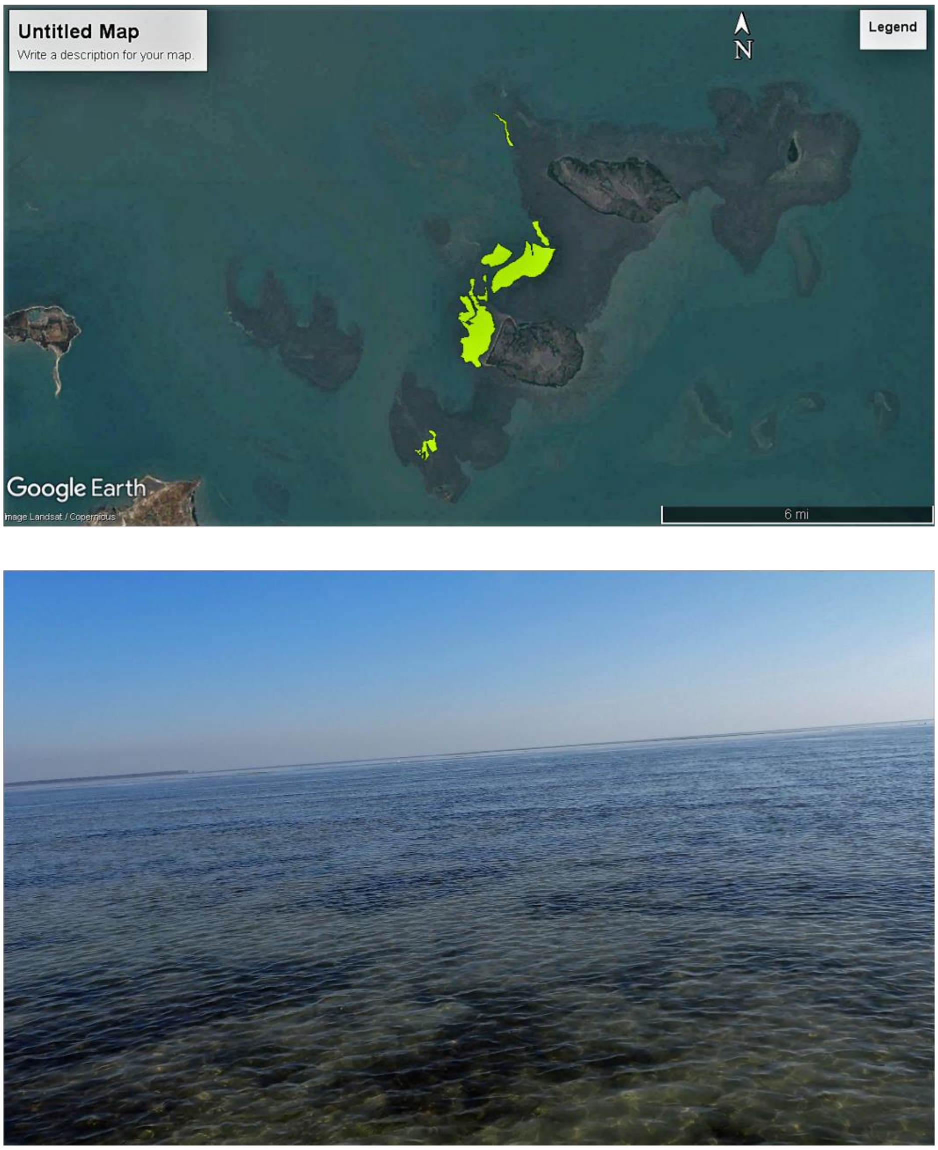


Fig 5 Foraging cold spots; top- mud-flats of Bhaidar island harbors largest *Halophila beccarii* meadow, bottom- seagrass patches growing between back-reef rocky intrusions were also categorized as non-foraging meadow region

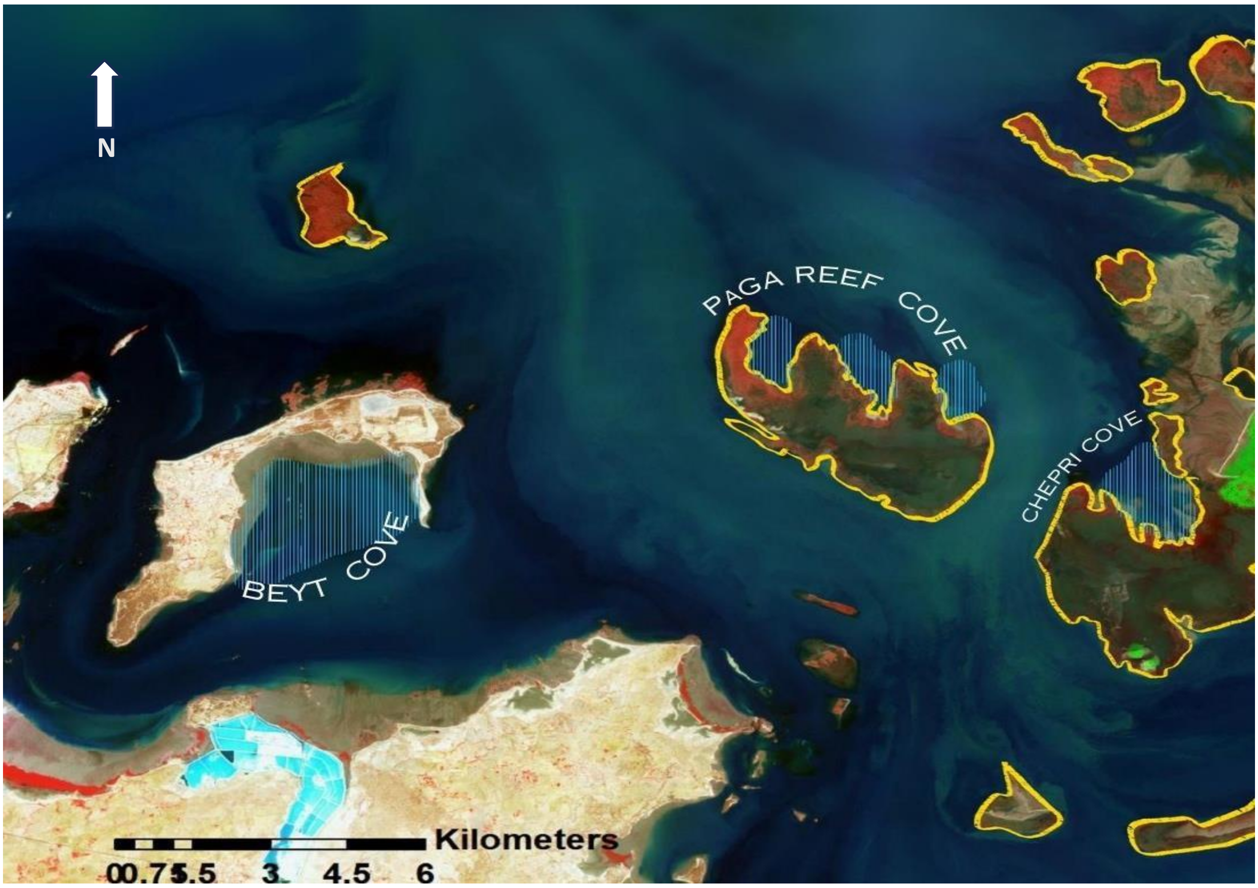


Fig 6 Dugong foraging areas in the subtidal zone. Subtidal meadows are the only foraging habitats available to dugongs during every low-tide period

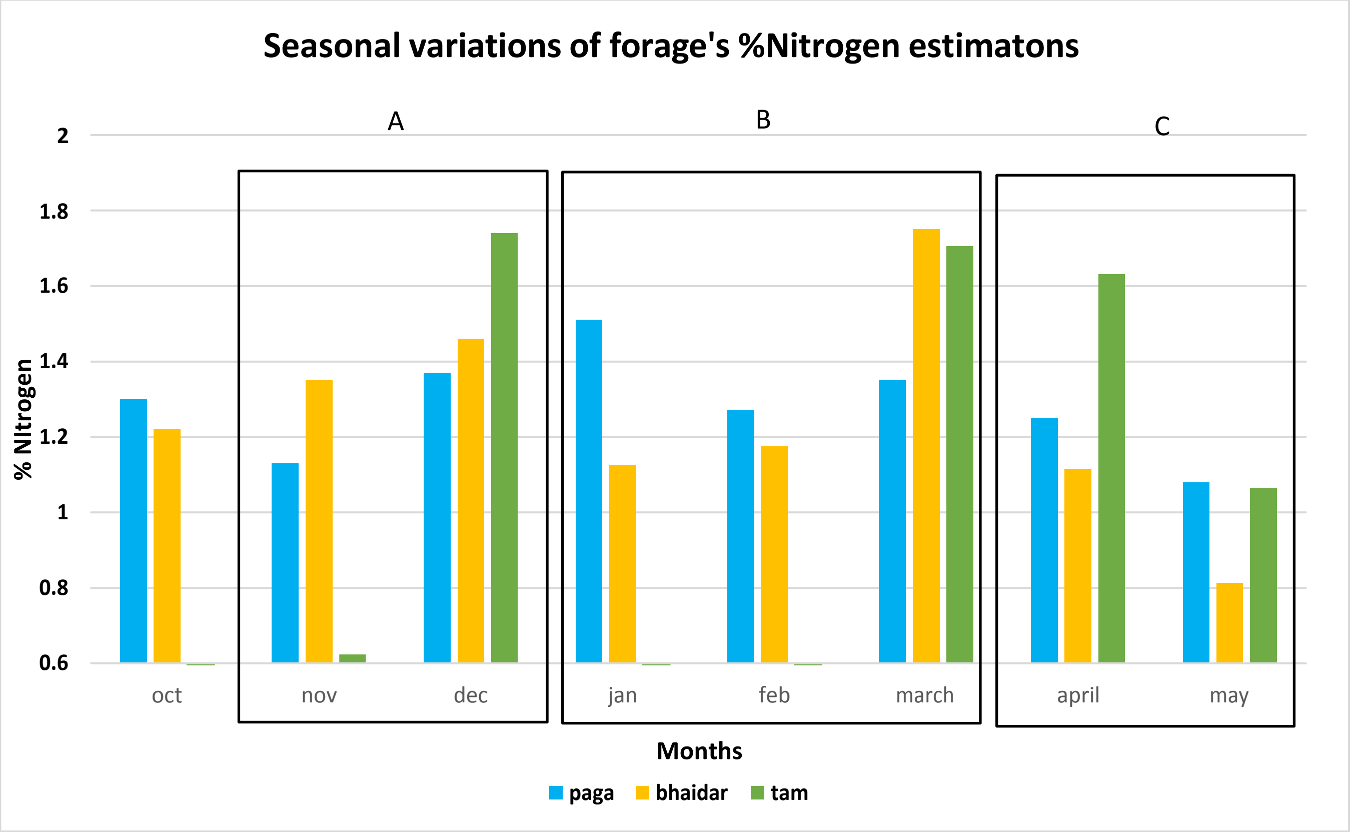


Fig 7 Seasonal variations in % nitrogen of forage from three topographically different foraging habitats; Paga- reef-top meadow, Bhaidar- High-elevation tidal creek meadow, Tam – Low elevation tidal creek meadow

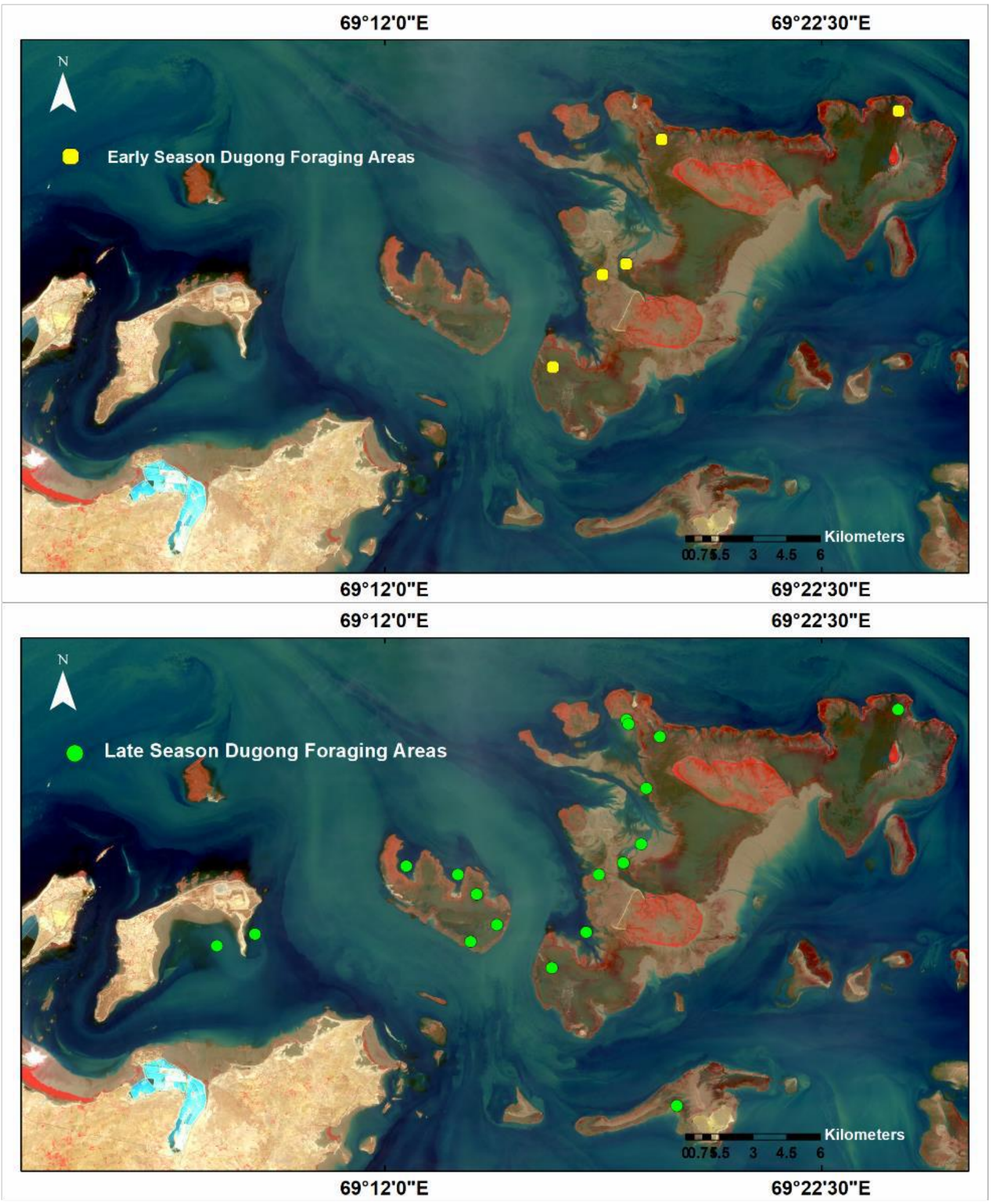


Fig 8 Spatial distribution of early and late-season foraging areas in the south-western Gulf of Kachchh.

