ECOLOGY OF SEAGRASS HABITATS AND ITS ASSOCIATED MACROBENTHIC INVERTEBRATES IN ANDAMAN ISLANDS, INDIA

Thesis submitted for the award of the degree of

DOCTOR IN PHILOSOPHY

IN

WILDLIFE SCIENCE

By

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TO

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DECLARATION

I, hereby, declare that the work conducted under this thesis titled "**Ecology of seagrass habitats and its associated macrobenthic invertebrates in Andaman Islands, India**" is a record of original and independent research work done by me and subsequently submitted for the award of the degree of **Doctor of Philosophy in Wildlife Science** to the **Saurashtra University, Rajkot (Gujarat)**. This research work has been carried out under the guidance and supervision of Dr. K. Sivakumar (Former Scientist G/ Sr. Prof., Wildlife Institute of India, Dehradun), Dr. J.A. Johnson (Scientist F, Wildlife Institute of India, Dehradun) and Dr. Himansu Das (Unit Head, Marine Threatened Species and Habitats, Environment Agency Abu Dhabi). 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, understanding and the particulars given in it are true to the best of my knowledge.

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Miss. SWAPNALI GOLE has researched on this thesis for more than six terms under our supervision and guidance. The work presented in this thesis has not been submitted for any other degree. It meets all of the specifications stated forth in the ordinances of Saurashtra University in Rajkot, Gujarat, and the Wildlife Institute of India.

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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.

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In loving memory of my Father

Sahebrao Gole (1957-2021)

"There is no greatness where there is not simplicity,
goodness and truth"

~ Leo Tolstoy

For the only path you taught us to tread on!

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Being the only woman, in an isolated set-up for extended periods, was a new normal for me. In such times when faraway from civilization, isolation was less geographical but more emotional! Pulling this off would not have been possible without the monumental support from my best field buddies, Sumit Prajapati and Saw Tapori. You guys were my only comfort in the non-female friendly camps of the remotest islands. Thank you for the memories to cherish, right from diving in crocodile-inhabited waters to overnight halts in the middle of the Sea! Our never-ending quest for seagrasses and dugongs, for stories of exploration, adventure, untouched beaches, sand flies, lighthouses, bioluminescence, and sunsets! Thank you, Rupa, Himani, Bhawna, Chinmaya, Supriya, Shrew Shree, Tista, Sourabh, Akarsh, Kalzang, Ali for elevating this journey. My acknowledgments are incomplete without thanking the core group who got me through the most challenging phase of Ph.D. and life; Mahesh, Sumit, Ankit, Mahi, Chandrika, Chaitanya! Thank you for not letting me give up. For motivating me to try 'Just one more time'! For trusting my journey more than I could have imagined and always standing by my side! I owe a big gratitude to my adhyatma yoga gurus; Greesha Ji, Shweta Ji, Krishna Ji and a very special one- Shubendhu Ji, for being my healers. Meeting you all changed me in ways I cannot thank enough for!

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Swapnali Gole

SUMMARY

The diversity, composition, and growth of species in plant communities are shaped mainly by their complex interactions with local environmental settings. Owing to the unprecedented global decline of seagrasses, it is crucial to understand *in-situ* ecological interactions for informing mitigation measures. However, several ecological aspects of seagrass ecosystems are under-studied in the tropical Indian waters, which fall in the highly productive Indo-Pacific seagrass distribution bioregion, offering many socio-ecological services. In this context, my study aimed to address the ecological gaps in India's unique seagrass biodiversity hotspot, the insular archipelago called the Andaman and Nicobar Islands (ANI).

The present study explored three main elements of the seagrass ecosystem in ANI: 1) seagrass ecology and environment, 2) associated fauna, and 3) linkage between seagrasses and local communities, all pertinent to the long-term management perspective of seagrass habitat. The first chapter of the thesis provides a general overview of seagrass as the socio-ecological-economic system and highlights the need to conserve these critical habitats. Further, a thorough literature review in Chapter 2 helped me identify critical research and management gaps in ANI, forming the foundation of my doctoral project. The following four chapters, 3 to 6, demonstrate the ecological and social linkages of biodiversity and people with seagrass ecosystems in ANI, which comprehensively contributed to the last chapter, management recommendations.

Objectives of the study were 1) To assess the spatial distribution patterns of seagrass habitats and associated macrobenthic invertebrates in the Andaman Islands, 2) To understand the seasonal variation in seagrass meadows and associated macrobenthic invertebrates, 3) To understand the structural diversity of seagrass meadows and its influence on associated macrobenthic invertebrates, and 4) To document the Traditional Ecological Knowledge on seagrass habitats. The four technical chapters of the thesis (chapters 3 to 6) revolve around these objectives. Chapters 3 and 4 represent objective 1: seagrass, macrobenthos, and environment. Chapter 5 is a cohesive representation of objectives 2 and 3, seagrasses' seasonality, and seagrass structural diversity's influence on community assemblages. Chapter 6 represents the findings of objective 4: seagrass and people.

The field study was carried out between 2018 and 2022, with a significant sampling period between January and May, as it is the best feasible season for fieldwork in ANI. However, sampling was also done during other seasons with limited sample sizes (for seasonality). A combination of different methods was deployed depending on the study objective. For the first objective, seagrass, and macro-benthos distribution trends, I extensively explored the shallow coastal waters of the Andaman and Nicobar Islands. Seagrass meadows were located using three approaches: a) interactions with local fishers, b) literature review and correspondences with previous seagrass researchers, and c) exploratory dives/ swims/ free diving wherever a potential sandy habitat was observed. Seagrass surveys were carried out from intertidal (0 m) to subtidal habitats (up to 37 m) of coastal areas. Intertidal meadows were surveyed on foot, whereas subtidal meadows were studied using SCUBA aids.

Line Intercept Transects (LIT) were deployed perpendicular to the shore to study the seagrass meadow characteristics and understand the distribution trends, richness, diversity, growth structure, etc. Seagrass and macrobenthos abundance were studied using a 0.5 × 0.5 m quadrat, placed at every 5 m on the 50 m long LIT. Sample collection for estimating shoot densities, total plant biomass, infaunal macroinvertebrates, and sediment profiling was restricted to three replicates per LIT. After the exploratory surveys for objective 1, I delineated three intertidal meadows in South Andaman and Ritchie's archipelago for objectives 2 and 3, which were accessible at all seasons. Seasonal sampling here was done in winter (January), summer (April), and monsoon (August) of 2021. I used a quadrat method (0.5 × 0.5 m) to assess seagrass seasonality, seagrass structural diversity concerning position in meadows (edge effect), and their collective influence on macrobenthic communities. For my last objective, I carried out semi-structured questionnaire surveys with small-scale fishers from 60 villages across the archipelago. Lastly, I used a combination of different parametric and non-parametric tests such as multivariate regression analysis, canonical correspondence analysis, Man- Whitney U test, and Kruskal Wallis test to delineate primary determinants for the observed trends in the study.

So far, 12 species of seagrasses have been reported from ANI, of which I could observe 11 species that formed sparse to highly dense meadows. Seagrasses occurred at 66 sites across 34 Islands; of these, 32 were newly discovered and, for the first time, studied for their ecological and environmental settings, filling the seagrass-coldspots of the region. Seagrass distribution varied across a depth range (0 m to 21 m), but the majority of the meadows occupied the shallow subtidal waters (< 8 m), either as mono-species or mixed-co-occurring habitats, a characteristic Indo-Pacific bioregion trait. The spatial diversity, distribution, and growth of seagrasses in the present study were primarily governed by the water depth, habitat heterogeneity, substrate types, and availability. Water depth was a key regulatory factor influencing all seagrass attributes, such as occurrence, richness, composition, and growth (coverage, total plant biomass, and shoot densities). I observed a declining trend in seagrass occurrence (*p* value = 3.72e-15) and species richness (11:4; intertidal/ shallow-subtidal: deep waters) with increased water depth. Habitat heterogeneity (dead coral with macroalgae *p* value = < 2e-16, rubble *p* value = 3.88e-10) too negatively influenced seagrass occurrence, while sand availability (*p* value = < 2e-16) had increased the probability of the same. Similarly, seagrass cover (β = -0.2759, SE = 0.02471, *p* value = < 2e-16), shoot densities (β = -0.3556, SE = 0.1231, *p* value= 0.005) and biomass (β= -0.3526, SE= 0.1159, *p* value =0.003) declined with water depth. Sand, alike occurrence further positively influenced seagrass cover (β = 0.2924, SE= 0.03124, *p* value = < 2e-16) and biomass (β = 0.295, SE= 0.1171, *p* value = 0.01).

The study could observe a significant negative correlation between seagrass species composition and water depth, as all 10 species (excluding the one-time occurrence of *Halophila beccarii*) mainly occupied the depth regimes within 5 m. Afterward, there was a steady decline in species richness and diversity as the depth increased. I observed only early colonizers in the deeper regimes such as *Halodule* and *Halophila* spp.; *H. ovalis* and *H. decipiens* marked the deepest record of 21 m in the study. Like species composition, the critical depth limit for seagrass growth was observed to be within 2 to 5 m, beyond which the growth declined. The observed differences in seagrass colonization and growth could be attributed to several covariates associated with water depth, such as light attenuation, species' biological traits to adapt to different depth regimes, habitat heterogeneity, and substratum availability. Thus, my study suggests that any alterations in the benthic habitat profile of these meadows are likely to affect the species distribution patterns and overall ecological services offered. Further, the study found that *Halodule* spp. and *Halophila* spp. are generalists, capable of occupying suitable habitats across different depth regimes, while larger-sized species such as *Enhalus acoroides*, *Thalassia hemprichii*, and *Cymodocea* spp.—exhibit specialist characteristics. In addition, seagrass presence in deeper waters further confirms the availability of conducive environments in these regimes in ANI, which is rare in the mainland coasts of India.

I could report 10 infaunal and 15 epifaunal groups from the 66 investigated meadows. Further, I observed a group-specific variation in macrofaunal responses to all the predictor variables. Seagrass presence, in general, positively influenced the macrofaunal densities, suggesting the significance of seagrass habitats in this association. However, three groups exhibited a highly significant relationship with seagrass vegetation, such as polychaetes (both in- and epifaunal), infaunal nematodes (*p* value = 0.005; vegetated = 152.1 ± 63 ind./m^2; unvegetated = 53.4 ± 6.3 ind./m^2) and epi-burrowers (*p* value = 0.0005, vegetated = 12.7 ± 11.4 ind./m^2; unvegetated = 3.7 ± 1.5 ind./m^2). Secondly, the seagrass richness positively influenced epifauna, where densities were much higher in the mixed-species meadows than in the mono-species composite (*p* value = 0.05). Contrary, infaunal assemblages showed a dominant preference for mono-specific meadows (*p* value = 0.008). Epifaunal holothuroids were the only group that positively correlated with seagrass species composition. For instance, holothuroids preferred structurally complicated meadows formed by large-sized seagrasses such as *Enhalus acoroides*, *Thalassia hemprichii*, and *Cymodocea* spp. as opposed to structurally simpler meadows dominated by early colonizers such as *Halophila* and *Halodule* spp. complex ('small-sized seagrass' vs. a) 'large-sized seagrass,' post-hoc Dunn *p* value = < 0.001 and b) 'mixed meadows,' post-hoc Dunn *p* value = 0.04).