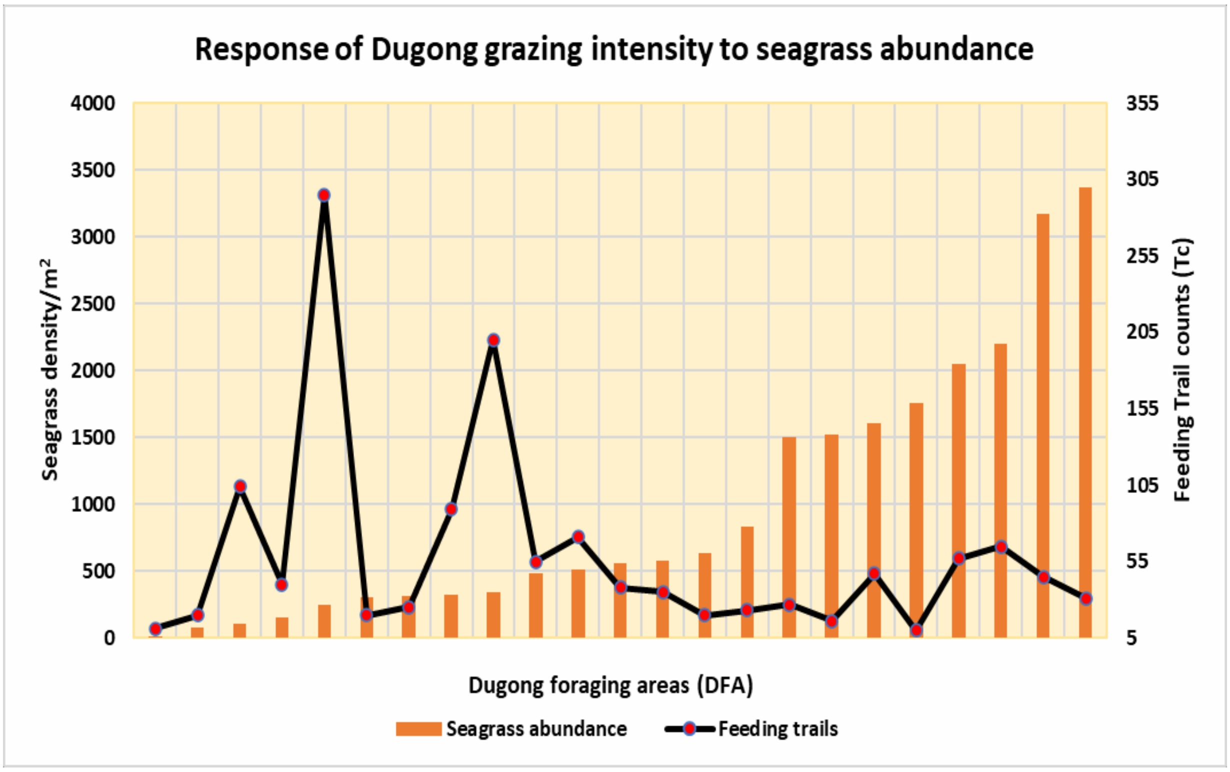


Fig 9 Graph showing variations in inter-site dugong foraging intensity (total foraging trail count) with forage density/m2 at surveyed foraging meadows (n-22)

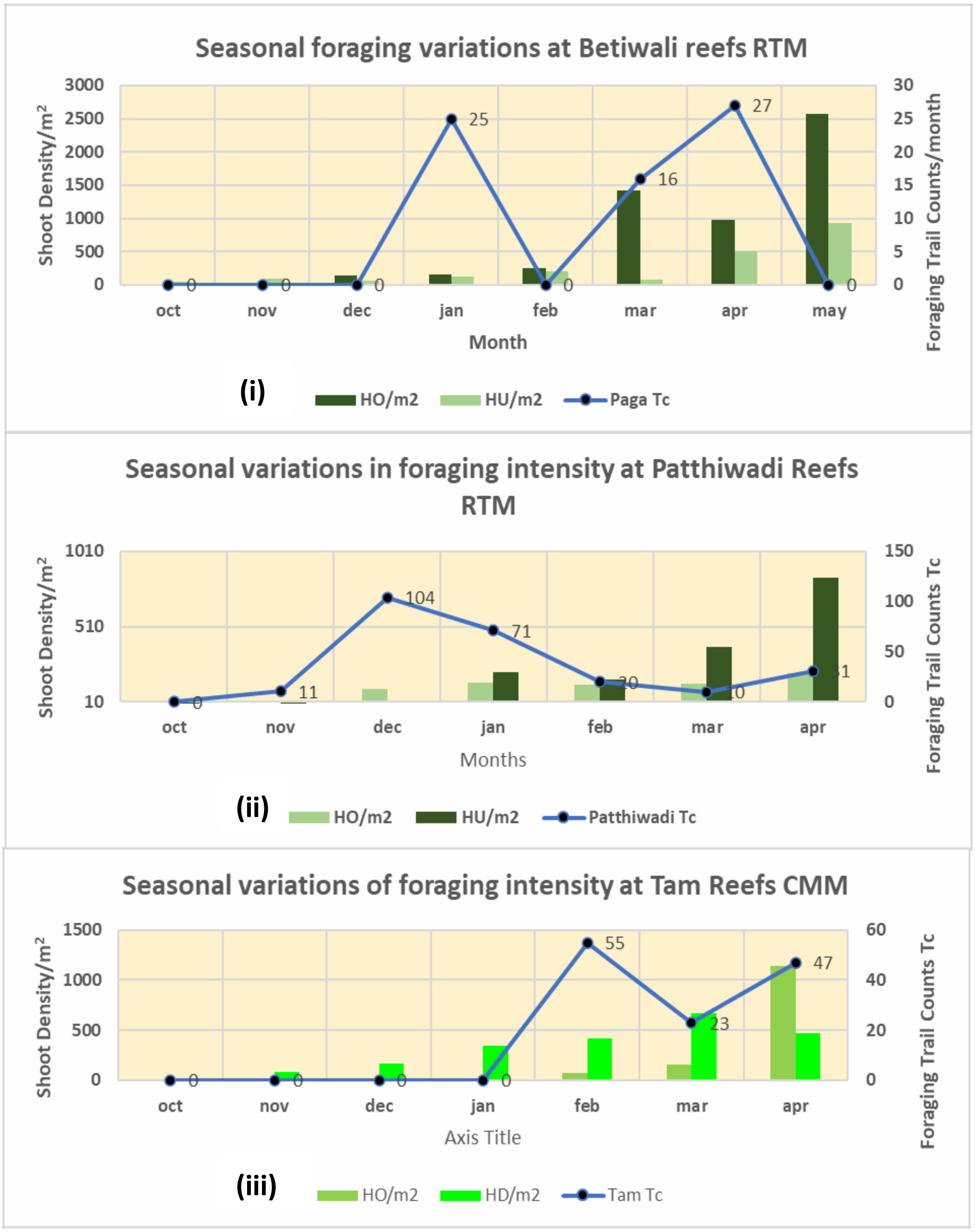


Fig 10 Graph showing variations in *intra-site* dugong foraging intensity (total foraging trail count) with forage density/m^2.

	Dependent variable-Trail number	***mlr***		**ANOVA**		
		p	**R^2**	**F:**	**df1, df2:**	**p:**
Tam Reef	HO Average SD/m2	**0.3**	**0.34**	2.3	2, 4	0.2
	HD Average SD/m2	0.2	0.4			
	Total species average SD/m2	**0.01**	**0.52**			
Bhaidar Reef: early season (Oct-Jan)	HO Average SD/m2	**0.02**	**0.72**	1309	2,1	0.01
	HU Average SD/m2	**0.01**	**0.11**			
	Total species average SD/m2	**0.01**	**0.98**			
Bhaidar Reef: (Feb-April)	HO Average SD/m2	0.11	0.09	2.1	2,4	0.23
	HU Average SD/m2	0.13	0.01			
	Total species average SD/m2	0.11	**0.26**			
Paga Reef: early season (Oct-Feb)	HO Average shoot Density/m2	0.11	**0.98**			
	HU Average shoot Density/m2	0.5	**0.70**			
	Total species average SD/m2	0.8	**0.95**			
Paga Reef: (March-May)	HO Average shoot Density/m2	0.7	0.01	0.029	2,5	0.9
	HU Average shoot Density/m2	0.6	0.04			
	Total species average SD/m2	0.8707	0.008			

Table 2 Multivariate regression model to estimate influence of the dugongs' site/forage species on foraging intensity (trail counts) during early and late-season.

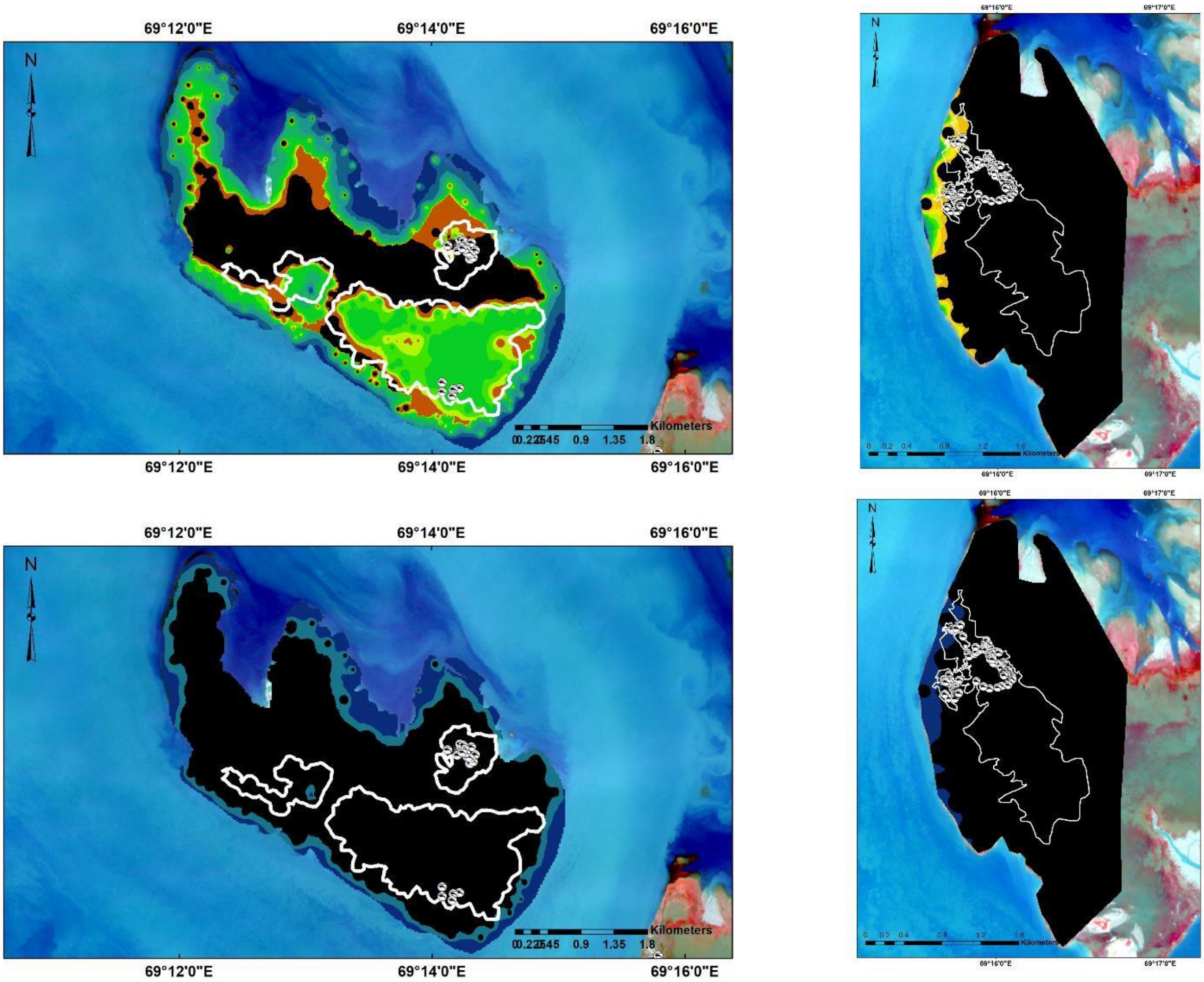


Fig 11 (i) Bathymetric map for reef-top meadows (white perimeter)/ dugong foraging areas (white marks) at top; high tide (2.4 mts) and, bottom- low tide height (0.4 mts).

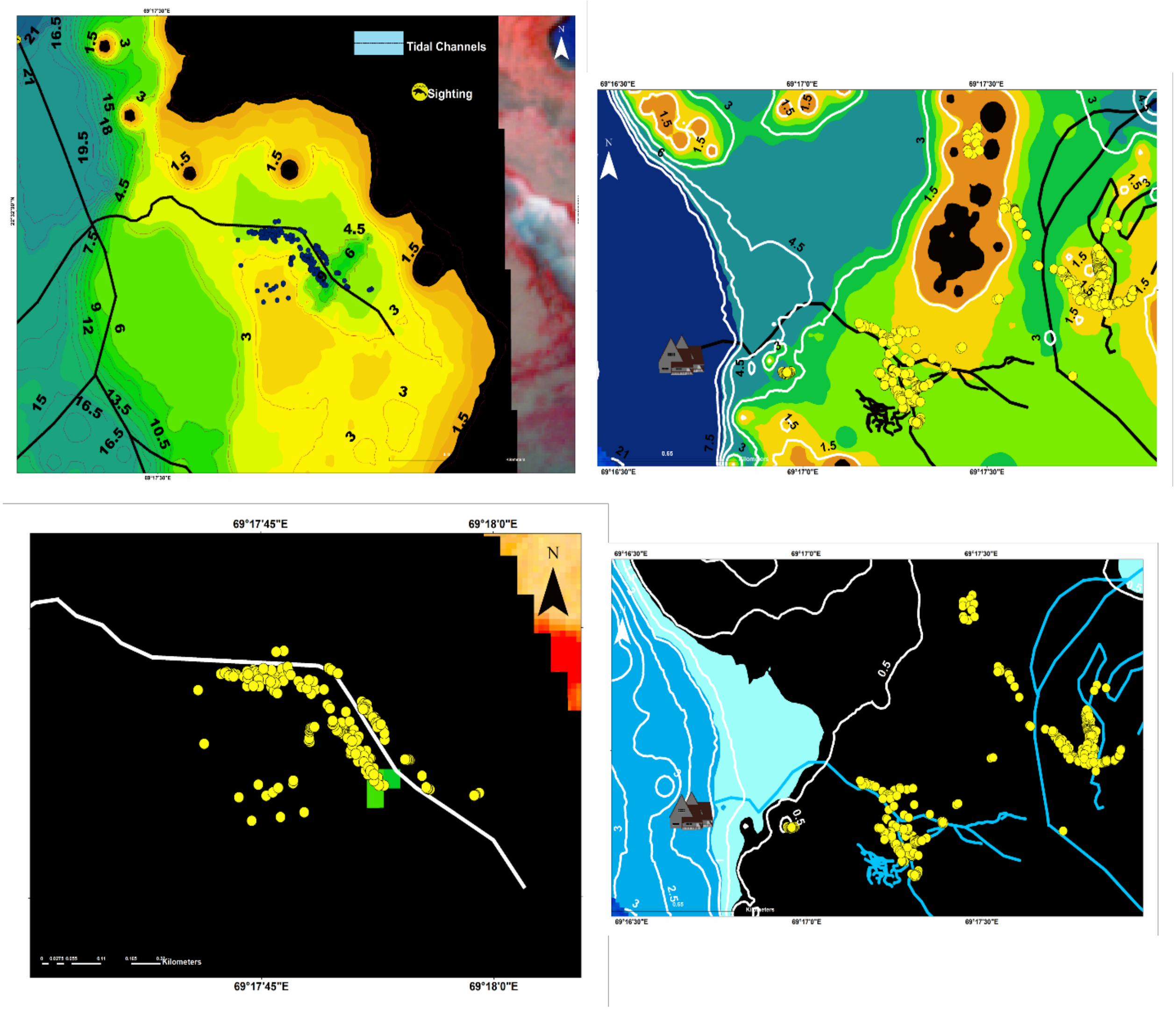


Fig 11 (ii)) Bathymetric map for tidal-creek meadows / dugong foraging areas (yellow marks) at top; high tide (2.4 mts) and, bottom- low tide height (0.4 mts).

Fig 12 Sediment composition of substratum of topographically different seagrass meadows

Synthesis- Importance of post-mortem analysis in conservation of dugongs and their foraging grounds in the south-western Gulf of Kachchh, Gujarat

Methods

We obtained dugong stranding information through a volunteer network developed in the fisher community of Beyt- Dwarka, and Arambada village of the GoK. This network comprised of fisherfolk who were sensitized through a series of community interaction programs (n = 3) conducted at Okha and Beyt-Dwarka fisher villages; Balapur, Arambada, and Rupen. Two dugong strandings were reported in the months of February 2018 and May 2018. Initial picture of Ajad Island dugong was taken when the carcass was relatively fresh (Fig1.a). The carcass was reported, and was necropsied after two weeks of the stranding event. Both necropsy examinations were done on-site under the supervision of the Gujarat state forest department.

Carcass photo-documentation and necropsy were performed using standard salvage and necropsy procedures. Each animal was examined for external marks, lesions, bruises and other injuries prior to internal examination. Since decomposition is relatively faster in intestines, Ajad dugongs' visceral organs after stomach, were rendered unexaminable.

Stomach content analysis was conducted on samples (300 g) collected from the cardiac end. The stomach content was preserved using 10% neutral- buffer formalin within nine hours of necropsy. Qualitative analysis of the gut content was done after diluting 5 grams of sample (n=2) with 50 ml of distilled water. To avoid crowding of seagrass segments, from the diluted sub-sample (50ml), a volume of 5 ml was used for making observations on a 2x2 cm^2 graded petri-plate.

Results

Ajad island stranding

A stage four ‘badly decomposed’(Eros et al, 2007) carcass was necropsied at the north-eastern part of Ajad Island (center point- 22°23' N, 69°19' E), where it was stranded. The animal was a 2.6 m (straight body length) adult female. The skin had been sloughed off completely but the remaining attached skin on the mid-dorsal side retained a hyperpigmented rake mark (Fig 1.a), evident of the fact that it had interacted with other adult male dugongs. The head showed clear signs of severe intramuscular haemorrhage with a cutaneous abscess on and around the nostrils (Fig 1.a). This haemorrhage could result from blunt force trauma to the head after a boat collision. On the dorsal side of the animal, the caudal vertebral processes were markedly visible (black arrow, Fig 1.a) indicating emaciation, but other signs of starvation such as caved in body mass around the peduncle could not be verified due to advanced stage of decomposition. Starvation was further ruled out as the stomach was full of seagrasses and blubber layer (Fig 1.e) was intact in both consistency and thickness. A cross-section examination of the dermal wall of the thorax (Fig 1.c) revealed the presence of a single oval and well-demarcated parasitic cyst of (dimensions; 32.11 x 40.40 mm) (Fig 1 (d)). Nematode, *Paradujardinia halicoris*, a common endoparasite in dugongs (Yashpal et al., 2018, Crusz et al., 1954), and manatees (Beck et al., 1988), was found in the stomach of the animal.

Positra island stranding

A sub-adult male dugong of the straight-body length of 2 m was reported by fishers of Positra near Man-marudi Island (center point- 22°25'59.56"N, 69°13'23.86"E) of the GoK. There were no signs of decomposition (bloating, discoloration, etc). Since the flippers had mobility when the carcass was found, rigor mortis had not set in, conclusively indicating mortality in the past few hours. Fishers confirmed mortality due to suffocation after net-entanglement which was factualised by rope-burn marks around the head and neck area (Fig 1.f). The skin was in a good condition and showed no signs of sloughing (Fig 1.g). The intact skin indicated various important clues to the type of interaction the dugong had undergone before its death. Small scars of several healed wounds (Fig 1.h) were found extending from the lower neck to the peduncle of the dorsum of the animal, the significance of which is discussed later.

Since the visceral organs were intact, a thorough examination of the gastrointestinal tract could be conducted. A localized single tumour on the duodenum which was sized 5 cm radius was found (Fig1.i). The outgrowth's purulence had a hard greasy consistency (Fig 1j). Moreover, the mesenteric lymph nodes appeared swollen (Fig 1k).

Tusk-rake scars

Several healed indentations and wounds were found on the dorsum of the animal from various interactions (Figure 2). The source of these wounds can be either biological via intraspecific interactions or non-biological source made by scratching behaviour of dugongs over sandy sediment (Anderson et al., 1978). Except for a few deep indentations, most of these marks were shallow. More important are the parallel marks on the back which are made due to the grazing action of pair of tusks. We discovered several counts of such *tusk-rake scars* (TRS) on the back of this dugong individual. Scars with different widths indicated that sexually mature conspecifics of different age-group had interacted with this male dugong (Fig 2). Based on width, five distinctly different scars were identified. These were then broadly categorized into t wo stages based on the progressiveness of healing (Fig 2). A new scar indicates a 'recent' (Stage -1) agnostic interaction, whereas completely healed marks appear shallow and discolored Lanyon et al., 2021) are evidence of older' (Stage-2) instances. Out of these, only one was recent looking (Stage 1) as it hadn't completely healed (scar 1 in Fig 2). The rest of the four scars (scars 2-5 in Fig 2) were older (Stage-2) and are probable to be made during a single event. Hence, at least two separate events of ritualistic sexual conflicts were experienced by the Positra dugong. Moreover, a scar inflicted by a relatively younger dugong (mark 4, width- 5.3 cms) was also observed.

Stomach content analysis

Leaf tip characteristics, leaf venation patterns, and numbers, leaf scars on rhizomes are the most prominent and important morphological features examined to identify seagrass species (Lanyon et al., 1986) (Fig 3); *Halophila beccarii*, *Halophila ovalis*, and *Halodule uninervis* were found in the stomach contents of both the stranded individuals. Both dugongs had also ingested fragments of nylon fishing net micro- filaments of length range; 0.23–30(fig 3).

Discussion

There is very little information regarding the social and reproductive behavior of dugongs in India. As concluded from the presence of tusk rake marks, both dugongs were involved in inter and intra-sexually aggressive conflicts which reflect positively on the social behavior of this small population in the Gulf. Similar teeth rake marks in bottlenose dolphins are reported to be a very reliable indicator of conflicts over resources and mates (Lee et al., 2019). Paired parallel in dugongs also provided insights to the diversity in age- class of the participant dugongs in the Gulf of Kachchh.

Dugong cows that are less than 2 mts long have almost certainly not born a calf (non-parous), whereas those larger than 2.50 m are likely to have been born young (parous) (Marsh et al., 1984). Hence, conclusively, the Ajad dugong was a sexually mature female, although due to the liquefaction of the ovaries, it could not be confirmed whether the cow had birthed a calf during her lifetime or not. Marine traffic exerts a growing pressure on marine megafauna (Peltier et al., 2019). This contributes to a net- entanglement as one of the leading causes of death for dugongs (Marsh et al., 2000, Reeves et al., 2013). Dugong population in the GoK, although range-resident, are highly mobile within the range. Their movement response is adapted to a dynamic tidal regime and local knowledge of the widely distributed seagrass habitats in the Gulf. This makes them mildly susceptible to harm caused by fishing activities that coincide with their foraging habitats.

Dugongs, like other marine mammals, are susceptible to a wide range of diseases, some of the infectious, non-infectious, or idiopathic (Eros et al., 2007). Both stranded animals, collectively, suffered from underlying conditions like visceral tumors, inflamed mesenteric lymph nodes, and parasitic cysts. This evidence might indicate the body’s immunoreactive state before its ultimate death. Our study reports that although the Ajad dugong might have suffered from head trauma due to boat collision and underlying parasitic infection. This can further be consolidated as the animal showed distinct signs of emaciation, yet had a relatively full stomach. A fishing net entanglement is evident from the rope impressions around the neck and is suspected to be the ultimate cause of its death. The same can be concluded for the Positra dugong. Seagrass meadows are known to reduce the velocity of tidal currents (Heiss et al., 2000), thereby causing sedimentation of fine particles (Suykerbuyk et al., 2016) and co-incidentally of fishing net micro-filaments. This naturally makes seagrass meadows extremely prone microplastic pollution, herbivory of which becomes a medium for plastic/nylon micro-filaments to enter to diverse food chains. Anthropogenic marine debris has also been documented in subtidal seagrass meadows of the Philippines (Abreo et al., 2018). However, the impact of micro-plastic sedimentation in dugong foraging habitats depends upon their bio-availability and post-consumption consequences in dugongs, which remains obscure. Although the clinical significance of ingestion of plastic micro-filaments is unknown in dugongs, it can have potentially lethal effects on sediment biota of seagrasses.

Photo-documentation and necropsy techniques as one of the key conservation tools to understand underlying stressors to the cryptic dugong population. Studying foraging behavior and reproductive status of dugongs in wild is close to impossible, especially for a small population wherein the chances of detecting a live animal become rare. This obscurity is further complemented by the turbid waters of the Gulf (0.5-2 mts visibility), which reduces the detection probability of the animal. Hence, an idea about their biology, reproductive status, and health, and natural and anthropogenic stressors can only be understood with relative clarity by salvaging information from carcasses. More importantly, the initiation of our research regarding dugong foraging ecology across the Gulf (Annual progress report 2019-2020) was an extension to conclusions drawn from the necropsy examinations. GoK is home to a variety of species that are ecologically significant and share the same habitat as dugongs. With dugongs being an umbrella species, their conservation may indirectly protect these ecological communities

Table 1. Measurements and healing stages of six different tusk-rakemarks observed on dugongs stranded in the Gulf of Kachchh, Gujarat,

India. The healing stage of TR56, i.e., recent or a healed scar was notclear from the photographic evidences

Tusk-rake scar (TRS)	Dugong case	Length (cm)	Width (cm)	Healing stage
TRS1	Beyt Dwarka	33.3	11.3	Stage 1
TRS2	Beyt Dwarka	26.5	8.7	Stage 2
TRS3	Beyt Dwarka	22	6.5	Stage 2
TRS4	Beyt Dwarka	18	5.3	Stage 2
TRS5	Beyt Dwarka	21.4	10	Stage 2
TRS6	Ajad	32	10.8	NA

Table 2. Body measurements of the two dugong individuals strandedin the Gulf of Kachchh

Body part measurement	Ajad dugong (cm)	Positra dugong (cm)
Straight body length	260	200
Girth (from under flippers)	–	138
Width (from and to the base of flippers)	85	61
Right flipper (dorsal proximal end to the tip of the flipper)	42.5	15
Left flipper	36	14.7
Maxilla	20	16.5
Teat length	6.5	–
Fluke length	88.7	78