In addition to seagrass meadow attributes, my study also reports a significant role of water depth and substratum variability in collectively influencing associated fauna in the meadows. For example, abundances of infaunal polychaetes (β estimate = -0.46; *p* value = 0.03), crustaceans (β estimate = -0.50; *p* value = 0.03), and epifaunal gastropods (β estimate = -0.75; *p* value = 0.002) declined with increasing water depth. Similarly, the abundances of infaunal crustaceans declined with silt content in sediments (β estimate = -0.71; *p* value = 0.0005), while infaunal mollusks (*p* value = 0.004) preferred homogeneous sandy habitats over heterogeneous beds. On the contrary, epifaunal polychaetes (*p* value = 0.02) and holothuroids (*p* value = 0.003) were abundant in heterogeneous seagrass beds. Overall, infauna was numerically dominant in structurally less complicated, homogeneous meadows formed by small-sized species such as *Halophila* spp. and *Halodule* spp. On the contrary, epifauna were found more in the structurally more diverse, heterogeneous meadows formed by large-sized species such as *Thalassia hemprichii*, *Cymodocea* spp., and *Enhalus acoroides*. Therefore, at a vast spatial scale of investigation, the predictor variables such as seagrass presence, richness, type, growth, and environment exert a differential effect on macrofaunal

assemblages. Therefore, I propose a collective role of seagrasses, habitat heterogeneity, substratum profile, and water depth in structuring macrofaunal assemblages from the investigated habitats.

Furthermore, I studied the effect of seasonal variation on the structural diversity of seagrass meadows and its associated macrofauna. The study found inter-meadow differences between the two sites despite the dominance of the same species, *Thalassia hemprichii*. Additionally, seagrass growth between sites varied in cover (*p* value= 0.004) and canopy height (*p* value = < 0.05), suggesting role of local edaphic and environmental factors in shaping meadow structure. Overall, the lowest growth was observed during the summer for both investigated meadows. Concerning the influence of seagrass seasonality on macrofauna, I observed the highest infaunal and epifaunal densities in summer and winter, respectively. I report no edge effect in seagrass growth as well as infaunal densities from the studied meadows, but to some extent on epifauna. For instance, epifaunal holothuroid densities were higher in the center than the edges of the meadows (negative edge; *p* value = < 0.05). For this study, based on the observed trends, I suggest that seagrass seasonality is a product of the local environment rather than the species composition. Additionally, seagrass seasonality substantially influenced macrofauna more than the edge effect. Infauna has largely preferred the low-growth meadows (in summer), as a reduced root-rhizome network might provide more space for burrowing. At the same time, epifauna preferred the calm seasons when the seagrass growth was more (winter), possibly to avoid the harsh environment that is commonly known to occur during the summer and monsoon seasons.

Lastly, the socio-ecological dynamics of seagrass ecosystems in ANI were studied by interacting with the small-scale fishers. The narratives and perceptions studied suggest that: a) the local fishers in ANI have observational knowledge of seagrasses but not of their value system, and b) seagrass habitats do offer a low degree of household food security, but it is largely opportunistic. Hence, the Local Ecological Knowledge documented during the study can complement scientific surveys addressing seagrass distribution from unexplored sites. Considering the poor understanding of local communities with respect to the value system of seagrass habitats and its conservation perspectives, it is suggested to have a well-informed seagrass sensitization program for small-scale fishers in ANI.

In conclusion, the outcomes of this study will have significant implications for the management and conservation of seagrass habitats in the Andaman and Nicobar Islands, India. The last chapter of the thesis, Management Recommendations, presents an in-depth introspection of what is required in the Islands to manage seagrass habitats better. These insights provide valuable baseline information for policymakers, conservationists, and stakeholders and contribute to the broader scientific understanding of seagrass ecosystems and their responses to environmental changes.

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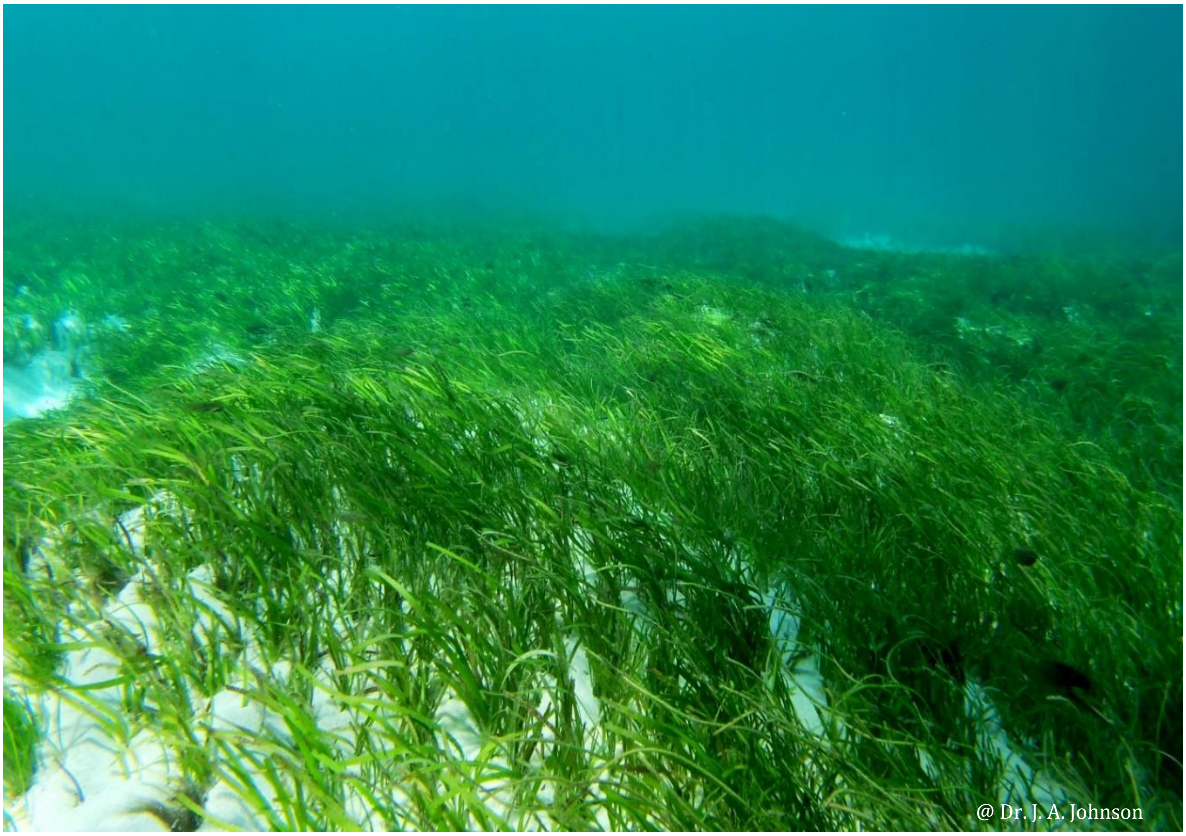

@ Dr. J. A. Johnson

"We need to respect the Oceans and take care of them as if our lives depended on it… Because they do"

~ Sylvia Earle

CHAPTER 1: SEAGRASS- AN INTRODUCTION

1.1. Evolution and Biology

Seagrass is a biological group of marine, flowering plants that adapted to the Sea approximately 100 million years ago (den Hartog, 1970). With an evolutionary polyphyletic origin, the present-day seagrasses occur in shallow, coastal waters of the tropics and temperate regions except Antarctica (Hemminga and Duarte, 2000). Seagrasses are modular, rhizomatous plants with a proper root system which bear fruits, flowers, seeds, and a repeating functional unit called ramet (Kuo and den Hartog, 2006). Thus, seagrass can exhibit both, vegetative growth as well as sexual reproduction (Hemminga and Duarte, 2000; Larkum et al., 2006). These specialized marine monocotyledons are placed under Alismatales, and represent < 0.02 % of the total angiosperms (Hemminga and Duarte, 2000; Newmaster et al., 2011). Evidently, seagrasses have an overall low taxonomic diversity of reported 71 species, unlike other significant habitats like scleractinian corals, which alone consist of about 1,000 species (Cairns, 1999; Newmaster et al., 2011). However, although seagrass ecosystems occupy only 0.15 % of oceans, these underwater grasslands contribute to 1.13 % of the total oceanic primary production (Duarte and Cebrián, 1996), thus rightly called as the *Prairies of the Sea*.

1.2. Seagrass as an ecosystem

Nevertheless, the low species diversity of seagrasses is compensated by greater biomass, allowing them to offer an array of ecological services. Owing to their massive spread, which may range up to 10,000 sq. km. in size and structural complexity, seagrasses offer several ecosystem services (Hemminga and Duarte, 2000). To name a few, seagrass ecosystems are a crucial blue carbon sink, with a sequestration potential of 0.012 to 1.33 metric tons of carbon ha^{-1} yr^{-1} (NISCAIR, 2013[1]; Singh et al., 2015; UNEP, 2020). Seagrass also contributes to nutrient recycling, trophic energy transfer, and regulation of a healthy marine environment (Hemminga and Duarte, 2000). As a foundation species in tropical waters, seagrass maintains the health of communities of adjacent interlinked habitats (Green and Short, 2003; Short et al., 2007; Heck et al., 2008). Seagrass, as an 'ecosystem engineer' plays a health regulatory role for coral reefs and mangroves, as they partake in recycling nutrients (Newmaster et al., 2011), facilitate sediment stabilization (de Boer, 2007; Infantes et al., 2022) and act as a barrier by reducing current velocity (Björk et al., 2008; Geevan and Dixit, 2012).

These functions positively influence the light intensity and reduce turbidity in the water column, supporting overall trophic productivity. Notably, seagrasses act as biological indicators for the habitat's overall health, which is attributed to their sensitivity to water quality change (Orth et al., 2006). Owing to

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[1] www.niscair.res.in/activitiesandservices/products/WoI-Extension-Bulletin-Seagrasses-Jan13.pdf (accessed on January 2018)

their trophic function as primary producers, supplemented with productivity from epiphytes, seagrasses fulfill abundant food requirements of critically endangered megaherbivores such as Dugongs, Manatees, and Green Sea turtles (Orth et al., 2006; Short et al., 2007; Fernando et al., 2014). Besides, habitat structural complexity in meadows contributed by shoot canopies and root-rhizome networks act as nesting, nursery, and refuge grounds supporting the rich biodiversity of macro-invertebrates and commercially essential fishes (Jagtap et al., 2003).

1.3. Socio-economic dynamics of seagrass habitats

With global recognition as a valuable marine ecosystem, seagrass shares a multifaceted relationship with its environment. Under the socio-economic context, seagrasses provide monetary services higher than terrestrial habitats (Costanza et al., 2014). Seagrasses have been reported to support substantial economy of the coastal communities by pooling monetary benefits worth 5000 – 7000 tons of dry seaweeds and 102,900 tons of fish annually (Thangaradjou et al., 2009). Additionally, seagrass beds offer nursery grounds to essential species in both commercial (both shallow water and offshore) as well as subsistence fisheries (in the form of marine invertebrate gleaning) (Hemminga and Duarte, 2000; Short et al., 2007; Unsworth et al., 2019a; Berkström et al., 2020; UNEP, 2020). Consequently, seagrasses provide livelihood opportunities, food security, and human well-being for millions of coastal communities (Mtwana Nordlund et al., 2016; Unsworth et al., 2019a; Jones et al., 2022a).