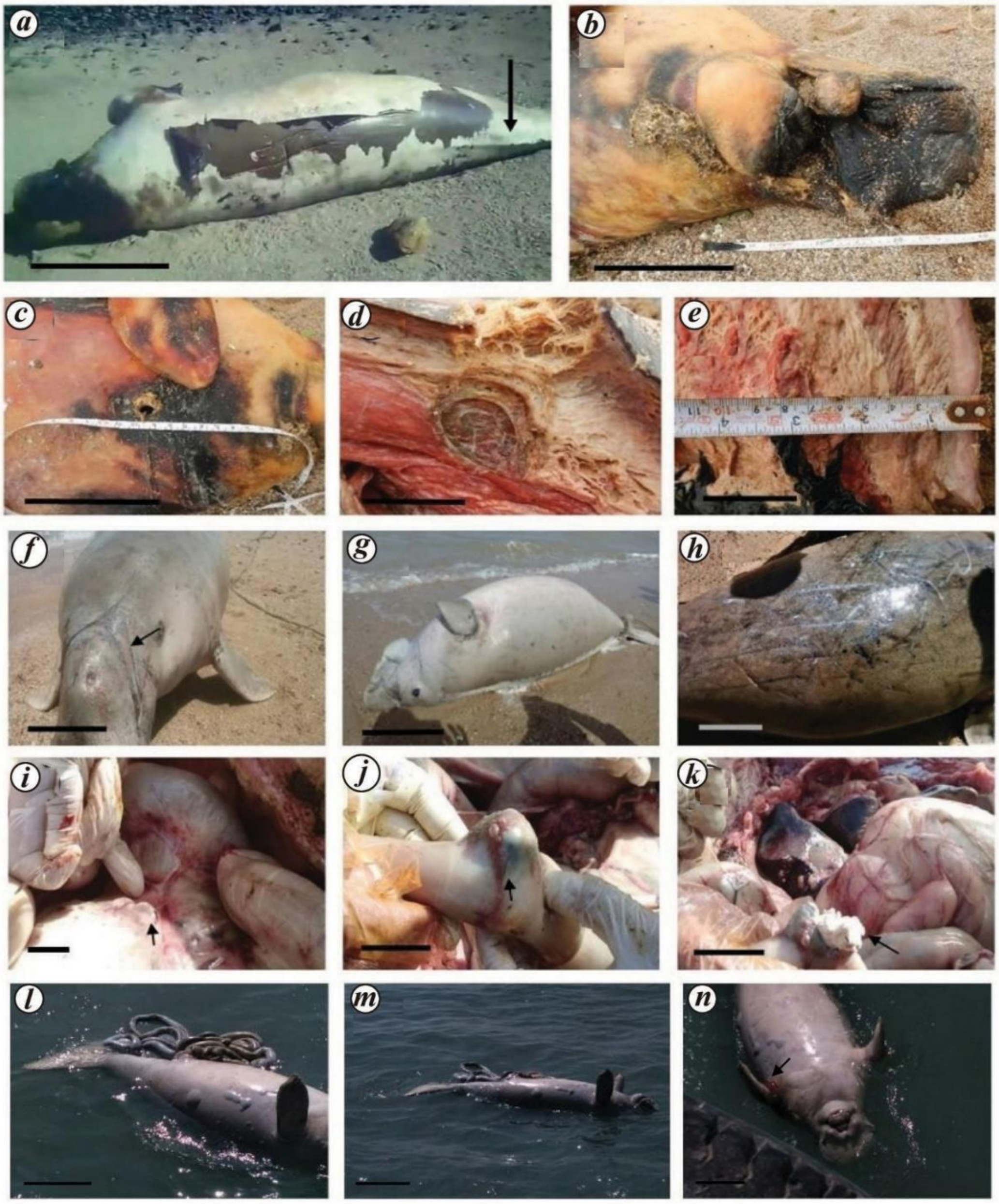


Figure 1 (***a–f***). Ajad Island dugong carcass in the Gulf of Kutch (GoK), Gujarat, India. (***a***) Decomposed carcass of a ma- ture female dugong (scale – 30 cm). (***b***) Rope burn marks around the neck (scale – 18 cm). (***c***) Thorax with cavity caused by parasitic infestation (scale – 15 cm). (***d***) Cross-section through the cavity showing cyst of an unidentified parasite (scale –3.2 cm). (***e***) Cross-section across the mid-ventral tissue layer (scale – 4 cm). (***f***) Rope burn marks (black arrow) visible around the snout (scale – 16 cm). (***g–k***) Positra dugong carcass (scale – 40 cm, GoK). (***h***) Numerous healed wounds on the back (scale – 15 cm). (***i***) Swollen mesenteric lymph nodes (scale – 2.5 cm). (***j***, ***k***) Purulent tumour in the small intestine (scale – 4.5 cm). (***l***, ***m***) Drifting bloated carcass exhibiting evisceration (scale – 20 cm). (***n***) Ante-mortem wound under flip- per (scale – 30 cm).

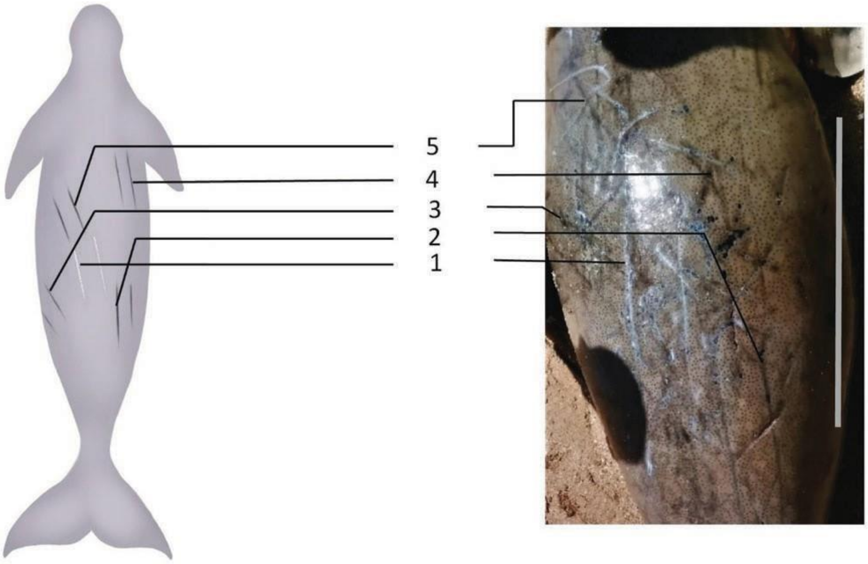


Fig 2 Illustration of tusk-rake scars as seen on the dorsum of the Positra dugong (scale -60 cm).

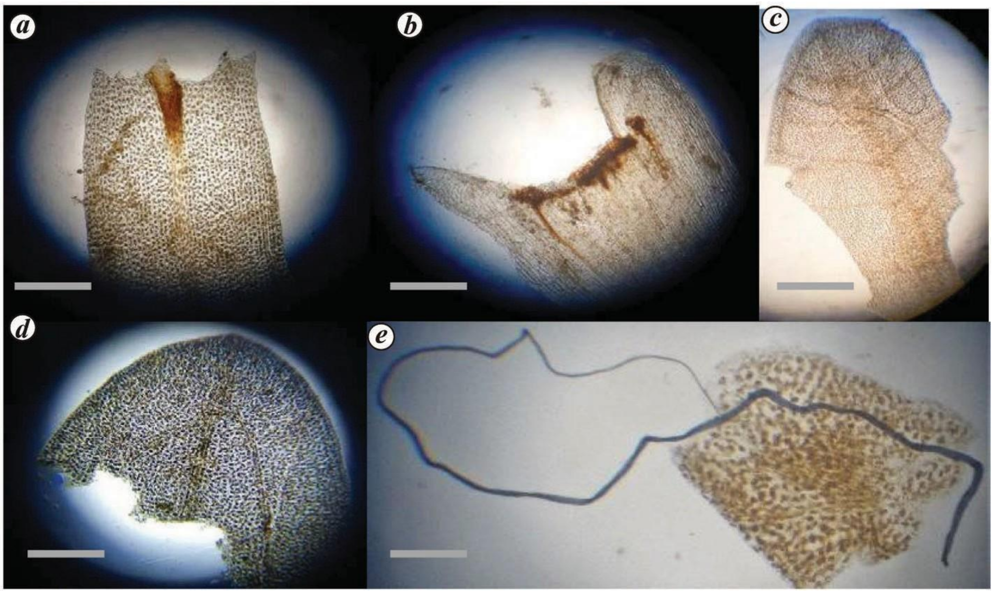


Figure 3. Photomicrographs of seagrass and plastic micro-filaments from the stomach content (scale – 2 mm). (***a***) *Halodule uninervis* leaf apex. (***b***) *H. uninervis* leaf sheath. (***c***) *Halophila beccarii.* (***d***) *Halophila ovalis.* (***e***) Nylon micro-filament from fishing nets.

References

Chapter 1- Introduction

Adhavan, D., Chandran, R., & Sivakumar, K. (2022). Diversity of seagrasses and site-specific strategy for their restoration in Gulf of Kachchh Marine National Park—Gujarat, India. *Journal of Coastal Conservation*, *26*(3), 20.

Ali, Rauf. "Seasonal variation and climate change influence coral bleaching in Pirotan Island, Gulf of Kachchh Marine National Park, Gujarat." *Current Science* 107.11 (2014): 1780

Biswas, Nilanjana. "Gulf of Kutch marine national park and marine wildlife sanctuary: a case study." (2009).

Dawes, Clinton J. "The dynamic seagrasses of the Gulf of Mexico and Florida coasts." *Proceedings of the symposium on subtropical-tropical seagrasses of the southeastern United States*. 1985.

Dawes, Clinton J. "The dynamic seagrasses of the Gulf of Mexico and Florida coasts." *Proceedings of the symposium on subtropical-tropical seagrasses of the southeastern United States*. 1985.

Ilangakoon, A. D., and Tint Tun. "Rediscovering the dugong (Dugong dugon) in Myanmar and capacity building for research and conservation." The Raffles Bulletin of Zoology 55.1 (2007): 195-199.

Kamboj, R. D. "Biology and status of seagrasses in Gulf of Kachchh Marine National Park and Sanctuary, India." *Indian Ocean Turtle Newsletter* 19 (2014): 9-11.

Khamis, Abdulqader, et al. "Long- term persistence of large dugong groups in a conservation hotspot around Hawar Island, Kingdom of Bahrain." *Aquatic Conservation: Marine and Freshwater Ecosystems* (2023).

Manassa, R. P., et al. "Capacity of a temperate intertidal seagrass species to tolerate changing environmental conditions: significance of light and tidal exposure." *Ecological Indicators* 81 (2017): 578-586.

Marsh, H., H. Penrose, C. Eros, J. Hugues. 2002. "Dugong. Status Report and Action Plans for Countries and Territories" (On-line pdf). Accessed September 19, 2009 at http://data.iucn.org/dbtw-wpd/edocs/2002-001.pdf.

McRoy, C.P. and McMillan, C., 1977. *Production ecology and physiology of seagrasses*. In: C.P. McRoy and C. Helfferich (Editors), *Seagrass Ecosystems: A Scientific Perspective, Marine Science,* 4, Marcel Dekker, New York, pp. 53-81

Mehta, Lyla, and Shilpi Srivastava. "Pastoralists without pasture: water scarcity, marketisation and resource enclosures in Kutch, India." *Nomadic Peoples* 23.2 (2019): 195-217.

Panyawai, Janmanee, and Anchana Prathep. "A systematic review of the status, knowledge, and research gaps of dugong in Southeast Asia." *Aquatic Mammals* 48.3 (2022): 203-222.

Polis, Gary A. "Why are parts of the world green? Multiple factors control productivity and the distribution of biomass." *Oikos* (1999): 3-15.

Preen, Anthony. "Distribution, abundance and conservation status of dugongs and dolphins in the southern and western Arabian Gulf." *Biological Conservation* 118.2 (2004): 205-218.

Raghunathan, C., et al. "A record of live corals along the Saurashtra coast of Gujarat, Arabian Sea." *Current Science* (2004): 1131-1138.

Shetye, Satish R. "Tides in the Gulf of Kutch, India." *Continental Shelf Research* 19.14 (1999): 1771-1782.

Short, F.T., McKenzie, L.J., Coles, R.G., Vidler, K.P., Gaeckle, J.L. 2006. SeagrassNet Manual for Scientific Monitoring of Seagrass Habitat, Worldwide edition. University of New Hampshire Publication. 75 p

Short, Frederick T., and Robert G. Coles, eds. *Global seagrass research methods*. Elsevier, 2001.

Srivastava, Shilpi, and Lyla Mehta. "The social life of mangroves: Neoliberal development and mangrove conservation in the changing landscape of Kutch." *Environment and Planning E: Nature and Space* (2021): 25148486211045360.

Thangaradjou, T., and J. R. Bhatt. "Status of seagrass ecosystems in India." *Ocean & Coastal Management* 159 (2018): 7-15.

Trivedi, J. N., Gadhavi, M. K., & Vachhrajani, K. D. (2012). Diversity and habitat preference of brachyuran crabs in Gulf of Kutch, Gujarat, India. *Arthropods*, *1*(1), 13.

Unnikrishnan, A. S., and J. L. Luick. "A finite element simulation of tidal circulation in the Gulf of Kutch, India." *Estuarine, coastal and shelf science* 56.1 (2003): 131-138.

Unnikrishnan, A. S., Gouveia, A. D., & Vethamony, P. (1999). Tidal regime in Gulf of Kutch, west coast of India, by 2D model. *Journal of waterway, port, coastal, and ocean engineering*, *125*(6), 276-284.

Unsworth, Richard KF, et al. "Solar radiation and tidal exposure as environmental drivers of Enhalus acoroides dominated seagrass meadows." *PLoS One* 7.3 (2012): e34133.

Velez-Juarbe, Jorge, Daryl P. Domning, and Nicholas D. Pyenson. "Iterative evolution of sympatric seacow (Dugongidae, Sirenia) assemblages during the past∼ 26 million years." PLoS One 7.2 (2012): e31294.

Whiting, Scott D. "Movements and distribution of dugongs (Dugong dugon) in a macro-tidal environment in northern Australia." *Australian journal of zoology* 56.4 (2008): 215-222.