1.4. Threats, the need for conservation and management

Despite their significant socio-economic-ecological contribution, seagrass ecosystems are threatened worldwide. Unprecedented human-induced stressors catalyze the natural factors impacting seagrasses (Orth et al., 2006; Unsworth et al., 2019b). The rise in anthropogenic footprints in the seagrass meadows is majorly attributed to dredging, marina construction, destructive fishing practices, land reclamation, nutrient and sediment loading, turbidity, and habitat alteration (Short et al., 2007). As a result, subsequent seagrass declines are reported worldwide (Waycott et al., 2009; Gunderson et al., 2016). Unfortunately, the degradation and loss of seagrass habitats significantly impact the valuable services offered (Duarte, 2002; Orth et al., 2006). For instance, Unsworth (2007) reported a reduction in fish and invertebrate stocks in the Wakatobi Marine National Park, Indonesia in response to seagrass degradation. Nevertheless, in the face of escalating pressures and their growing spatial extent on all marine habitats (Halpern et al., 2008), seagrass-centric protective measures need revisions.

1.5. Research rationale and objectives

Global seagrass loss is predicted to accelerate in developing countries since these regions critically lack legislative measures (Duarte, 2002). Sadly, in the tropics seagrass management has received little attention than the adjacent coral reefs (Mumby et al., 2006). Although positive human interventions have reported an optimistic reversing of seagrass losses (Elliott et al., 2007; de los Santos et al., 2019; Tan et al., 2020), such initiatives, along with *in situ* seagrass management are yet substantially lacking in the tropics, including Indian waters.

India, being a developing nation, disparagingly lacks the funds, logistics, and manpower required to perform marine surveys. These constraints are further reflected in the need for more robust research addressing basic seagrass ecology such as the relationship between seagrass, its environment, and people. The Andaman and Nicobar Islands (ANI) form the country's second most varied seagrass habitats (Thangaradjou and Bhatt, 2018). Prior research studies have given valuable baselines on species distribution, natural history, descriptive habitat preferences, and spatial extent of seagrasses in ANI (Jagtap, 1991, 1992; Das, 1996; Thangaradjou et al., 2010a, b; Paulose et al., 2013; D'Souza et al., 2015; Ragavan et al., 2016; Savurirajan et al., 2018).

However, a data gap is still reflected in many of the management crucial aspects of the region. Published literature broadly lacks precise spatial information (locality) on occurrence, hindering spatiotemporal comparisons like other global initiatives (Sudo et al., 2021). Although most of the seagrass meadows in ANI are recovering from the impact of the 2004 tsunami, the shallow-water coastal habitats here are threatened by geological vulnerability and booming coastal development. It is thus essential to update information on the species composition, distribution, and factors that determine the existing trends. Further, since several ecological communities and people depend on these habitats, it is imperative to understand the socio-ecological dynamics of seagrasses, which needs to be improved from ANI.

With this background, I explored three intrinsic elements of the seagrass ecosystems in ANI: 1) seagrass and environment, 2) associated fauna, and 3) people, categorized as four primary objectives as follows;

1) To assess the spatial distribution patterns of seagrass habitats and associated macrobenthic invertebrates in the Andaman Islands,

2) To understand the seasonal variation in seagrass meadows and associated macrobenthic invertebrates,

3) To understand the structural diversity of seagrass meadows and its influence on associated macro benthic invertebrates, and

4) To document the Traditional Ecological Knowledge on seagrass habitats.

My thesis structural framework (Figure 1.1) was designed to substantially represent these intertwined aspects of seagrass ecosystems as follows;

1) Chapters 1 and 2 present the role of seagrasses in social-economic and ecological services, seagrass research status in India, data gaps, research rationale, and objectives.

2) The first part of objective 1 is presented as Chapter 3. Here, I explored the basic seagrass ecology, including spatial distribution trends, species depth ranges, and, most importantly, seagrass-environment interactions.

3) The second part of objective 1 is presented in Chapter 4, where I studied the lesser-known fauna, the seagrass-associated macrobenthos. In this chapter, I present a detailed quantification of the seagrass-associated macroinvertebrates and the potential role of seagrass and other critical environmental variables in shaping these communities.

4) For objectives 2 and 3 (Chapter 5), I checked if seasonal seagrass variation and edge effect (and subsequent structural variability) influenced the associated macrofaunal communities.

5) Lastly, for my last objective (Chapter 6), I explored the seagrass-human dynamics to document the perceived knowledge, value system, and dependency of small-scale fishers on seagrass ecosystems.

6) My last chapter in the thesis (Chapter 7) revolves around the management recommendations for seagrass conservation in the Andaman and Nicobar Islands.

Chapters 1 and 2

AN OVERVIEW

- Seagrass: Social-Ecological-Economic System
- Ecosystem Services
- Threats
- Seagrasses in India- Status and Need
- Research Gap
- Study Rationale

Chapter 3

SEAGRASS ECOLOGY

- Plant Community Composition
- Spatial Distribution Trends
- Depth Ranges
- Seagrass-Environment Relationship

Chapter 4

ECOLOGICAL HABITAT VALUE

- Seagrass-Macrobenthos
- Quantified Baseline: Diversity and Distribution
- Infauna and Epifauna
- Dominant Guilds
- Role of Seagrass Meadow Architecture and Environment

Chapter 5

SEASONALITY AND EDGE EFFECT

- Seasonal variation in Seagrasses
- Edge Effect in Meadows
- Collective influence on associated communities

Chapter 6

SOCIO-ECOLOGICAL DYNAMICS

- Local Ecological Knowledge of Small-scale Fishers
- Perceptions
- Value system

Chapter 7

MANAGEMENT RECOMMENDATIONS

- Top-down
- Bottom-up
- Collaborative

Figure 1.1: An Illustrative framework of thesis

1.6. Study area and general methodology

India's Andaman and Nicobar Islands (ANI, 6° 44' 54.26" N, 93° 54' 08.80" E to 13° 38' 7.91" N, 93° 1' 50.66" E) located in the Bay of Bengal, support a tropical insular ecosystem as part of two global biodiversity hotspots (Myers et al., 2000). This archipelago ~ 1200 kms east of mainland India, has a long and sheltered coastline spanning 1962 km (Andaman and Nicobar Administration, 2023[2]). With a total geographic area of 8249 km^2, ANI provides favorable conditions for the growth and diversification of shallow coastal habitats such as coral reefs, mangroves, and seagrasses (Tigga and Rao, 2004). The Andaman archipelago (6,408 km^2) is much more significant in size than the Nicobar group (1841 km^2) and is separated by the 10-degree (latitude) channel.

The climate regime in ANI is tropical, and the Islands receive rainfall from the southwest and northeast monsoon winds. Out of the total 836 islands, only 31 are inhabited by communities broadly categorized as a) Indigenous and b) Settlers. The former comprises six tribes: Jarawas, Onges, Great Andamanese, Sentinelese, Nicobarese, and the Shompens (Sircar, 2004). The latter includes settlers who inhabited the Islands at different timelines broadly presented as pre- and post-independence settlements (Independence attained in 1947). Dominant ethnicities in the Islands are Bengali, Tamil, Telugu, and Burmese.

My study area spanned across the coastal waters of the entire archipelago ANI (Figure 1.2). For spatially vast objective 1, I conducted exploratory surveys

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[2] www.andaman.gov.in (accessed on February 2023)

for seagrasses and their associated fauna where a conducive field environment was presented (SCUBA per se). For this objective, my study area ranged from Landfall and East Islands (the northernmost tip of ANI) to Great Nicobar (the southernmost island in the archipelago). Parallelly, for objective 4, I carried out interview surveys with the local fishing communities. A semi-structured questionnaire approach was adopted for social surveys targeting major fishing villages in the Islands.

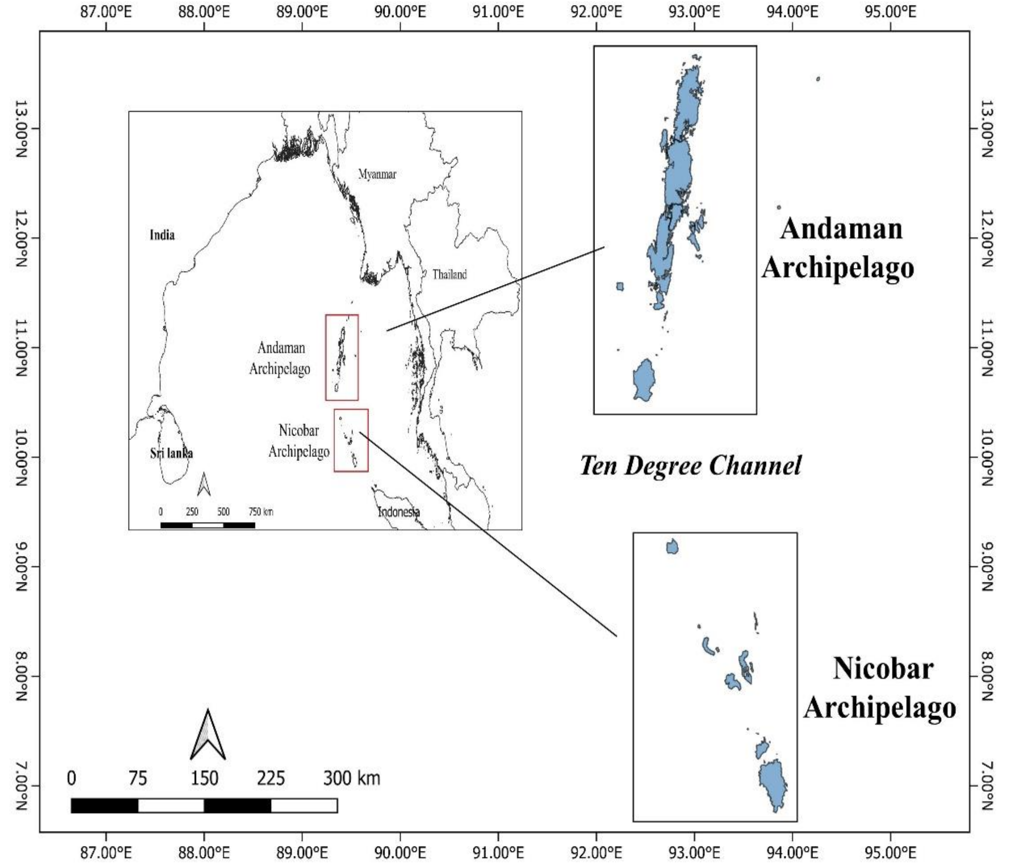

Figure 1.2: An overview of the study area- The Andaman and Nicobar Islands

Later, after the reconnaissance survey, I narrowed my study sites for objectives 2 and 3 to only three intertidal meadows: one in South Andaman and two in Ritchie's archipelago. I used multiple methods for the conventional systematic surveys, including Line Intercept Transects (LIT) and quadrat sampling (English et al., 1997; Rattanachot et al., 2020). For objective 1, the LIT method was used, while for objectives 2 and 3, I chose quadrat sampling. The entire duration of fieldwork was between 2018 and 2022 (majorly January to May) when the waters are comparatively much calmer in the Islands to carry out SCUBA-aided surveys. Required permits were obtained from concerned authorities to carry out the field work in forest and tribal protected waters, along with community interactions (Annexure 1).