Zeh, Daniel R., et al. "Evidence of behavioural thermoregulation by dugongs at the high latitude limit to their range in eastern Australia." *Journal of Experimental Marine Biology and Ecology* 508 (2018): 27-34.

Chapter 2- Mapping Seagrass meadows

Adhavan, D., R. Chandran, and K. Sivakumar. "Diversity of seagrasses and site-specific strategy for their restoration in Gulf of Kachchh Marine National Park—Gujarat, India." Journal of Coastal Conservation 26.3 (2022): 20.

Appolloni, Luca, et al. "The use of remote sensing for monitoring Posidonia oceanica and Marine Protected Areas: A systemic review." Ecological Questions 31.2 (2020): 7-17.

Ballard, Megan S., et al. "Application of acoustical remote sensing techniques for ecosystem monitoring of a seagrass meadow." The Journal of the Acoustical Society of America 147.3 (2020): 2002-2019.

Boudouresque, C. F., Pergent, G., Pergent-Martini, C., Ruitton, S., Thibaut, T., & Verlaque, M. (2016). The necromass of the Posidonia oceanica seagrass meadow: fate, role, ecosystem services and vulnerability. Hydrobiologia, 781, 25-42.

Cabaco, S., Santos, R., & Duarte, C. M. (2008). The impact of sediment burial and erosion on seagrasses: a review. Estuarine, Coastal and Shelf Science, 79(3), 354-366.

Coles, R., McKenzie, L., De'ath, G., Roelofs, A., & Long, W. L. (2009). Spatial distribution of deepwater seagrass in the inter-reef lagoon of the Great Barrier Reef World Heritage Area. Marine Ecology Progress Series, 392, 57-68.

DeWitt, T. H. (2009). 10.0 The Effects of Bioturbation and Bioirrigation on Seagrasses. Seagrasses and Protective Criteria: A Review and Assessment of Research Status.

Ferguson, Randolph L., and Karl Korfmacher. "Remote sensing and GIS analysis of seagrass meadows in North Carolina, USA." Aquatic Botany 58.3-4 (1997): 241-258.

Fonseca, Mark, et al. "Modeling seagrass landscape pattern and associated ecological attributes." Ecological Applications 12.1 (2002): 218-237.

Fornes, A., et al. "Mapping Posidonia oceanica from IKONOS." ISPRS Journal of Photogrammetry and Remote Sensing 60.5 (2006): 315-322.

Geevarghese, Gejo Anna, et al. "A comprehensive geospatial assessment of seagrass distribution in India." Ocean & Coastal Management 159 (2018): 16-25.

Green, Alix E., et al. "Historical analysis exposes catastrophic seagrass loss for the United Kingdom." Frontiers in plant science 12 (2021): 261..

Himes-Cornell, Amber, Linwood Pendleton, and Perla Atiyah. "Valuing ecosystem services from blue forests: A systematic review of the valuation of salt marshes, sea grass beds and mangrove forests." Ecosystem services 30 (2018): 36-48.

Ivajnšič, Danijel, et al. "Evaluating Seagrass Meadow Dynamics by Integrating Field-Based and Remote Sensing Techniques." Plants 11.9 (2022): 1196.

Mtwana Nordlund, Lina, et al. "Seagrass ecosystem services and their variability across genera and geographical regions." Plos one 11.10 (2016): e0163091.

Murphey, Patricia L., and Mark S. Fonseca. "Role of high and low energy seagrass beds as nursery areas for Penaeus duorarum in North Carolina." Marine Ecology Progress Series 121 (1995): 91-98.

Nayak, Shailesh, and Anjali Bahuguna. "Application of remote sensing data to monitor mangroves and other coastal vegetation of India." (2001).

Preen, Anthony. "Impacts of dugong foraging on seagrass habitats: observational and experimental evidence for cultivation grazing." Marine Ecology Progress Series 124 (1995): 201-213

R.D Kamboj (2014). Biology and status of seagrasses in Gulf of Kachchh Marine national park and sanctuary, India Indian Ocean Turtle Newsletter No. 19 pp. 8-11

Tuya, Fernando, Ricardo Haroun, and Fernando Espino. "Economic assessment of ecosystem services: Monetary value of seagrass meadows for coastal fisheries." Ocean & Coastal Management 96 (2014): 181-187.

Yaakub, Siti M., et al. "The diversity and distribution of seagrass in Singapore." Nature in Singapore 6 (2013): 105-111.

Chapter 3- Seasonal dyanamics of seagrass meadows

Ahmad-Kamil, E. I., et al. "The effects of water parameters on monthly seagrass percentage cover in Lawas, East Malaysia." *The Scientific World Journal* 2013 (2013).

Borowitzka, MAß, and R. C. Lethbridge. "Seagrass epiphytes." Elsevier Science Pub., 1989. 458-499.

Dennison, W. C. (1987). Effects of light on seagrass photosynthesis, growth and depth distribution. *Aquatic Botany*, *27*(1), 15-26.

Govindasamy, C., et al. "Seasonal variations in seagrass biomass and productivity in Palk Bay, Bay of Bengal, India." *Int. J. Biodivers. Conserv* 5.7 (2013): 408-417.

Heinsohn, George Edwin, et al. "The dugong (Dugong dugon (Müller)) in the seagrass system." *Aquaculture* 12.3 (1977): 235-248

Hernández, Ana L. Molina, and Brigitta I. van Tussenbroek. "Patch dynamics and species shifts in seagrass communities under moderate and high grazing pressure by green sea turtles." *Marine Ecology Progress Series* 517 (2014): 143-157.

Longstaff, Benjamin J., and William Cullen Dennison. "Seagrass survival during pulsed turbidity events: the effects of light deprivation on the seagrasses *Halodule* pinifolia and *Halophila ovalis*." *Aquatic Botany* 65.1-4 (1999): 105-121.

Lyons, Mitchell B., Chris M. jagtap seagrass, and Stuart R. Phinn. "Towards understanding temporal and spatial dynamics of seagrass landscapes using time-series remote sensing." *Estuarine, Coastal and Shelf Science* 120 (2013): 42-53.

Olesen, Birgit, et al. "Recolonization dynamics in a mixed seagrass meadow: the role of clonal versus sexual processes." *Estuaries* 27.5 (2004): 770-780.

Ondiviela, Barbara, et al. "The role of seagrasses in coastal protection in a changing climate." *Coastal Engineering* 87 (2014): 158-168.

Prarikeslan, Widya, et al. "Density, coverage and biomass of seagrass ecosystem in the Lobam Island, Bintan Regency-Indonesia." *IOP Conference Series: Earth and Environmental Science*. Vol. 314. No. 1. IOP Publishing, 2019.

Preen, Anthony. "Impacts of dugong foraging on seagrass habitats: observational and experimental evidence for cultivation grazing." *Marine Ecology Progress Series* 124 (1995): 201-213.

Rajamani, Leela Rajamani Ramnath. *The conservation biology of the dugong (Dugong dugon) and its seagrass habitat in Sabah, Malaysia: a basis for conservation planning*. Diss. University Malaysia Sabah, 2009.

Ralph, P. J., Durako, M. J., Enriquez, S., Collier, C. J., & Doblin, M. A. (2007). Impact of light limitation on seagrasses. *Journal of experimental marine biology and ecology*, *350*(1-2), 176-193.

Roelfsema, Chris M., et al. "Multi-temporal mapping of seagrass cover, species and biomass: A semi-automated object-based image analysis approach." *Remote Sensing of Environment* 150 (2014): 172-187.

Senft, R. L., et al. "Large herbivore foraging and ecological hierarchies." *BioScience* 37.11 (1987): 789-799.

Short, F. T. & Wyllie-Echeverria, S. Natural and human-induced disturbance of seagrasses. Environ. Conserv. 23, 17–27 (1996). 22.

Short, F. T. et al. Extinction risk assessment of the world’s seagrass species. Biol. Conserv. 144, 1961–1971 (2011).

Short, Frederick T., and Hilary A. Neckles. "The effects of global climate change on seagrasses." *Aquatic Botany* 63.3-4 (1999): 169-196.

Strydom, S., McMahon, K., Kendrick, G. A., Statton, J., & Lavery, P. S. (2017). Seagrass *Halophila ovalis* is affected by light quality across different life history stages. *Marine Ecology Progress Series*, *572*, 103-116.

Taquet, Coralie, et al. "Foraging of the green sea turtle Chelonia mydas on seagrass beds at Mayotte Island (Indian Ocean), determined by acoustic transmitters." *Marine Ecology Progress Series* 306 (2006): 295-302.

Trautman, Donelle A., and Michael A. Borowitzka. "Distribution of the epiphytic organisms on Posidonia australis and P. sinuosa, two seagrasses with differing leaf morphology." *Marine Ecology Progress Series* 179 (1999): 215-229.

Vonk, Jan Arie, Marjolijn JA Christianen, and Johan Stapel. "Abundance, edge effect, and seasonality of fauna in mixed-species seagrass meadows in southwest Sulawesi, Indonesia." *Marine Biology Research* 6.3 (2010): 282-291.

Jagtap, Tanaji G. "Distribution of seagrasses along the Indian coast." Aquatic Botany 40.4 (1991): 379-386.

Jagtap, T. G. "Some quantitative aspects of structural components of seagrass meadows from the southeast coast of India." (1996): 39-46.

Parthasarathy, N., et al. "Distribution of seagrasses along the coast of Tamil Nadu, Southern India." Aquatic Botany 40.2 (1991): 145-153.

Ramamurthy, Kandasamy. "Seagrasses of coromandel coast, India." (1992).

Erftemeijer, Paul LA, and Peter MJ Herman. "Seasonal changes in environmental variables, biomass, production and nutrient contents in two contrasting tropical intertidal seagrass beds in South Sulawesi, Indonesia." *Oecologia* 99 (1994): 45-59.

Unnikrishnan, A. S., A. D. Gouveia, and P. Vethamony. "Tidal regime in Gulf of Kutch, west coast of India, by 2D model." *Journal of waterway, port, coastal, and ocean engineering* 125.6 (1999): 276-284.

Hemminga, M. A., P. G. Harrison, and F. Van Lent. "The balance of nutrient losses and gains in seagrass meadows." *Marine Ecology Progress Series* (1991): 85-96.

Seddon, S., R. M. Connolly, and Karen Susan Edyvane. "Large-scale seagrass dieback in northern Spencer Gulf, South Australia." Aquatic Botany 66.4 (2000): 297-310.

Deshpande, Medha, et al. "Changing status of tropical cyclones over the north Indian Ocean." *Climate Dynamics* 57 (2021): 3545-3567.

Mcmillan, Calvin. "Flowering under controlled conditions by Cymodocea serrulata, Halophila stipulacea, Syringodium isoetifolium, Zostera capensis and Thalassia hemprichii from Kenya." *Aquatic Botany* 8 (1980): 323-336.

Chapter 4- Foraging habitats of dugongs

Anderson, P. K. "Shark Bay dugongs (Dugong dugon) in summer. II: Foragers in a Halodule-dominated community." (1998): 409-426.

Anderson, Paul K., and A. Birtles. "Behaviour and ecology of the Dugong, Dugong dugon (Sirenia): observations in Shoalwater and Cleveland Bays, Queensland." *Wildlife Research* 5.1 (1978): 1-23.

Aragones, Lemnuel V., et al. "Dugong grazing and turtle cropping: grazing optimization in tropical seagrass systems?." *Oecologia* 149 (2006): 635-647.

Avila-Ospina, Liliana, et al. "Autophagy, plant senescence, and nutrient recycling." *Journal of Experimental Botany* 65.14 (2014): 3799-3811.

Binzer, Thomas, Jens Borum, and Ole Pedersen. "Flow velocity affects internal oxygen conditions in the seagrass Cymodocea nodosa." *Aquatic Botany* 83.3 (2005): 239-247.

Boström, Christoffer, Emma L. Jackson, and Charles A. Simenstad. "Seagrass landscapes and their effects on associated fauna: a review." *Estuarine, Coastal and shelf science* 68.3-4 (2006): 383-403.

Charnov, Eric L. "Optimal foraging, the marginal value theorem." *Theoretical population biology* 9.2 (1976): 129-136.

Cleguer, Christophe, Claire Garrigue, and Helene Marsh. "Dugong (Dugong dugon) movements and habitat use in a coral reef lagoonal ecosystem." *Endangered Species Research* 43 (2020): 167-181.

Cleguer, Christophe, et al. "Spatial mismatch between marine protected areas and dugongs in New Caledonia." *Biological Conservation* 184 (2015): 154-162.

De Iongh, H. H., et al. "A review of research on the interactions between dugongs (Dugong dugon Müller 1776) and intertidal seagrass beds in Indonesia." *Hydrobiologia* 591 (2007): 73-83

De Iongh, H. Hi, B. J. Wenno, and E. Meelis. "Seagrass distribution and seasonal biomass changes in relation to dugong grazing in the Moluccas, East Indonesia." *Aquatic Botany* 50.1 (1995): 1-19.

Derville, Solène, Christophe Cleguer, and Claire Garrigue. "Ecoregional and temporal dynamics of dugong habitat use in a complex coral reef lagoon ecosystem." *Scientific reports* 12.1 (2022): 1-15.

Fonseca, Mark S., and Jennifer A. Cahalan. "A preliminary evaluation of wave attenuation by four species of seagrass." *Estuarine, Coastal and Shelf Science* 35.6 (1992): 565-576.

Forbes, Ryan E., and Graham IH Kerley. "Do ruminants and hindgut fermenters differ in their activity? Comparison of syntopic black wildebeest and Cape Mountain zebra." *Behaviour* 1.aop (2022): 1-17.

Gannon, Janet G., et al. "Habitat selection by manatees in Sarasota Bay, Florida." *Marine Mammal Science* 23.1 (2007): 133-143.

Gibson, R. N. "Hydrostatic pressure and the rhythmic behaviour of intertidal marine fishes." *Transactions of the American Fisheries Society* 113.4 (1984): 479-483.

Gibson, Robin N. "Go with the flow: tidal migration in marine animals." *Migrations and Dispersal of Marine Organisms: Proceedings of the 37th European Marine Biology Symposium held in Reykjavík, Iceland, 5–9 August 2002*. Springer Netherlands, 2003.

Hansen, Tayler L., and Laurie M. Lawrence. "Composition factors predicting forage digestibility by horses." *Journal of Equine Veterinary Science* 58 (2017): 97-102.

Heng, Harris Wei Khang, et al. "Dugong feeding grounds and spatial feeding patterns in subtidal seagrass: A case study at Sibu Archipelago, Malaysia." *Estuarine, Coastal and Shelf Science* 264 (2022): 107670.

Hernández, Ana L. Molina, and Brigitta I. van Tussenbroek. "Patch dynamics and species shifts in seagrass communities under moderate and high grazing pressure by green sea turtles." *Marine Ecology Progress Series* 517 (2014): 143-157.

Kneib, R. T., and S. L. Wagner. "Nekton use of vegetated marsh habitats at different stages of tidal inundation." *Marine Ecology Progress Series* (1994): 227-238.

LaCommare, Katherine S., Caryn Self-Sullivan, and Solange Brault. "Distribution and habitat use of Antillean manatees (Trichechus manatus manatus) in the Drowned Cayes area of Belize, Central America." *Aquatic Mammals* 34.1 (2008): 35.

Lieber, Lilian, et al. "Fine-scale hydrodynamic metrics underlying predator occupancy patterns in tidal stream environments." *Ecological Indicators* 94 (2018): 397-408.

Mae, Tadahiko. "Leaf senescence and nitrogen metabolism." *Plant cell death processes* (2004): 157-168.

Marsh, Helene, Alana Grech, and Kathryn McMahon. "Dugongs: seagrass community specialists." *Seagrasses of Australia*. Springer, Cham, 2018. 629-661.

Masini, Raymond J., Paul K. Anderson, and Arthur J. McComb. "A Halodule-dominated community in a subtropical embayment: physical environment, productivity, biomass, and impact of dugong grazing." *Aquatic Botany* 71.3 (2001): 179-197.

Mendes, Sónia, et al. "Influence of the tidal cycle and a tidal intrusion front on the spatio-temporal distribution of coastal bottlenose dolphins." *Marine Ecology Progress Series* 239 (2002): 221-229.

Nakanishi, Yoshiei, et al. "The distribution of seagrass meadows and dugong feeding trails in the dry season around Talibong Island, Trang Province, Thailand." *Proceedings of the 3rd International Symposium on SEASTAR2000 and Asian Bio-logging Science (The 7th SEASTAR2000 workshop)*. Graduate school of Informatics, Kyoto University, 2006.

Nakaoka, Masahiro, and Keiko Aioi. "Growth of seagrass *Halophila ovalis* at dugong trails compared to existing within-patch variation in a Thailand intertidal flat." *Marine Ecology Progress Series* 184 (1999): 97-103.

Nakaoka, Masahiro, and Keiko Aioi. "Growth of seagrass *Halophila ovalis* at dugong trails compared to existing within-patch variation in a Thailand intertidal flat." *Marine Ecology Progress Series* 184 (1999): 97-103.

Pace, Matthew, Joseph A. Borg, and Charles Galdies. "Influence of hydrodynamic setting on Posidonia oceanica meadow landscape and architecture." *PeerJ PrePrints* (2015).

Passadore, Cecilia, et al. "High site fidelity and restricted ranging patterns in southern Australian bottlenose dolphins." *Ecology and evolution* 8.1 (2018): 242-256.

Pathan, Sameeha, et al. "Scars of hope and forewarn of a bleak future: Post-mortem findings of dugongs (Dugong dugon)." *parasitology* 40.5 (1954): 499-507.

Perry, C. J., and W. C. Dennison. "Microbial nutrient cycling in seagrass sediments." *AGSO Journal of Australian Geology and Geophysics* 17.5/6 (1999): 227-232.

Preen, Anthony Robert. *Interactions between dugongs and seagrasses in a subtropical environment*. Diss. James Cook University, 1992.

Preen, Anthony. "Impacts of dugong foraging on seagrass habitats: observational and experimental evidence for cultivation grazing." *Marine Ecology Progress Series* 124 (1995): 201-213.

Ruiz-Montoya, L., et al. "The role of hydrodynamics on seed dispersal in seagrasses." *Limnology and oceanography* 57.5 (2012): 1257-1265.

Schoener, Thomas W. "Theory of feeding strategies." *Annual review of ecology and systematics* 2.1 (1971): 369-404.

Scott, Michael D., Randall S. Wells, and A. Blair Irvine. "A long-term study of bottlenose dolphins on the west coast of florida 11." *The bottlenose dolphin* 235 (1990).

Sheppard, James K., et al. "Dugong habitat use in relation to seagrass nutrients, tides, and diel cycles." *Marine mammal science* 26.4 (2010): 855-879.

Sheppard, James K., et al. "Effects of tidal and diel cycles on dugong habitat use." *The Journal of Wildlife Management* 73.1 (2009): 45-59.

Sheppard, James K., et al. "Movement heterogeneity of dugongs, Dugong dugon (Müller), over large spatial scales." *Journal of Experimental Marine Biology and Ecology* 334.1 (2006): 64

Statton, John, et al. "Seed dormancy and germination of *Halophila ovalis* mediated by simulated seasonal temperature changes." *Estuarine, Coastal and Shelf Science* 198 (2017): 156-162.

Tol, Samantha J., Rob G. Coles, and Bradley C. Congdon. "Dugong dugon feeding in tropical Australian seagrass meadows: implications for conservation planning." *PeerJ* 4 (2016): e2194.

West, Neil E., Kenneth H. Rea, and Roy O. Harniss. "Plant demographic studies in sagebrush- grass communities of southeastern Idaho." *Ecology* 60.2 (1979): 376-388.

Wirsing, Aaron J., Michael R. Heithaus, and Lawrence M. Dill. "Living on the edge: dugongs prefer to forage in microhabitats that allow escape from rather than avoidance of predators." *Animal Behaviour* 74.1 (2007): 93-101.

Yamamuro, Masumi, and Anong Chirapart. "Quality of the seagrass *Halophila ovalis* on a Thai intertidal flat as food for the dugong." *Journal of Oceanography* 61 (2005): 183-186.

Zakari, Shamsu Ado, et al. "Nitrogen deficiency regulates premature senescence by modulating flag leaf function, ROS homeostasis, and intercellular sugar concentration in rice during grain filling." *Journal of Genetic Engineering and Biotechnology* 19.1 (2021): 1-14.

Cleguer, Christophe, Claire Garrigue, and Helene Marsh. "Dugong (Dugong dugon) movements and habitat use in a coral reef lagoonal ecosystem." *Endangered Species Research* 43 (2020): 167-181.

Marsh, H., and G. B. Rathbun. "Development and application of conventional and satellite radio tracking techniques for studying dugong movements and habitat use." Wildlife Research 17.1 (1990): 83-100.

Holley, David K. "Movement patterns and habitat usage of Shark Bay dugongs." (2006).

Chilvers, B. Louise, et al. "Diving behaviour of dugongs, Dugong dugon." *Journal of Experimental Marine Biology and Ecology* 304.2 (2004): 203-224.

Whiting, Scott D. "Movements and distribution of dugongs (Dugong dugon) in a macro-tidal environment in northern Australia." *Australian journal of zoology* 56.4 (2008): 215-222.

Amamoto, Nanako, et al. "The depth of water effects the feeding ground selection by dugongs in dry season." *Journal of Advanced Marine Science and Technology Society* 15.2 (2009): 149.

Iongh, Hans H. de, Paul Langeveld, and Mark van der Wal. "Movement and home ranges of dugongs around the Lease Islands, East Indonesia." *Marine Ecology* 19.3 (1998): 179-193.

Chapter 5 (ii) – Salvage of information from postmortem analysis of dugongs

Eros, C., Marsh, H., Bonde, R., O'Shea, T., Beck, C., Recchia, C., Dobbs, K., Turner, M., Lemm,S., Pears, R. and Bowater, R., Procedures for the Salvage and Necropsy of the Dugong (Dugong dugon)-. 2007, *Research Publication No. 85*

Yashpal, Anand, Highland Hyacinth, Linz Buoy George, and R. D. Kamboj. "Parasitic nematodein dead stranded dugong on Mithapur coast, Okha, Gujarat, India." *Current Science* 115, no. 7 (2018): 1249-1250.

Crusz, H., and V. S. V. Fernand. "The trematode parasites of the dugong with descriptions of twonew monostomes and histopathological changes in the host." *The Journal of parasitology* 40, no. 5 (1954): 499-507.

Beck, Cathy, and Donald J. Forrester. "Helminths of the Florida manatee, Trichechus manatuslatirostris, with a discussion and summary of the parasites of sirenians." *The Journal of parasitology* (1988): 628-637.

Anderson, Paul K., and A. Birtles. "Behaviour and ecology of the Dugong, Dugong dugon (Sirenia): observations in Shoalwater and Cleveland Bays, Queensland." *Wildlife Research* 5, no. 1(1978): 1-23.

Lanyon, Janet M., Chrissa Athousis, Helen L. Sneath, and Elizabeth A. Burgess. "Body scarringas an indicator of social function of dugong (Dugong dugon) tusks." *Marine Mammal Science* (2021)

Lanyon, Janet. *Guide to the identification of seagrasses in the Great Barrier Reef region*. GreatBarrier Reef Marine Park Authority, 1986.

Lee, Harry H., Megan M. Wallen, Ewa Krzyszczyk, and Janet Mann. "Every scar has a story:age and sex-specific conflict rates in wild bottlenose dolphins." *Behavioral Ecology and Sociobiology* 73, no. 5 (2019): 1-11.

Marsh, Helene, George E. Heinsohn, and P. W. Channells. "Changes in the

ovaries and uterusof the dugong, Dugong dugon (Sirenia: Dugongidae), with age and reproductive
activity." *Australian Journal of Zoology* 32, no. 6 (1984): 743-766.

Peltier, Hélène, Alain Beaufils, Catherine Cesarini, Willy Dabin, Cécile Dars, Fabien Demaret,Frank Dhermain et al. "Monitoring of marine mammal strandings along French coasts reveals the importance of ship strikes on large cetaceans: a challenge for the European Marine Strategy Framework Directive." *Frontiers in Marine Science* 6 (2019): 486.

Reeves, Randall R., Kate McClellan, and Timothy B. Werner. "Marine mammal bycatch in gillnet and other entangling net fisheries, 1990 to 2011." *Endangered Species Research* 20, no. 1(2013): 71-97.

Marsh, Helene. "Evaluating management initiatives aimed at reducing the mortality of dugongsin gill and mesh nets in the Great Barrier Reef World Heritage Area." Marine Mammal Science 16 (2000): 684-694.

Heiss, Wiebke M., Abigail M. Smith, and P. Keith Probert. "Influence of the small intertidalseagrass Zostera novazelandica on linear water flow and sediment texture." (2000): 689-694.

Suykerbuyk, Wouter, Tjeerd J. Bouma, Laura L. Govers, Kris Giesen, Dick J. de Jong, Peter Herman, Jan Hendriks, and Marieke M. van Katwijk. "Surviving in changing seascapes: sedimentdynamics as bottleneck for long-term seagrass presence." *Ecosystems* 19, no. 2 (2016): 296-310.

Abreo, Neil Angelo S., Edison D. Macusi, and Lea A. Jimenez. "Survey of subtidal anthropogenic marine debris (AMD) in Mayo Bay, Mati City, davao oriental, Philippines." *ThePhilippine Journal of Crop Science* 147, no. 4 (2018): 597-600.
Solanki, Jitesh B., Viral C. Bajaniya, H. V. Parmar, Ketan V. Tank, and H. L. Parmar. "Availability of commercially important of marine fin fish and shell fish along Okha fish landingcenter, Gujarat." (2020)

Annual progress report, 2019-2020: *Recovery of Dugongs and their Habitats in India, WildlifeInstitute of India,* Dehradun, Uttarakhand.

Scars of hope and forewarn of a bleak future: post-mortem findings of dugongs (*Dugong dugon*) belonging to a relict population in the Gulf of Kachchh, India

Sameeha Pathan[1], Anant Pande[1,2], Kuppusamy Sivakumar[1,3] and J. A. Johnson[1,*]

[1]Wildlife Institute of India, Dehradun 248 001, India
[2]Marine Program, Wildlife Conservation Society, Bengaluru 560 097, India
[3]Department of Ecology and Environment, Pondicherry University, Puducherry 605 014, India

A relict dugong population resides in the Gulf of Kachchh (GoK), Gujarat, India. Very little is known about this population stemming from a lack of focused studies and inadequate examination of previous strandings. The present study gathers crucial ecological information through a systematic post-mortem examination of stranded dugongs in GoK. As indicated through dorsal tusk-rake scars on two carcasses, this study presents records of derivative physical evidence. Progressive healing and differences in the width of the scars indicated more than two individuals had participated in a sexual agnostic or courtship event. Conversely, our findings report that both animals suffered relative effects of asphyxiation after fishing net entanglement. The implication of a prior pathological condition(s) in the form of dermal cysts, swollen mesenteric lymph nodes and endoparasites is also reported. Stomach content was examined for a qualitative dietary characterization. *Halophila beccari*, *Halophila ovalis* and *Halodule uninervis* were found in the stomach content. Other potential threats as well as fishing net microfilaments found in the stomach contents of both dugongs are discussed.

Keywords: Dugongs, necropsy, relict population, stomach content analysis, Tusk-rake scars.

INDIAN dugong populations are considered 'Regionally Endangered' compared to the global IUCN Red List status of the species as 'Vulnerable'[1], making them the most threatened marine mammal species along the Indian coastline. Their foraging range along the shallow near-shore areas brings them in direct conflict for using space with artisanal fisheries and other coastal activities such as tourism, port activities[2], etc. The current range of dugongs in the country is restricted to parts of the Gulf of Kachchh (GoK), Gujarat; Palk Bay and Gulf of Mannar (Tamil Nadu) and Andaman & Nicobar Islands (except in Great Nicobar)[1]. Although ecological information (such as foraging behaviour[3] and abundance[4,5]) about dugong populations in Tamil Nadu and Andaman and Nicobar Islands is available, there is a dearth of knowledge regarding the GoK population.