CHAPTER 2: SEAGRASS HABITATS IN INDIA- AN OVERVIEW

2.1. Introduction

In Indian waters, the mention of seagrasses dates back to the pre-colonial era of the late 19th century, documented as the "Flora of British India" (Hooker, 1888, 1893). However, only in the late 20th century did the scientific community in India begin exploring seagrass ecosystems to understand their distribution and natural history trends. These pioneering investigations (Figure 2.1) confirmed seagrass presence from the peninsular coastline's west and east coasts and India's insular systems (Table 2.1). Subsequently, research progressed from conventional studies to advanced genres of technology, seagrass-environment interactions, productivity, habitat value, health of ecosystems, and ecological services, to name a few (Figure 2.1). An extensive literature review of 128 publications suggests a stark decadal rise in the attention received by these threatened ecosystems in India, with the last decade (2010 to 2020) being the most productive time (Figure 2.2). However, a region-specific bias exists with a strong local-scale contribution to seagrass research asymmetry. For instance, Tamil Nadu alone is the highest contributor (44.2 %, n=57, Figure 2.3) to the available published literature, followed by Lakshadweep and Andaman & Nicobar group of Islands (15.5 and 14 %, respectively). Meanwhile, the remaining six regions collectively contributed to only 13.2 % of the total studies and the rest to collective pan-India studies (Figure 2.3).

MAJOR SEAGRASS RESEARCH IN INDIA: AN OVERVIEW

I. SPATIAL EXPLORATION

(Late 20th Century: 1970's to 1999)

Pan India: *Jagtap (1991), Kannan et al. (1999)*
Lakshadweep: *Qasim & Bhattathiri (1971), Qasim et al. (1972), Ansari (1984), Jagtap (1987), Nayak et al. (1989); Ansari et al. (1991), Jagtap (1998), Sathe & Raghukumar (1991)*
Tamil Nadu: *Balasubramaniam (1974), Balasubramaniam & Wafar (1975), Lakshmanan & Rajeshwari (1979), Parthasarathy et al. (1988), Ganesan & Kannan (1995), Jagtap (1996), Kannan et al. (1998)*
Andaman & Nicobar: *Jagtap (1992), Das (1996)*
Goa: *Untawale & Jagtap (1977), Jagtap & Untawale (1981)*

II. ECOLOGY

(2000 to 2023)

Status & Distribution Trends: *Nair (2002), Pattnaik (2003), Prabhakaran (2008), Dilipan et al. (2011), Kaladharan et al. (2011), Manikandan et al. (2011a), D'Souza et al. (2013a, b), Kamboj (2014), Mishra & Apte, (2020)*
Seasonality: *Prabhakaran (2007), Sridhar et al. (2010a), Govindasamy et al. (2013)*
Seagrass & Environment: *Pati et al. (2014a), Thangaradjou & Kannan (2005, 2007), Arumugam et al. (2013), Gangal et al. (2012), Savurirajan et al. (2018), Rao et al. (2023)*
Biomass & Productivity: *Kannan & Thangaradjou (2006), Susila et al. (2012), Pati et al. (2014b)*
New distribution records: *Savurirajan et al. (2015), Gole et al. (2022a)*
Associated Fauna: *Kelkar et al. (2013), Anand & Pillai (2007), Susan et al. (2011), Manikandan et al. (2011b), Jayabarathi et al. (2012), D'Souza et al. (2015)*
Phenology: *Lakshmanan & Rajeshwari (1985), Patankar et al. (2019), Gole et al. (2023b)*
Genetics: *Lucas et al. (2012), Nguyen et al. (2013), Dilipan et al. (2017), Vanitha et al. (2016)*

III. HABITAT HEALTH

Kannan et al. (1992), Vinithkumar et al. (1999), Jagtap (1983), Thangaradjou et al. (2010c; 2013), Govindasamy et al. (2011), Mishra & Farooq (2022), Mishra et al. (2023)

IV. TECHNOLOGY (REMOTE SENSING)

Nayak et al., 1989, Jagtap & Inamdar (1991), Desai et al. (1991), Nayak & Bahuguna (2001), Umamaheswari et al. (2009a), Sridhar et al. (2010b), Nobi & Thangaradjou (2012), Nobi et al. (2010, 2012, 2013), Paulose et al. (2013), Geevarghese et al. (2018)

V. SEAGRASS-HUMAN INTERACTIONS

Newmaster et al. (2011)

VI. BIOTECHNOLOGY

Kumar et al. (2008), Umamaheswari et al. (2009b), Mayavu et al. (2009), Ravikumar et al. (2010, 2011a, b), Arumugam et al. (2010), Kannan et al. (2010a, b, c; 2012a, b; 2013), Ali et al. (2012), Ramalingam et al. (2013), Chanthini et al. (2015)

VII. ECOSYSTEM SERVICES & THREATS

Sobithabai et al. (2005), Asir et al. (2004, 2007), Thangaradjou et al. (2009; 2010d), Pradeebha et al. (2011), Nobi et al. (2016), Chanda et al. (2022)

VIII. CONSERVATION MEASURES, LEGISLATION & MANAGEMENT

Mahalingam & Kamala (1987), Bensam & Udhayashankar (1990), Geevan & Dixit (2012), Thangaradjou (2000), Singh et al. (2004), Ghosh & Pattnaik (2005), Patterson & D'Souza (2015), Thangaradjou & Kannan (2008a, b), Ramesh et al. (2019)

Figure 2.1: An overview of significant research on seagrass ecosystems in India

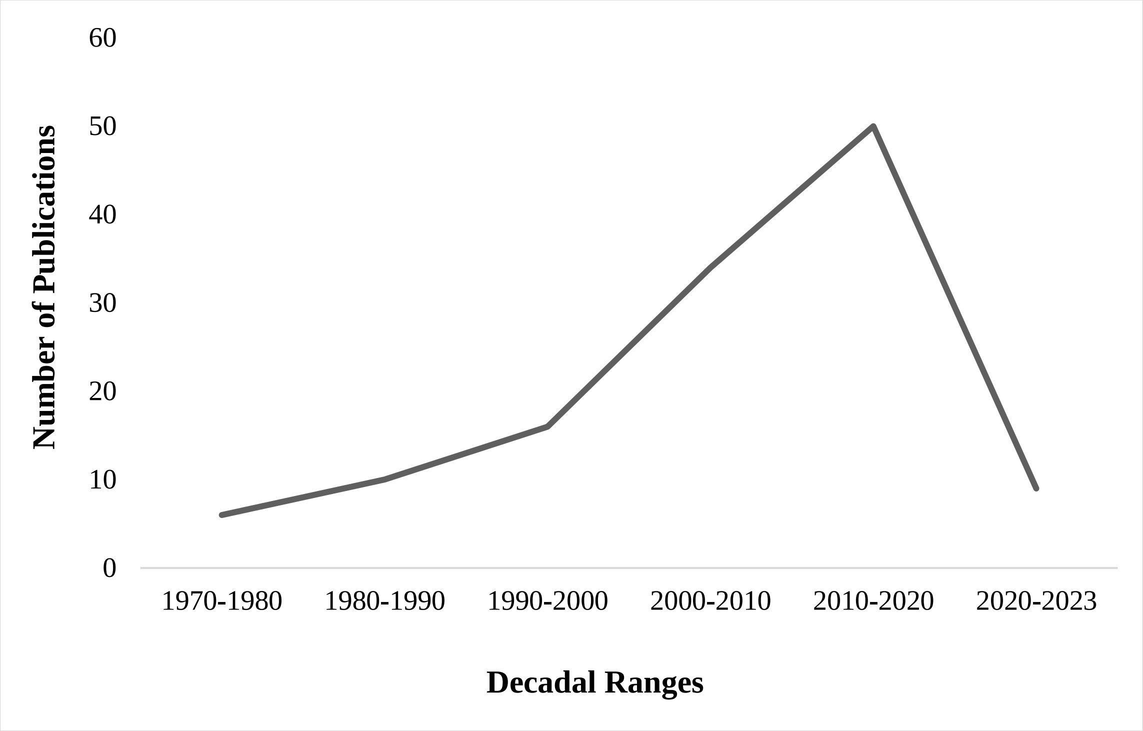

Figure 2.2: Decadal status of seagrass research in India

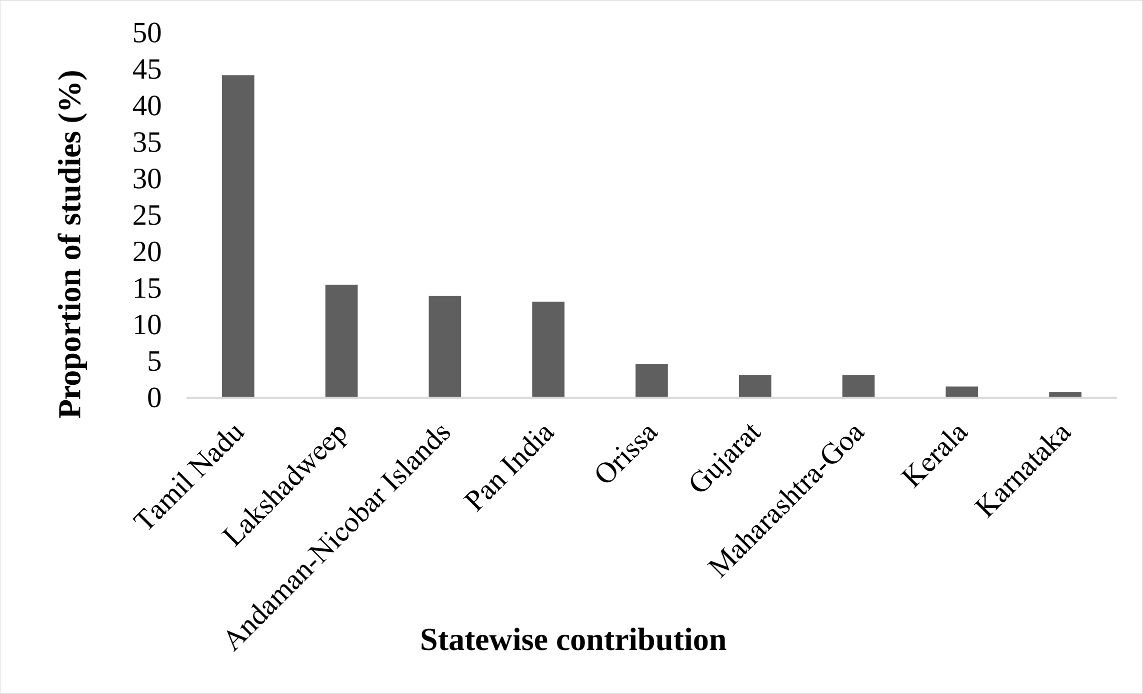

Figure 2.3: State-wise contribution to seagrass research in India

Based on several taxonomic interventions, the updated species checklists inform a total of 15 species and a subspecies in shallow coastal waters of India (Table 2.1). These comprise seven genera from Hydrocharitaceae, Cymodoceaceae, and Ruppiaceae. In order of high species richness, Tamil Nadu (n=15), followed by Andaman and Nicobar Islands (n=12), Lakshadweep (n=10), and Gujarat (n=6) form the significant seagrass habitats in the country (Thangaradjou and Bhatt, 2018, Table 2.2).