To date, no extant dugong population has been confirmed from the west coast of India, except for the small population in GoK, estimated to be around 15 animals[6], making it an important dugong habitat in the region. This population is known to be restricted to the islands and reefs of the southern coast of GoK[7]. Naturally low fecundity and slow growth rate make dugong populations around the world extremely sensitive to adult mortalities[8]. Further, the low population size and the elusive nature of dugongs make it difficult to study them in the wild. For a small marine mammal population, studying the type and consequences of anthropogenic pressure becomes a difficult task in the wild. Given the lack of long-term datasets on this geographically isolated population, stranding events provide a rare window to collect essential data about health, feeding ecology, reproductive status, etc., which otherwise ecological data is hard to get for behaviourally cryptic animals. Here, we present a brief discussion on salvaged information deduced from two dugong carcasses of stage I and stage IV decomposition states. This study provides crucial insights into a relict dugong population on the verge of extinction.

Methods

We obtained dugong stranding information through a volunteer network developed in the fisher community of Beyt Dwarka and Arambada village in GoK. This network comprised of fisherfolk who were sensitized through a series of community interaction programmes ($n = 3$) conducted at Okha and Beyt Dwarka fisher villages, viz. Balapur, Arambada, and Rupen. Two dugong strandings were reported in February and May 2018 respectively. The initial photograph of the Ajad Island dugong was taken when the carcass was

---

*For correspondence. (e-mail: jaj@wii.gov.in)

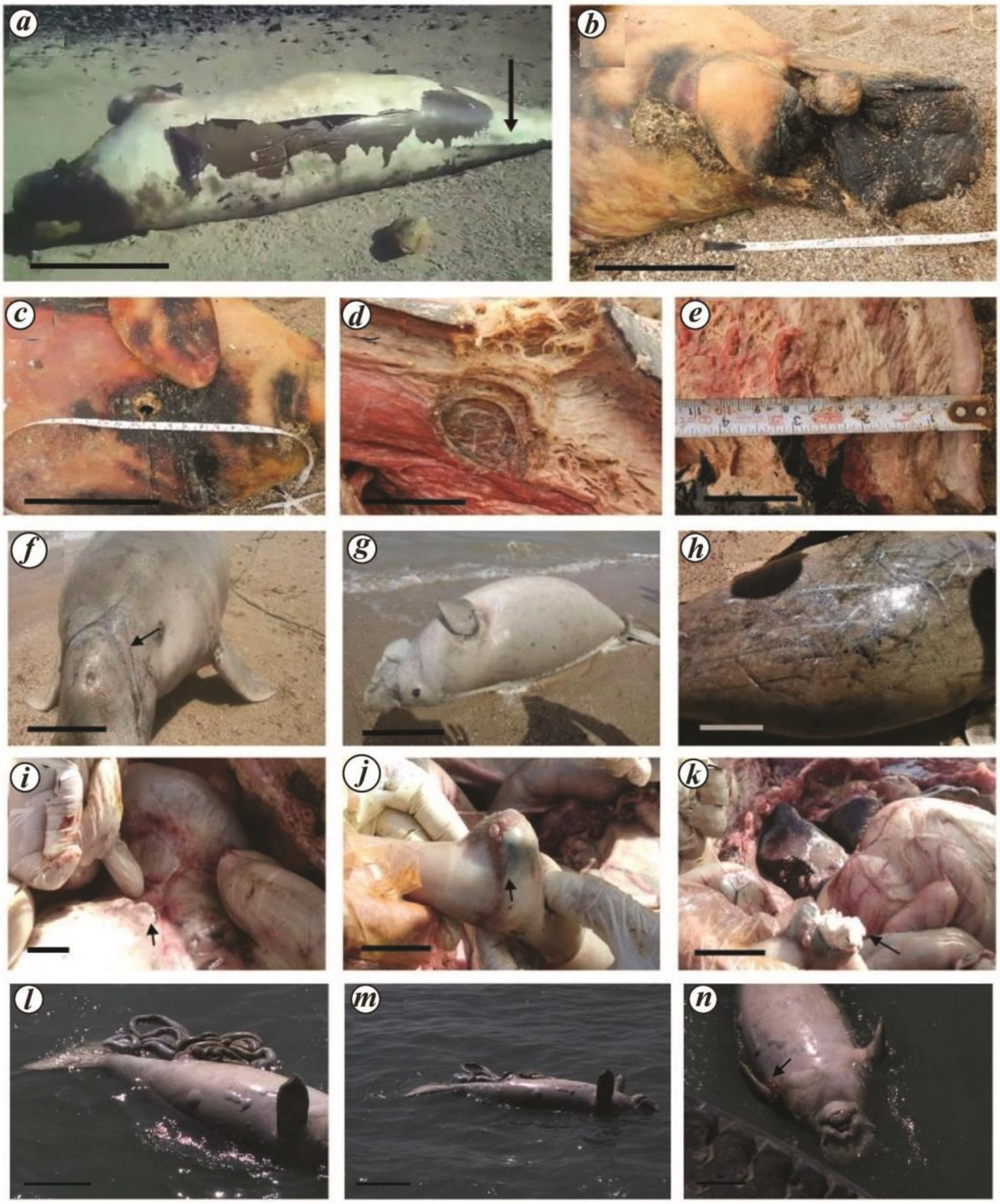


Figure 1. ***a–e***, Ajad Island dugong carcass in the Gulf of Kachchh (GoK), Gujarat, India: ***a***, Decomposed carcass of a mature female dugong (scale – 30 cm); ***b***, Rope burn marks around the neck (scale – 18 cm); ***c***, Thorax with cavity caused by parasitic infestation (scale – 15 cm); ***d***, Cross-section through the cavity showing cyst of an unidentified parasite (scale – 3.2 cm); ***e***, Cross-section across the mid-ventral tissue layer (scale – 4 cm). ***f–k***, Positra dugong carcass (scale – 40 cm, GoK): ***f***, Rope burn marks (black arrow) are visible around the snout (scale – 16 cm); ***h***, Numerous healed wounds on the back (scale – 15 cm); ***i***, Swollen mesenteric lymph nodes (scale – 2.5 cm); ***j***, ***k***, Purulent tumour in the small intestine (scale – 4.5 cm); ***l***, ***m***, Drifting bloated carcass exhibiting evisceration (scale – 20 cm); ***n***, Ante-mortem wound under flipper (scale – 30 cm).

relatively fresh (Figure 1 *a*). The carcass was reported and was necropsied two weeks after the stranding event.

Carcass photo-documentation and necropsy were performed using standard salvage and necropsy procedures[9]. Each animal was examined for external marks, lesions, bruises and other injuries prior to internal examination. Morphometric data (Supplementary Table 1) was also noted. Since decomposition is relatively faster in the intestines, visceral organs after the stomach of the Ajad Island dugongs were rendered unexaminable.

Stomach content analysis was performed on samples (300 g) collected from the cardiac end. The stomach content was preserved using 10% neutral-buffer formalin within 9 h of necropsy. Qualitative analysis of the gut contents was done after diluting 5 g of the sample ($n = 2$) with 50 ml of distilled water. To avoid crowding of seagrass segments, a volume of 5 ml was used from the diluted subsample (50 ml) for observations on a 2×2 cm^2 graded Petri plate.

Results

Ajad island stranding

A stage IV, badly decomposed carcass was necropsied[9] in the northeastern part of Ajad Island (centrepoint – 22°23′N, 69°19′E), where it was stranded. The animal was a 2.6 m (straight body length) adult female. The skin had been sloughed-off completely, but the remaining attached skin on the mid-dorsal side retained a hyperpigmented rake mark (Figure 1 *a*), indicating that it had interacted with an adult male dugong. The head showed clear signs of severe intramuscular haemorrhage with a cutaneous abscess on and around the nostrils (Figure 1 *a*). This haemorrhage could result from blunt force trauma to the head after a collision with a boat. On the dorsal side of the animal, the caudal vertebral processes were markedly visible (black arrow, Figure 1 *a*) indicating emaciation, but other signs of starvation such as caved-in body mass around the peduncle could not be verified due to the advanced stage of decomposition. Starvation was further ruled out as the stomach was full of seagrass and the blubber layer was intact in both consistency and thickness (Figure 1 *e*). A cross-sectional examination through the cavity of the dermal wall of the thorax (Figure 1 *c*) revealed the presence of a single, oval and well-demarcated parasitic cyst of dimensions 32.11 × 40.40 mm (Figure 1 *d*). Nematode *Paradujardinia halicoris*, a common endoparasite in dugongs[10,11] and manatees[12], was found in the animal's stomach.

Positra island stranding

A sub-adult male dugong with the straight-body length of 2 m was reported by fishers of Positra near Man-marudi Island (centrepoint – 22°25′59.56″N, 69°13′23.86″E) in GoK. There were no signs of decomposition (bloating, discolouration, etc.). Since the flippers had mobility when the carcass was found, rigor mortis had not set in, conclusively indicating mortality in the past few hours. Fishers confirmed mortality due to suffocation after net-entanglement, which was factualized by rope-burn marks around the head and neck (black arrow, Figure 1 *f*). The skin was in good condition and showed no signs of sloughing (Figure 1 *g*). The intact skin revealed various important clues to the type of interaction the dugong had undergone before its death. Small scars of several healed wounds were found extending from the lower neck to the peduncle of the animal's dorsum (Figure 1 *h*), the significance of which will be discussed later in that text. Since the visceral organs were intact, a thorough examination of the gastrointestinal tract could be conducted. A localized, single tumour of radius 5 cm was found on the duodenum (Figure 1 *j*). The purulence of the outgrowth had a hard, greasy consistency (Figure 1 *k*). Moreover, the mesenteric lymph nodes appeared swollen (Figure 1 *i*).

Tusk-rake scars

Several healed indentations and wounds were found on the dorsum of the animal from various interactions (Figure 2). The source of these wounds can be either biological through intraspecific interactions or non-biological due to the scratching behaviour of dugongs over sandy sediments[13]. Except for a few deep indentations, most of these marks were shallow. More important were the parallel marks on the back, which were made due to the grazing action of a pair of tusks. We discovered several counts of such tusk-rake scars (TRS) on the back of this dugong individual. Scars of different widths indicated that sexually mature conspecifics of different age groups had interacted with this male dugong (Figure 2). Based on width, five distinctly different scars were identified. These were then broadly categorized into two stages depending on the progressiveness of healing (Table 1). A new scar indicates a 'recent' (stage I) agnostic interaction, whereas completely healed marks appearing shallow and discoloured are evidence of 'older' (stage II) instances[14]. Only one of the five scars that appeared was recent (stage I), as it had not completely healed (scar 1, Figure 2). The remaining four scars (scars 2–5, Figure 2) were older (stage II) and probably inflicted during a single event. Hence, at least two separate events of ritualistic sexual conflicts were experienced by the Positra dugong. Moreover, a scar inflicted by a relatively younger dugong (mark 4, width – 5.3 cm) was also observed.

Stomach content analysis

Leaf tip characteristics, leaf venation patterns and numbers and leaf scars on rhizomes are the most prominent and important morphological features examined to identify seagrass species[15] (Figure 3); *Halophila beccarii* (oblong leaf, parallel venation, smooth; trichome-less lamina), *Halophila ovalis* (oval leaf, cross venations, smooth; trichome-less lamina) and *Halodule uninervis* (trident apex, strap-shaped leaf) were found in the stomach contents of both the stranded individuals. The dugongs also had ingested fragments of nylon fishing net microfilaments of length ranging from 0.23 to 30 mm.

Discussion and conclusion

There is little information regarding the social and reproductive behaviour of dugongs in India. As concluded from

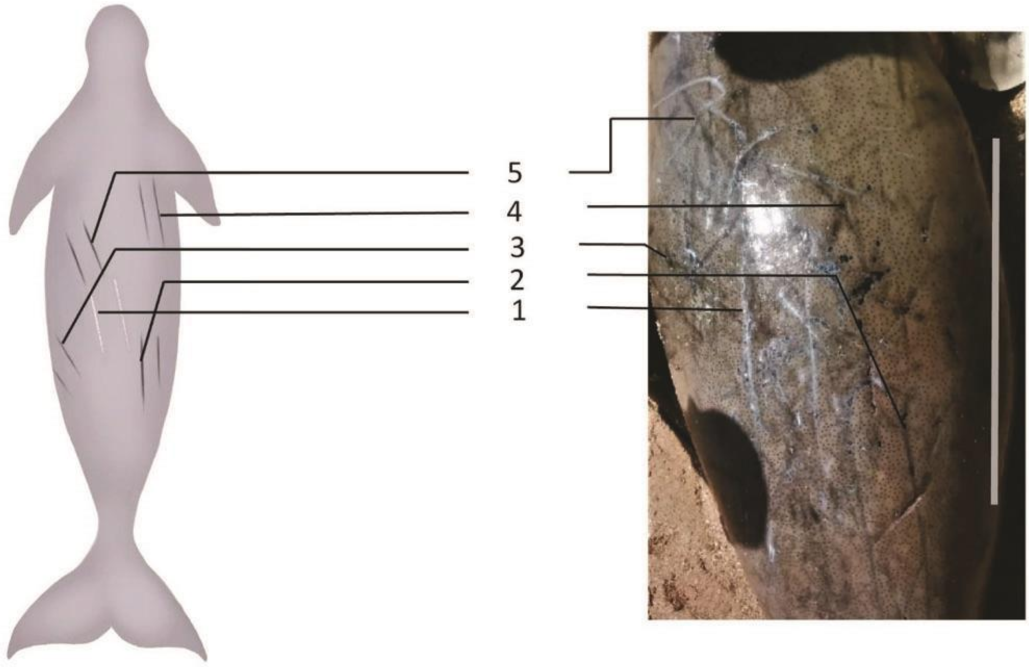


Figure 2. Illustration of tusk-rake scars as seen on the dorsum of the Positra dugong (scale – 60 cm).