Table 2.1. Region-specific seagrass species richness in India

Sites	**Total no. of species**	**Sources**
Tamil Nadu	15, one subspecies	Balasubramaniam, 1974; Lakshmanan and Rajeshwari, 1979; Parthasarathy et al., 1988; Jagtap, 1991; Umamaheswari et al., 2009a; Manikandan et al., 2011a
ANI	12	Jagtap, 1991; Jagtap, 1992; Das, 1996; D’Souza et al., 2015; Savurirajan et al., 2015
Lakshadweep	10	Qasim et al., 1972; Jagtap, 1987; Jagtap, 1991; Dilipan et al., 2011
Orissa	7	Pattnaik, 2003; Ghosh and Pattnaik, 2005
Gujarat	6	Jagtap, 1991; Singh et al., 2004; SAC, 2010
Maharashtra	2	den Hartog, 1971; Jagtap, 1991
Goa	2	Untawale and Jagtap, 1977; Jagtap, 1991
Karnataka	2	Jagtap, 1991; Kaladharan et al., 2011
Kerala	2	Nair et al., 1983; Jagtap, 1991

Table 2.2. Species diversity and distribution of seagrass in India

Family	**Genus**	**Species**	**Sites**								
			GJ	**MH**	**GO**	**KAR**	**KL**	**TN**	**OR**	**ANI**	**LK**
Hydrocharitaceae	*Enhalus*	*acoroides*	-	-	-	-	-	+	-	+	+
	Halophila	*ovalis*	+	-	+	+	+	+	+	+	+
		H. ovalis ramamurthiana	-	-	-	-	-	+	-	-	-
		ovata	+	-	-	-	-	+	+	+	+
		decipiens	-	+*	-	-	-	+	-	+	+
		beccarii	+	+	+	+	+	+	+	+	-
		stipulacea	-	-	-	-	-	+	-	-	-
		minor	-	-	-	-	-	+	+	+	-
	Thalassia	*hemprichii*	+	-	-	-	-	+	-	+	+
Cymodoceaceae	*Cymodocea*	*serrulata*	+	-	-	-	-	+	-	+	+
		rotundata	-	-	-	-	-	+	-	+	+
	Halodule	*uninervis*	+	-	-	-	-	+	+	+	+
		wrightii	-	-	-	-	-	+	-	-	-
		pinifolia	-	-	-	-	-	+	+	+	+
	Syringodium	*isoetifolium*	-	-	-	-	-	+	-	+	+

Ruppiaceae	*Ruppia*	*maritima*	-	-	-	+	-	-	+	-	-
Total No. of Species			6	2	2	2	2	15	7	12	10

[*One time record, + Present, - Absent; GJ, Gujarat; MH, Maharashtra; GO, Goa; KAR, Karnataka; KL, Kerala; TN, Tamil Nadu; OR, Orissa; ANI, Andaman and Nicobar Islands; LK, Lakshadweep]

2.2. Seagrass diversity and distribution in India

Indian seagrass ecosystems fall in the highly diverse and productive ‘Tropical Indo-Pacific’ bioregion of global seagrass distribution (Short et al., 2007). Remarkably, the vast coastline of ~ 7500 km supports 15 species of seagrasses, indicating rich growth conditions to support high taxonomic diversity, thus imparting global importance to seagrasses from this region.

***2.2.1. The west coast*:** Comparatively, the west coast of India has received scattered scientific attention, possibly due to its low diversity and extent. Sparse research confirms seven seagrass species from the region, with *Halophila beccarii* having a much more comprehensive distribution range (Table 2.2). *H. beccarii, H. ovalis, H. ovata*, and *Halodule uninervis* were the first seagrass reports from the Gulf of Kutch (Jagtap, 1991). After a considerable gap, Singh et al. (2004) reported six species from the region, with *Cymodocea serrulata* and *Thalassia hemprichii* as new records, updating the local checklist to six species. Maharashtra coast supports *H. decipiens* (den Hartog, 1971) and *H. beccarii* (Jagtap, 1991), while Untawale and Jagtap (1977), along with Jagtap (1991) testified *H. beccarii* and *H. ovalis* from the shores of Goa. Meanwhile, *H. beccarii* and *Ruppia maritima* are the only species reported from the Karnataka coast (Jagtap, 1991; Kaladharan et al., 2011). Limited explorations from Kerala's coastal zones confirm the presence of *H. ovalis* and *H. beccarii* (Nair et al., 1983; Jagtap, 1991).

***2.2.2. The east coast*:** Only two states are representatives of seagrass ecosystems from the East Coast of India: Tamil Nadu and Orissa. Extensive seagrass explorations in Tamil Nadu confirm 15 species and one subspecies collectively from the Gulf of Mannar and Palk regions (Table 2.2). Pioneer work by Balasubramaniam (1974) described five species from the Gulf of Mannar coast, namely *Syringodium isoetifolium, C. serrulata, H. ovalis, H. stipulacea,* and *Halodule uninervis.* The study assessed seasonal variation in 'chlorophyll a' in phytoplankton from seagrass habitats. Later, Lakshmanan and Rajeshwari (1979), and Parthasarathy et al. (1988) reported *R. maritima* and *H. decipiens* as new records from the Tamil Nadu coast, respectively. In 1991, apart from the species mentioned above, Tamil Nadu got five new records, namely, *H. ovata, H. beccarii, C. rotundata, Enhalus acoroides,* and *T. hemprichii* (Jagtap, 1991). Recent additions to the checklist of the Gulf of Mannar are *Halodule pinifolia* (Umamaheswari et al., 2009a), *Halodule wrightii,* and *H. minor* (Manikandan et al., 2011a). All these species, except *R. maritima and H. minor,* are found in Palk Bay (Manikandan et al., 2011b). In Orissa Coast, seagrass habitats are explored only in the Chilika Lake, Asia's largest brackish water lagoon. Pattnaik (2003), along with Ghosh and Pattnaik (2005) reported seven seagrass species from the region, namely *Halodule uninervis, Halodule pinifolia, H. ovalis, H. ovata, H. minor, H. beccarii* and *R. maritima.*

2.2.3. The Island Groups

2.2.3.1. Andaman and Nicobar Islands (ANI): Jagtap (1991, 1992) and Das (1996) were pioneers of seagrass research in ANI. Their study collectively reported nine species of seagrasses throughout the distribution range. *Halodule uninervis, T. hemprichii*, and *H. ovata* were the first seagrass records from ANI (Jagtap, 1991). Subsequently, Jagtap (1992) exclusively reported the Nicobar Islands' marine flora, including four new regional records viz., *H. ovalis, C. rotundata, E. acoroides,* and *S. isoetifolium*. Later, Das (1996) surveyed the entire archipelago and reported *C. serrulata* and *Halodule pinifolia* as new records. For nearly a decade after this exploratory phase, no concrete research was conducted on seagrass habitats in ANI. Additionally, significant seagrass habitats were lost during the Indian Ocean tsunami in 2004, leaving work done by Jagtap (1991, 1992) and Das (1996) as the only baseline studies. Thangaradjou et al. (2010a) were the first to assess the damage incurred by the seagrass habitats post-tsunami throughout their local distribution range and reported a shift in species composition in the Islands. Recently, a notable work by D'Souza et al. (2015) and Savurirajan et al. (2015) reported *H. minor, H. decipiens,* and *H. beccarii* as new additions to the list, making the total ANI seagrass species to 12 (Table 2.2).

2.2.3.2. Lakshadweep archipelago: Like ANI, marine floral taxonomic work in the Lakshadweep Islands has been patchy. A total of 10 seagrass species have been reported from the Lakshadweep Islands. Qasim et al. (1972) attempted to study the total primary production of an atoll in Lakshadweep, including the first documented seagrass species of the Islands, *T. hemprichii* and *S. isoetifolium.* Later, Jagtap (1987, 1991), while assessing the distribution of seagrass and other coastal habitats, reported six new records, namely *C. rotundata, C. serrulata, Halodule uninervis, H. ovalis, H. ovata* and *E. acoroides* from the region. In a maiden effort, Dilipan et al. (2011) reported *H. decipiens* and *Halodule pinifolia* from the Agatti, Ameni, and Kalpeni Islands of Lakshadweep.

2.3. Seagrass Research in India

The late 20th century was the pioneering exploratory phase for ecological studies on seagrass in Indian waters (Figure 2.1). However, in the early 21st century, conventional studies truly began to understand different aspects of seagrass ecosystems. Broadly, the seagrass research in India can be categorized into nine broad components such as 1) ecology, 2) seagrass genetics, 3) biotechnological potential, 4) habitat health, 5) ecosystem services and threats, 6) seagrass-human interactions, 7) mapping technology (remote sensing), 8) conservation measures and legislation and, 9) Pan-India status review (Figure 2.4). Overall, ecological studies had the maximum contribution (45.2 %, n=57), followed by biotechnological potential (14.3 %), conservation issues and legislative measures (9.5 %), remote sensing (7.9 %), habitat health (7.1 %), ecosystem services and threat evaluation (5.6 %), and the least on seagrass-human dynamics and genetics studies (Figure 2.4).

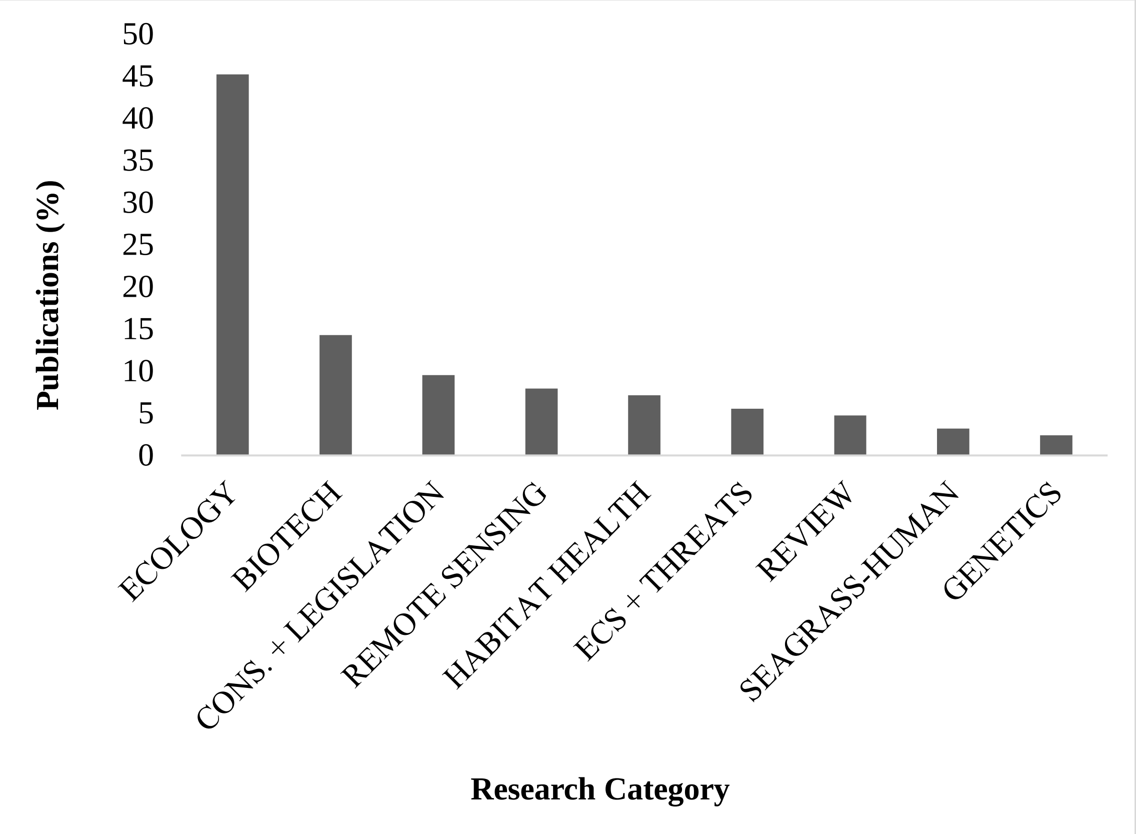

Figure 2.4: Research category-specific contribution in seagrass research [n=128; Biotech, Biotechnology; Cons., Conservation; ECS, Ecosystem services]

2.3.1. Seagrass ecology and genetics

In addition to seagrass occurrence and distribution trends, several studies demonstrated the relationship of seagrasses with their local environment. For instance, at a local scale, key determinants in shaping plant community structure were reported to be substratum availability, sediment texture, and water depth (Thangaradjou and Kannan, 2005, 2007; Gangal et al., 2012; Arumugam et al., 2013; Pati et al., 2014a; Savurirajan et al., 2018; Rao et al., 2023). Studies have further focused on assessing the seagrass productivity and seasonal variation in the biomass (Kannan and Thangaradjou, 2006; Susila et al., 2012; Pati et al., 2014b).

T. hemprichii and *S. isoetifolium* were the key species contributing to the total primary production in an atoll in Lakshadweep, where species' photosynthetic rates were independent of their respiration rates (Qasim et al., 1972). From ANI, a recent assessment reported biomass variation and growth rate of *H. ovalis* concerning dugong herbivory (D'Souza et al., 2015). This study focused on understanding the sustainability of seagrass meadows as feeding grounds for dugongs, primarily regulated by the biomass and growth rate of *H. ovalis.* Based on their findings, maximum and minimum species’ growth rates were reportedly March and June, respectively. All the afore mentioned studies reported site-level differences in primary production and biomass of seagrasses.

Due to the high primary production of seagrasses, nutritional value, and structural complexity, it is needless to say that seagrasses are functionally critical habitats which act as either direct foraging grounds for species like green sea turtles (Kelkar et al., 2013) and dugongs (D'Souza et al., 2015) or as a refugia and nursery grounds for fishes (Anand and Pillai, 2007). Moreover, due to the sequestration potential of seagrass sediments, the substratum harbors numerous benthic faunal communities (Ansari, 1984; Ansari et al., 1991; Manikandan et al., 2011b; Jayabarathi et al., 2012). Thus, from a conservation perspective, quantifying seagrass-associated faunal communities is an important management aspect, but contrary to the species diversity and meadow extent in India, only a few studies have focused on documenting this facet (Figures 2.1 and 2.5). Lastly, since relying only on morphological features of seagrasses is compounding, recent advancements in genetic studies could be a potential tool in inventorising and resolving existing taxonomic discrepancies (Lucas et al., 2012; Nguyen et al., 2013; Dilipan et al., 2017; Vanitha et al., 2016).

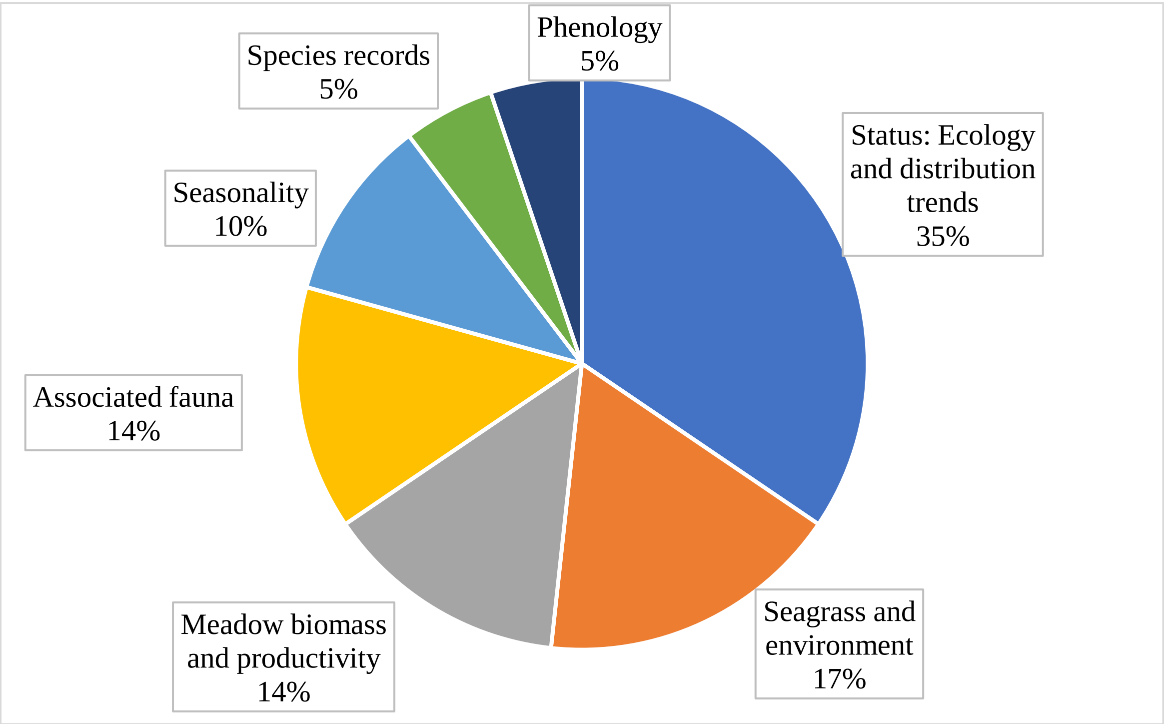

Figure 2.5: Different aspects of ecological studies on seagrass ecosystems in Indian waters

2.3.2. Biotechnological potential

Biotechnological applications of seagrasses have comparatively been a new niche in India (Figure 2.4), where workers have explored the bioactive potential of certain seagrass species. For instance, several studies have demonstrated the antioxidant, antimicrobial, antibacterial, and hemolytic properties of *E. acoroides, C. serrulata,* and *H. ovalis* against a variety of human and bacterial pathogens (Kumar et al., 2008; Mayavu et al., 2009; Ravikumar et al., 2010; Umamaheswari et al., 2009b; Arumugam et al., 2010; Athiperumalsamy et al., 2010; Kannan et al., 2010a, b, c, 2012a, b, 2013). Ramalingam et al. (2013) and Chanthini et al. (2015) studied the cytotoxic potential of *C. serrulata*, while Ali et al. (2012) observed the larvicidal bioactivity of seagrass *S. isoetifolium* against *Aedes egypti*. Additionally, *C. serrulata* is reported to be effective against poultry and bacterial fish pathogens (Ravikumar et al. 2011a, b).

2.3.3. Habitat health

Seagrass habitats could indicate metal pollution, as these coastal habitats act as potential sinks to bioaccumulate heavy metals in proportion to their environmental concentration (Thangaradjou et al., 2010c). Studies taken to quantify metal pollution in Indian coastal waters are sparse (Figure 3), and priority should be given to this aspect, owing to the growing anthropogenic pressure on these habitats. Another critical aspect of monitoring seagrass habitat health is studying diseases affecting seagrasses, as plants exhibit massive die-offs due to environmental stresses, including diseases. Wasting disease whose causative agent is a unicellular pathogenic slime mold *Labyrinthula* spp*.*, has resulted in massive die off of seagrass habitats potentially compromising recovery (Muehlstein, 1992). Although this has never been reported in Indian waters, Ragavan et al. (2013) documented an unusual phenomenon of leaf reddening in *H. ovalis* and *T. hemprichii* from the Andaman and Nicobar Islands. While leaf reddening cannot be linked with the unhealthy state of seagrasses, the phenomenon is thought to be enhanced by UV radiation and needs further monitoring (Ragavan et al., 2013).

2.3.4. Seagrass-human interactions

Despite the wide application of local ecological knowledge in marine conservation, such seagrass-centric studies are very limited from India (Newmaster et al., 2011). This baseline study highlighted the importance of environmental information possessed by coastal populace on seagrass ecosystems, their degree of utility and the lack of such studies from Indian waters. The work further emphasized on the role of community-based seagrass conservation using the local knowledge repository.

2.3.5. Technology in Seagrass Monitoring

Understanding seagrass spatial coverage using traditional techniques such as exploratory surveys and ground truthing, is time-consuming and logistically constraining. Yet this knowledge is essential for continuous monitoring of the spatio-temporal changes in seagrass habitats. In the Indian waters, understanding seagrass distribution using advanced tools has recently gained impetus when researchers attempted to map seagrasses using remote sensing (RS) tools coupled with visual interpretation techniques and GIS (Figure 2.1).

Usage of IRS LISS III and IV have been widely gaining attention for mapping and habitat characterization of seagrasses habitats in Gulf of Mannar, Palk Bay, Gulf of Kutch, Andaman and Nicobar and Lakshadweep islands (Nayak et al., 1989; Desai et al., 1991; Sridhar et al., 2010b; Nobi et al., 2012, 2013). Nobi et al.

(2013), using the IRS tool, have successfully identified changes in habitat extent in response to coastal activities and detected maximally impacted sites in Lakshadweep suitable for restoration. IRS tool is cheaper and provides better resolution with good repeatability, thus minimizing manual time consumption and cost involved in field surveys. Recent advancements using more fine-scaled spatial resolution, such as Landsat 8 OLI data, have changed the narrative of RS in India (Geevarghese et al., 2018).

2.3.6. Ecosystem services and threats

Seagrass habitats provide several ecological services and are crucial from a local communities’ perspective. Since these ecosystems contribute significantly to the local economy, evaluating the commercial chain generated by seagrass habitats is critical yet remains poorly studied in Indian waters (Thangaradjou, 2000; Thangaradjou et al., 2009; 2010d; Pradeebha et al., 2011; Nobi et al., 2016; Chanda et al., 2022). Traditionally, coastal communities of Kerala have been using seagrasses as fertilizers for coconut plantations (Asir et al., 2004, 2007; Sobithabai et al., 2005). Another interesting study on the nutritional value of seagrasses imply biochemical and calorific properties in seagrass leaves and rhizomes, equivalent to edible tubers and lentils (Pradeebha et al., 2011). This aspect of seagrass ecosystem services could be explored keeping human well-being as central.