Table 1. Measurements and healing stages of six different tusk-rake marks observed on dugongs stranded in the Gulf of Kachchh, Gujarat, India. The healing stage of TR56, i.e. recent or a healed scar was not clear from the photographic evidences

Tusk-rake scar (TRS)	Dugong case	Length (cm)	Width (cm)	Healing stage
TRS1	Beyt Dwarka	33.3	11.3	Stage 1
TRS2	Beyt Dwarka	26.5	8.7	Stage 2
TRS3	Beyt Dwarka	22	6.5	Stage 2
TRS4	Beyt Dwarka	18	5.3	Stage 2
TRS5	Beyt Dwarka	21.4	10	Stage 2
TRS6	Ajad	32	10.8	NA

NA, Healing stage could not be inferred on-field due to advanced decomposition.

the presence of tusk-rake scars, both dugongs were involved in inter- and intra-sexually aggressive conflicts which reflect positively on the social behaviour of this small population in GoK. Similar teeth-rake marks in bottlenose dolphins are reported to be a reliable indicator of conflicts over resources and mates[16]. Paired parallel tusk rake marks in dugongs also provide insights into the diversity in age – a class of the dugongs under study in GoK.

Dugong cows less than 2 m long have almost certainly not been born a calf (non-parous), whereas those larger than 2.50 m are likely to have given birth (parous)[17,18]. Hence, conclusively, the Ajad Island dugong was a sexually mature female, although due to liquefaction of the ovaries, it could not be confirmed whether the cow had birthed a calf during her lifetime or not. Marine traffic exerts a growing pressure on marine megafauna[19]. This contributes to net entanglement as one of the leading causes of death for dugongs[20,21]. Although range-resident, the dugong population in GoK is highly mobile within this range. Their movement response is adapted to a dynamic tidal regime and local knowledge of the widely distributed seagrass habitats in GoK. This makes them mildly susceptible to threats due to fishing activities in their foraging habitats.

Dugongs, like other marine mammals, are susceptible to a wide range of diseases, infectious, non-infectious and idiopathic[9]. Both stranded animals, collectively, suffered from underlying conditions like visceral tumours, inflamed mesenteric lymph nodes and parasitic cysts. This might indicate the immunoreactive state of the body before its ultimate death. We infer that the Ajad Island dugong might have suffered from head trauma due to a boat collision and underlying parasitic infection. This can further be consolidated as the animal showed distinct signs of emaciation and had a relatively full stomach. A fishing net entanglement is evident from the rope impressions around the neck and is suspected to be the ultimate cause of its death. The same can be concluded for the Positra dugong.

Seagrass meadows are known to reduce the velocity of tidal currents[22], thereby causing sedimentation of fine particles[23] and coincidentally of fishing net microfilaments. This naturally makes seagrass meadows extremely prone to microplastic pollution, herbivory becoming a medium for plastic/nylon microfilaments to enter into diverse food chains. Anthropogenic marine debris has also been documented in subtidal seagrass meadows of the Philippines[24]. However, the impact of microplastic sedimentation in dugong foraging habitats depends upon their bioavailability and

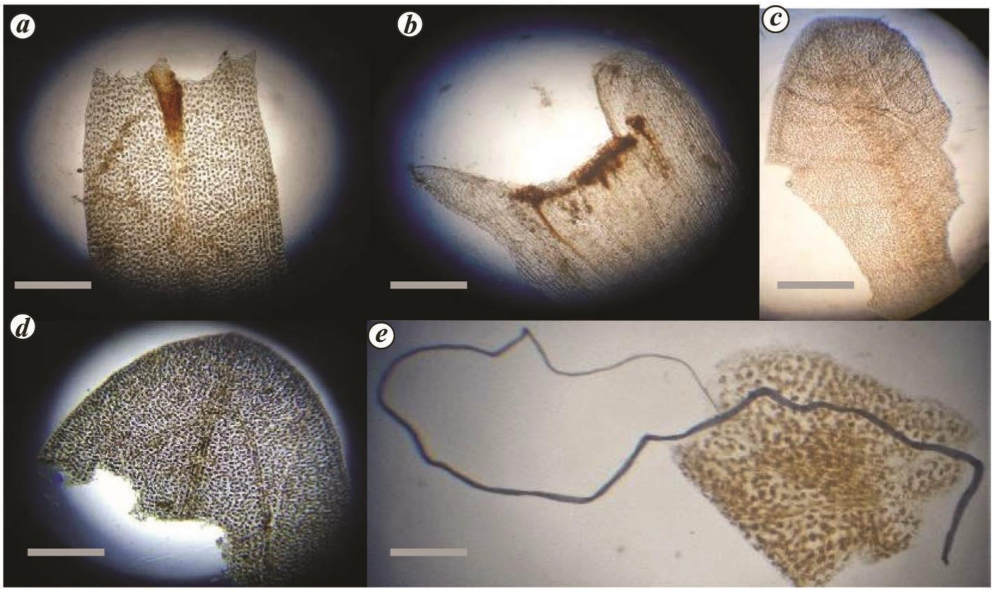


Figure 3. Photomicrographs of seagrass and plastic micro-filaments from the stomach content (scale – 2 mm). ***a***, *Halodule uninervis* leaf apex. ***b***, *H. uninervis* leaf sheath. ***c***, *Halophila beccarii*. ***d***, *Halophila ovalis*. ***e***, Nylon micro-filament from fishing nets.

post-consumption consequences in these animals, which remain obscure. Although the clinical significance of ingestion of plastic micro-filaments is unknown in dugongs, it can have potentially lethal effects on sediment biota of seagrasses.

Photo-documentation and necropsy techniques serve as key conservation tools to understand the underlying stressors of the cryptic dugong population. However, even with limited logistics to access the carcasses, unavailability of laboratory facilities locally and a lack of trained workforce to conduct marine mammal necropsies, the data presented here are critical for the study of dugong species in GoK. Studying the foraging behaviour and the reproductive status of dugongs in the wild is considered difficult owing to their rarity and cryptic behaviour. This is more so for a small population wherein the chances of detecting, observing and following a live animal are further reduced by the turbid waters of GoK (<0.5–2 m visibility). Hence salvaging information from carcasses proves to be a boon to understand their biology, reproductive and health status, and natural and anthropogenic stressors.

The initiation of our study regarding dugong foraging ecology across GoK was an extension of conclusions drawn from necropsy examinations[25]. GoK is home to various ecologically significant species and shares the same habitat as dugongs. With dugongs being an umbrella species, their conservation may also indirectly protect these ecological communities.

1. Marsh, H., *Dugong: Status Report and Action Plans for Countries and Territories*, UNEP/Earthprint, 2002.
2. Sivakumar, K. and Nair, A., Dugong distribution, habitat and risks due to fisheries and other anthropogenic activities in India. Wildlife Institute of India – Technical Report, 2013, 5, p. 74.
3. DSouza, E. and Patankar, V., First underwater sighting and preliminary behavioural observations of dugongs (*Dugong dugon*) in the wild from Indian waters, Andaman Islands. *J. Threaten. Taxa*, 2009, 49–53.
4. D'Souza, E. *et al*., Long-term occupancy trends in a data-poor dugong population in the Andaman and Nicobar archipelago. *PLoS ONE*, 2013, **8**(10), e76181.
5. Srinivas, Y. *et al*., Mitochondrial phylogeography reveals high haplotype diversity and unique genetic lineage in Indian dugongs (*Dugong dugon*). *Aquat. Conserv.: Mar. Freshw. Ecosyst.*, 2021, **31**(4), 818–829.
6. Sivakumar, K., Status and conservation of *Dugong dugon* in India: strategies for species recovery. In *Ecology and Conservation of Tropical Marine Faunal Communities*, Springer, Berlin, Germany, 2013, pp. 419–432.
7. Anand, Y., Tatu, K. and Pandey, C. N., First record of feeding trails of dugong in Gulf of Kachchh (GoK), Gujarat. *Indian For.*, 2012, **138**(10), 968–969.
8. Heinsohn, R., Lacy, R. C., Lindenmayer, D. B., Marsh, H., Kwan, D. and Lawler, I. R., Unsustainable harvest of dugongs in Torres Strait and Cape York (Australia) waters: two case studies using population viability analysis. In *Animal Conservation Forum*, Cambridge University Press, UK, 2004, vol. 7, No. 4, pp. 417–425.
9. Eros, C. *et al*., Procedures for the salvage and necropsy of the Dugong (*Dugong dugon*). Research Publication No. 85, 2007.
10. Yashpal, A., Hyacinth, H., George, L. B. and Kamboj, R. D., Parasitic nematode in dead stranded dugong on Mithapur coast, Okha, Gujarat, India. *Curr. Sci.*, 2018, **115**(7), 1249–1250.
11. Crusz, H. and Fernand, V. S. V., The trematode parasites of the dugong with descriptions of two new monostomes and histopathological changes in the host. *J. Parasitol*., 1954, **40**(5), 499–507.
12. Beck, C. and Forrester, D. J., Helminths of the Florida manatee, *Trichechus manatus latirostris*, with a discussion and summary of the parasites of sirenians. *J. Parasitol*., 1988, 628–637.
13. Anderson, P. K. and Birtles, A., Behaviour and ecology of the Dugong, *Dugong dugon* (Sirenia): observations in Shoalwater and Cleveland Bays, Queensland. *Wildlife Res.*, 1978, **5**(1), 1–23.
14. Lanyon, J. M., Athousis, C., Sneath, H. L. and Burgess, E. A., Body scarring as an indicator of social function of dugong (*Dugong dugon*) tusks. *Mar. Mammal Sci.*, 2021.

15. Lanyon, J., *Guide to the Identification of Seagrasses in the Great Barrier Reef Region*, Great Barrier Reef Marine Park Authority, 1986.
16. Lee, H. H., Wallen, M. M., Krzyszczyk, E. and Mann, J., Every scar has a story: age and sex-specific conflict rates in wild bottlenose dolphins. *Behav. Ecol. Sociobiol.*, 2019, **73**(5), 1–11.
17. Marsh, H., Heinsohn, G. E. and Channells, P. W., Changes in the ovaries and uterus of the dugong, *Dugong dugon* (Sirenia: Dugongidae), with age and reproductive activity. *Austr. J. Zool.*, 1984, **32**(6), 743–766.
18. Marsh, H., Heinsohn, G. E. and Marsh, L. M., Breeding cycle, life history and population dynamics of the Dugong, *Dugon lisette* (Sirenia: Dugongidae). *Austr. J. Zool*., 1984, **32**(6), 767–788.
19. Peltier, H. *et al.*, Monitoring of marine mammal strandings along French coasts reveals the importance of ship strikes on large cetaceans: a challenge for the European Marine Strategy Framework Directive. *Front. Mar. Sci*., 2019, **6**), 486.
20. Reeves, R. R., McClellan, K. and Werner, T. B., Marine mammal bycatch in gillnet and other entangling net fisheries, 1990 to 2011. *Endanger. Spec. Res.*, 2013, **20**(1), 71–97.
21. Marsh, H., Evaluating management initiatives aimed at reducing the mortality of dugongs in gill and mesh nets in the Great Barrier Reef World Heritage Area. *Mar. Mammal Sci*., 2000, **16**, 684–694.
22. Heiss, W. M., Smith, A. M. and Keith Probert, P., Influence of the small intertidal seagrass *Zostera novazelandica* on linear water flow and sediment texture. *New Zealand J. Mar. Freshw. Res.*, 2000, **34**(4), 689–694.
23. Suykerbuyk, W. *et al.*, Surviving in changing seascapes: sediment dynamics as bottleneck for long-term seagrass presence. *Ecosystems*, 2016, **19**(2), 296–310.
24. Abreo, N. A. S., Macusi, E. D. and Jimenez, L. A., Survey of subtidal anthropogenic marine debris (AMD) in Mayo Bay, Mati City, Davao Oriental, Philippines. *Philipp. J. Crop Sci*., 2018, **147**(4), 597–600.
25. Annual progress report, 2019–2020: Recovery of Dugongs and their Habitats in India, Wildlife Institute of India, Dehradun; https://www.wii.gov.in/dugong_publications

ACKNOWLEDGEMENTS. We thank the Gujarat Forest Department for providing the necessary facilities to conduct the necropsy procedures, and the National CAMPA Advisory Council, Ministry of Environment, Forests and Climate Change, Government of India for funds. We also thank field assistants Junus Babbar and Sattar Nagiya for their support as key informants, and Vabesh Tripura for help with the figures.

Received 23 January 2022; revised accepted 20 July 2022

doi: 10.18520/cs/v123/i7/919-924

BENGALURU

14th Student Conference on Conservation Science Bengaluru 2023

nature conservation foundation

ncbs
National Centre for Biological Sciences
Tata Institute of Fundamental Research

9th – 12th October 2023

CERTIFICATE OF PARTICIPATION

This is to certify that **MS. SAMEEHA PATHAN** participated in the **Student Conference on Conservation Science (SCCS)-Bengaluru** that was held between **October 09-12, 2023**, at the J N Tata Auditorium, Indian Institute of Science, Bengaluru.

Srinivasan Kasinathan
Member
Organizing Committee

P62

59th ANNUAL MEETING OF THE
ASSOCIATION FOR TROPICAL
BIOLOGY AND CONSERVATION

Certificate

of presentation

Awarded to

Sameeha Pathan, Gem Christian, J Johnson, Sivakumar Kuppusamy

in sincere appreciation for the valuable contribution
“Studying the unseen; Foraging habitats and their use by remnant population of Dugongs in the macro-tidal basin of GoK, Gujarat,”
presented as part of the **oral session**
“Marine and coastal ecology”.

Coimbatore, India, July 02-06, 2023

RAMESH KRISHNAMURTHY
CHAIR
ATBC 2023

LUCIA G. LOHMANN
Executive Director
ATBC

ASSOCIATION FOR TROPICAL BIOLOGY AND CONSERVATION
IRALE Indian Regional Association for Landscape Ecology
KUMARAGURU Institutions
भारतीय वन्यजीव संस्थान Wildlife Institute of India
SACON
OSAI ...Voice for Nature
GOVERNMENT ARTS COLLEGE OOTY
IISERB