Seagrass habitats are also economically crucial in 'trap netting' fishery in Palk Bay, Tamil Nadu (Thangaradjou et al., 2010d). Trap net fishery depends on seagrass habitats as the nets are deployed in the meadows, and this fishery contributes to family income of around 6000-15000 INR (25-320 USD) per month.

This work also highlights the negative impacts of fishing practices on seagrass habitats, which are altering the health of these habitats. According to Thangaradjou et al. (2009), monsoonal cyclones and destructive fishing practices primarily affect the meadows in Tamil Nadu. Boat anchorage was estimated to uproot approximately 1 kg of seagrass per anchor per day, while 25-40 kgs of seagrasses are lost daily to trawling and bottom set gill net operations.

Additionally, the destructive harvesting practice of *Tellina angulata*, a gastropod with promising economic value found in seagrass habitats, has resulted in the loss of 153 ha of meadows in two years (Thangaradjou et al., 2009). On the other hand, coastal developmental activities and pollution are concerning as in Lakshadweep, suspended solid disposal leading to eutrophication has affected the growth of seagrasses, which is further magnified by tourism activities (Thangaradjou et al., 2009). Seagrass habitats in the Andaman and Nicobar archipelago are prone to natural (Tsunamis, cyclones) as well as anthropogenic stressors such as intensive shipping and tourism (Thangaradjou et al., 2009; D'Souza et al., 2015).

2.3.7. Conservation measures and legislation

Conserving seagrasses through restoration remains one of the most crucial yet neglected in Indian waters. Thangaradjou (2000) and Patterson and D'Souza (2015) attempted seagrass restoration on an experimental basis in the Tuticorin coast, southern India yielding more than 75% success rate. In this earliest attempt, a patch of 1 km^2 of seagrass was transplanted successfully, indicating dissemination of such ideas to restore the other seagrass habitats in the region. A novel approach of axenic culturing of four seagrass species viz; *E. acoroides, S. isoetifolium, T. hemprichii,* and *Halodule pinifolia* has given a new dimension to seagrass research in India (Thangaradjou and Kannan, 2008a, b).

2.4. Research gaps and discussion

A thorough understanding of the socio-economic and ecological dynamics is critically required for effective seagrass management and conservation. The present review found significant areas of immediate concern revolving around aspects disparagingly lacking from Indian waters. A few of the critical features which require attention are as follows;

a) Survey and Monitoring**:** Recent reports of species distribution records (Savurirajan et al., 2015; Gole et al., 2022a) highlight the need for more seagrass exploration since, at present, seagrass research in India is sporadic. Long-term monitoring programs such as the Karumba Port monitoring program (Unsworth et al., 2009) should be taken as a reference, to assess micro and macro-level spatio-temporal changes and establish a wet and dry seasonal baseline for species in seagrass habitats in India. Such initiatives will help conservationists and policymakers to diligently regulate coastal developmental impacts on seagrass habitats (port construction, destructive fishing, dredging).

b) Addressing essential ecological gaps**:** Although studies now focus on seagrasses' spatial and distribution ecology, quantifying the seagrass-environment relationship needs to be more quantitative as most studies are descriptive.

***c) Ecological role as habitats for associated fauna*:** Most of the studies under this category are scattered and primarily focused on mega species such as dugongs and sea turtles (Kelkar et al., 2013; D'Souza et al., 2015). Very few assessments have detailed documentation on lesser-known faunal groups in seagrass meadows such as marine invertebrates (Jayabarathi et al., 2012; Chandra et al., 2018).

***d) Socio-ecological dimension*:** Seagrass habitats hold a substantial ethno-biological value, with millions of people largely dependent on utilizing livelihood resources offered by these habitats (Thangaradjou et al., 2010d). Local communities form a crucial knowledge repository due to their dependency on natural resources; thus, documentation of this information is critical in management and conservation yet substantially lacks from India.

***e) Assessment/quantification of threat*:** Seagrass-centric threat assessment is an understudied aspect of India, yet it is essential to inform management.

***f) Development and implementation of a conservation plan for the country*:** Once the significant data gaps, including ecology, habitat value, socio-economic dependency, and threats, are addressed, a comprehensive roadmap for seagrass conservation could be scaled for seagrass conservation in India.

CHAPTER 3: SPATIAL DISTRIBUTION PATTERNS OF SEAGRASSES IN THE ANDAMAN AND NICOBAR ISLANDS

3.1. Introduction

Diversity and distribution of seagrass is influenced by several regulatory factors, including benthic light availability, sediment profile, wave exposure, water temperature, and nutrient dynamics (Dennison and Alberte, 1987; Duarte, 1991; Malmer and Grip, 1994; Greve and Binzer, 2004). These factors play a crucial role in the growth and persistence of seagrass populations, as seagrasses rely on optimal light for photosynthesis, suitable sediments for proliferation, and nutrients for growth (Duarte, 2002). Resultant declines in seagrass populations are reported due to light reduction (Short and Wyllie-Echeverria, 1996), altered nutrient dynamics (Lee and Dunton, 2000), and wave action (Japar Sidik et al., 2018). Impacts of wave exposure are more prominently seen in intertidal zones, which are at the transition of land and sea. Only species able to cope with the heavy tidal fluctuations and associated parameters can thrive in these littoral zones, thus restricting the upslope distribution of seagrasses (Hemminga and Duarte, 2000). Variations in water temperature, whether seasonal or due to climate change (marine heat waves), are also known to influence seagrass photosynthesis and productivity (Barber and Behrens, 1985; Seddon and Cheshire, 2001; Díaz-Almela et al., 2009; Garrabou et al., 2022). Nevertheless, seagrasses exhibit wide-ranging acclimation strategies as a response to changes in their natural environment (Vermaat et al., 1997; Lee et al., 2007). An experimental study in the Philippines demonstrated that seagrass species have a varied tolerance to enhanced siltation and altered light irradiance in the water column (Bach, 1998; Terrados et al., 1998). Besides, the shift in turbidity levels resulted in local variation in seagrass diversity, growth, and depth limits. Accordingly, global research provides substantial evidence that natural variability in the environment influences seagrass ecosystems at local and regional scales.

Escalating seagrass loss reflects threats to these ecosystems and subsequent impacts on biodiversity and the local communities they support (see sections 1.2- 1.4). The widely accepted global seagrass distribution model classifies India into a diverse Indo-Pacific bioregion (Short et al., 2007). Additionally, the ecologically rich Andaman and Nicobar Islands (ANI) form the country's second most varied seagrass habitats (Thangaradjou and Bhatt, 2018). Seagrass meadows in ANI are crucial to supporting the dugong's remnant insular population (D'Souza et al., 2015). A recent study highlighted the importance of resource-rich seagrass beds for aggregating dugongs, possibly for calf protection (Gole et al., 2023a). Despite the crucial ecological significance of seagrass meadows, more information on their spatiotemporal changes, threats, and ecological and economic impacts in ANI must be provided. A report by Paulose et al. (2013) outlines the large-scale seagrass denudation in ANI (~1619 ha) caused by the Sumatra-Andaman earthquake and the 2004 Indian Ocean Tsunami. The severe deposition of marine debris from this disturbance has further altered the species distribution trends (Thangaradjou et al., 2010a). In addition, ANI is also a geologically vulnerable region, with reports of ~ 486 earthquakes (Richter scale > 4; United States

Geological Survey, 2023[3]) and 25 cyclonic storms/ depressions (Indian Meteorological Department, 2023[4]) that have recently hit the islands' coastline (2018 to 2022). Unfortunately, the extent of seagrass loss to these threats remains uncertain due to sparse and discontinuous spatial seagrass assessments in the Islands.

For effective seagrass management, the accuracy of spatial studies and robust ecological knowledge is of utmost importance. Detailed information on species' checklists, distribution ranges, depth limits, and, most importantly, regulatory factors governing distribution and growth is essential for translating seagrass science to management and conservation (International Seagrass Biology Workshop 13, 2013[5]; Mckenzie et al., 2020). A few significant challenges to studying seagrasses in ANI are the inaccessibility of sites to researchers, funds, and logistics required to perform marine surveys. Even after intensive prior research, a data gap is still reflected in many of the crucial management aspects of the region (see sections 1.5 and 2.4). Despite three decades of seagrass exploration and research, only limited studies have quantified the relationship between seagrass and the environment (Savurirajan et al., 2018). Likewise, recent reports of new species' local distribution and range (Savurirajan et al., 2015; Gole et al., 2022a) indicate more seagrass exploration to upgrade species checklist and distribution trends. As most of the seagrass meadows in ANI are recovering from the impact of the 2004

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[3] https://earthquakes.usgs.gov/(accessed on March 2023)

[4] https://mausam.imd.gov.in/(accessed on March 2023)

[5] https://wsa.seagrassonline.org/(accessed on January 2023)

tsunami, it is essential to update existing information on the species composition, distribution, and factors that determine the existing trends.

To address these knowledge gaps, this study aimed to investigate the spatial diversity and distribution patterns of seagrass meadows along the accessible coastline of ANI. Contrary to prior spatial assessments, I instead focused on studying the complex interactions of seagrass species with their natural environment. Thus, I aimed to understand the regulatory factors influencing local seagrass occurrence and distribution in ANI. By conducting a comprehensive assessment of seagrass ecology, this study will complement the existing knowledge on seagrasses and collectively contribute to developing effective management and conservation strategies for seagrass habitats in ANI.

3.2. Materials and Methods

3.2.1. Study area and site selection

I explored the coastal waters of ANI, ranging from a depth of 0.2 m (intertidal) to 37 m (deep waters), for seagrass presence between 2018 and 2022 (January to April). Three approaches were used to confirm seagrass presence: a) tapping local knowledge of fishers through community interactions, b) published literature and correspondences with prior seagrass researchers, and c) exploratory free dives or swims in potential sandy habitats. Based on the geographical proximity of the investigated regions, assuming these sites will have a shared environment for seagrasses, I broadly divided ANI into five island groups: 1) North and Middle Andaman (NMA), 2) South Andaman (SA), 3) Ritchie's archipelago (RA), 4) Little Andaman (LA), and 5) Nicobar Islands (NIC) (Figure 3.1).

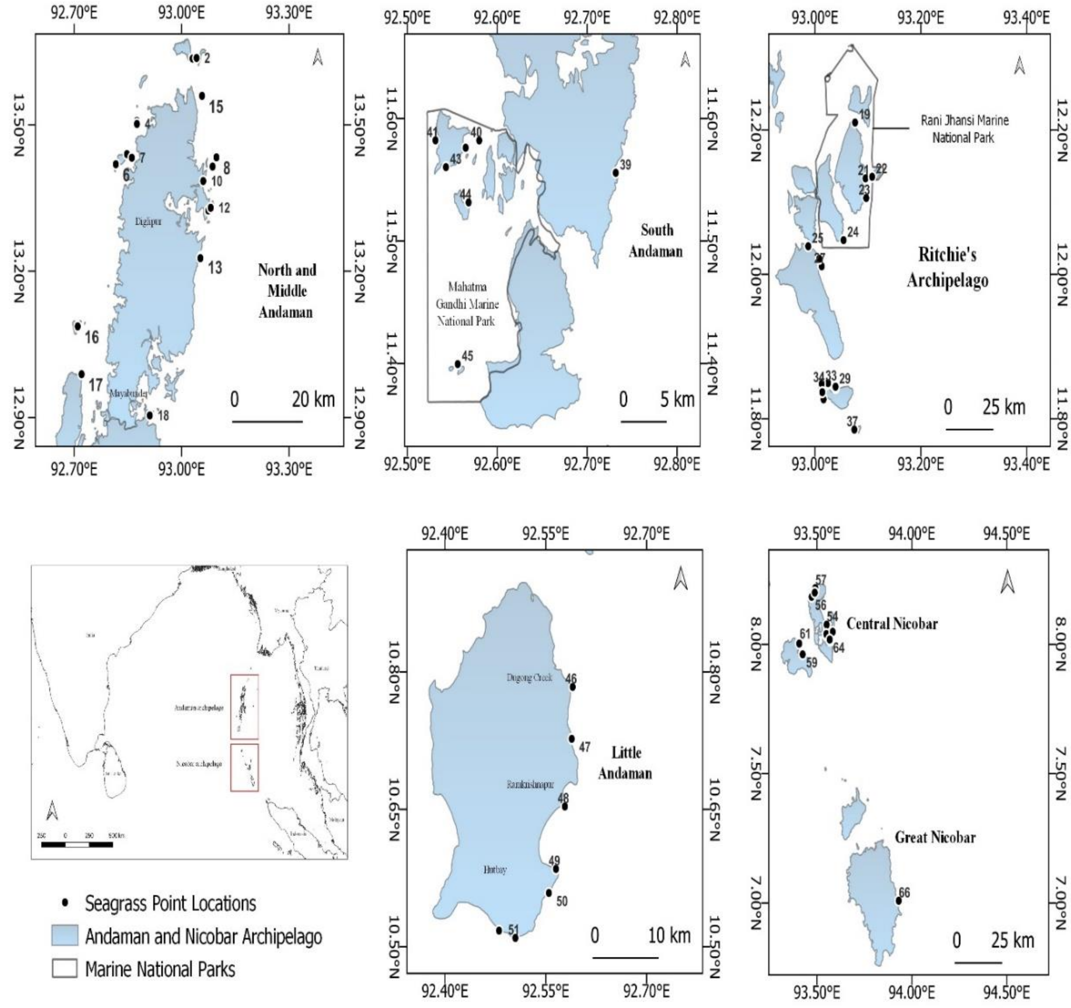

Figure 3.1: Seagrass distribution sites in the Andaman and Nicobar Islands [Sites codes and names in Annexure 2]

3.2.2. Field surveys

I conducted intertidal surveys (0.3 to 0.5 m) during the spring tides when the region was maximally exposed, extending to the reef ward edges. Subtidal exploration was performed using SCUBA diving-assisted surveys in shallow and deep waters. However, due to saltwater crocodile hotspots in more than 80% of the sampled regions, deepwater investigations were limited to approximately 10 m, except for RA, which has a flourishing tourism industry and diving-friendly sites, allowing efforts up to 37 m. Coasts with strong wave action that hindered SCUBA exploration were excluded from the study. The line intercept transects (LIT; English et al., 1997) method was employed for systematically sampling seagrass meadows after locating them intertidally and subtidally. I surveyed 18 sites from NMA (25 LITs), 19 sites from RA (44 LITs), 8 from SA (11 LITs), 7 from LA (14 LITs), and 14 from NIC (20 LITs). At each site, the 50 m long LITs were placed perpendicular to the shore, and spatial replicates (3 to 4 LITs) were spaced 150-200 m apart. Within each transect, a 50 x 50 cm quadrat was used at every 5 meters to record seagrass meadow characteristics, including species composition, total and species-specific seagrass cover, shoot density, shoot length, total biomass (above and below ground, dry weight), and algal cover (epiphytic and non-epiphytic).

In addition, I recorded the following predictor variables at each sampling point: water depth (using a Dive Computer for subtidal meadows), pH and water temperature (measured using a handheld multi-parameter tester - Eutech Oaklon-PCS Testr 35), and salinity (measured using a handheld refractometer - LABART). Major substrate types, such as sand, dead coral with macroalgae, rock, rubble, and live coral, were recorded from the same quadrat for fine-scale habitat characterization. The habitat profile was calculated as the mean cover (%) from each sampling point, and it was further classified as either homogenous (100% sand) or heterogenous (approximately 50% sand along with other substrate types). The seagrass meadows were characterized based on the three criteria: a) observed depth gradient, b) seagrass cover, and c) species composition. I classified meadows' depth profile as intertidal (0.2 to 0.5 m), shallow-subtidal (< 8 m), and deep waters (> 8 m; McKenzie et al., 2020). Based on the total seagrass cover, meadows were further profiled as a) sparse (0-25 % cover), b) moderate (25-50 % cover), c) dense (50-75 % cover) and d) very dense (75-100 % cover; Sabilah and Amran, 2020), and grouped as either mono-specific (single species) or mixed-species (2 or more co-occurring species).

3.2.3. Laboratory assessments

To estimate shoot density and total plant biomass (above and below ground), samples were collected from a 20 x 20 cm smaller quadrat within each transect (n= 3/ transect). The collected seagrass samples were stored in zip-lock bags and transported to the field base for further processing. Seagrass samples were rinsed to remove sediment particles and algae, and seagrass shoots (species-specific) were counted to estimate shoot densities (shoots/m^2). Lastly, samples were air-dried, and total biomass (above and below ground - g/m^2) was calculated on a micro-scale weighing balance (WENSAR PGB-220/ 0.001 to 200 g). Sediments were hand-scooped in triplicates from 0.4 m^2 within the sampled seagrass beds and air-dried for texture analysis to assess the habitat suitability of the seagrass species.

3.2.4. Data analysis

3.2.4.1. Step 1-Data normalization and collinearity: I used a generalized linear model (GLM) framework to elucidate the influence of 11 potential explanatory variables on four response variables, namely seagrass occurrence, cover, biomass, and density. Since the normal distribution was not observed for three quantitative response variables (seagrass cover, density, and biomass), the data were transformed using Z-score normalization. Before GLM, collinearity among the 11 quantified explanatory variables (water depth, pH, water temperature, salinity, epiphytic macroalgae, non-epiphytic macroalgae, sand, rubble, dead coral with macroalgae, live coral, and rock) was assessed using Variance Inflation Factor (VIF) values. The VIF value for sand, the primary substrate for seagrass occurrence and growth, was considerably higher than the other independent variables. Therefore, I conducted a bivariate regression analysis to determine the strength and relationship of other independent variables with sand (Table 3.1). I observed that the least important variables for seagrass growth, such as live coral and rock, correlated with sand (Table 3.1), so these two variables were removed from further analysis. The VIF values were rechecked, and it was found that all nine remaining explanatory variables exhibited low collinearity (VIF < 3), which is recommended for regression analysis (Bolker, 2008).

Table 3.1. Bivariate regression analysis carried out on 11 explanatory variables considered for the generalized linear model framework

	water depth	**pH**	**temp**	**sal**	**sand**	**ru**	**dca**	**cor**	**rock**	**non-epi. al**	**ep. al**
water depth	**1**	0.053	0.035	-0.121	0.203	-0.102	-0.123	0.023	-0.147	-0.146	0.014
pH	0.053	**1**	0.327$^{\#}$	-0.240	-0.124	-0.042	0.206	0.013	0.013	0.030	-0.181
temp	0.035	0.327$^{\#}$	**1**	-0.340$^{\#}$	-0.079	0.079	0.014	0.000	0.056	0.057	-0.141
sal	-0.121	-0.240	-0.340$^{\#}$	**1**	0.118	0.021	-0.115	-0.003	-0.100	0.020	0.112
sand	0.203	-0.124	-0.079	0.118	**1**	-0.472*	-0.636*	-0.332	-0.484*	-0.053	0.086
ru	-0.102	-0.042	0.079	0.021	-0.472	**1**	-0.045	0.015	-0.037	0.042	-0.023

dca	-0.123	0.206	0.014	-0.115	-0.636*	-0.045	**1**	0.075	-0.032	0.043	-0.024
cor	0.023	0.013	0.000	-0.003	-0.332$^{\#}$	0.015	0.075	**1**	0.024	-0.012	-0.010
rock	-0.147	0.013	0.056	-0.100	-0.484*	-0.037	-0.032	0.024	**1**	0.012	-0.108
non-epi. al	-0.146	0.030	0.057	0.020	-0.053	0.042	0.043	-0.012	0.012	**1**	-0.068
ep. al	0.014	-0.181	-0.141	0.112	0.086	-0.023	-0.024	-0.010	-0.108	-0.068	**1**

[values expressed as Spearman's correlation co-efficient, * indicates significant correlation, $^{\#}$ indicates moderate correlation; temp, sea surface temperature; sal, salinity; ru, rubble; dca, dead coral algae; cor, live coral; non-epi.al, non-epiphytic algae; ep. al, epiphytic algae]

***3.2.4.2. Step 2-Regression analysis*:** Assuming the response variable of seagrass occurrence follows a binomial distribution, an analysis was performed on the seagrass presence-absence matrix. An 'Intercept-only' model was created with the response variable, and nine independent models were built for each predictor variable versus seagrass occurrence (Johnson and Omland, 2004). I excluded models with Akaike Information Criterion (AIC) values higher than the 'Intercept-only' model from further analysis (Johnson and Omland, 2004; Arnold, 2010). I then generated different combinations of informative models, and the model with the lowest AIC value and highest corresponding AIC weight was selected as the best-fit model. For quantitative variables, I assumed that the normalized data (Z-score) for seagrass cover (mean percentage), shoot densities (shoots/ 0.04 m^2), and seagrass biomass (above and below dry weight, gm/ 0.04 m^2) followed a Gaussian distribution. Thus, GLM analyses were performed on their respective matrices. However, the AIC values of informative models were similar, making it challenging to select one best-fit model and potentially discard relevant explanatory variables. To overcome this, I employed an information-theoretic model averaging approach. I created multiple combinations of models using the function 'dredge' in the Mumin package in R (version 4.2.1). 512 models were created for each seagrass cover, density, and biomass. The models with the lowest AIC and AIC delta < 2 (indicating a slight difference in AIC values) were averaged (Burnham and Anderson, 2002), providing a more robust understanding of the influence of potential explanatory variables on seagrass cover, density, and biomass.

***3.2.4.3. Step 3-Species habitat and substratum preference*:** Canonical Correspondence Analysis (CCA) allows exploring relationships between species abundances and environmental variables. I performed CCA on the species-densities matrix to assess the impact of habitat and sediment profile on seagrass species densities. All data analysis was conducted in R (version 4.2.1) using packages such as *CAR*, *AICcmodavg*, and *ggplot2*. Functions like *glm*, *AIC*, *Loglik*, and *aictab* were utilized to perform GLM analysis, calculate AIC values and likelihoods, and create plots (R core development team, 2019[6]).

3.3. Results

3.3.1. Spatial distribution of seagrasses

The Andaman and Nicobar Islands coastal waters host 12 species of seagrasses, of which I report 11 species. These species occurred in 66 seagrass meadows across 34 islands of five Island clusters (Table 3.2). Seagrasses exhibited varying distribution patterns, ranging from dense, continuous beds to moderate and sparse stands. They were found in both homogeneous and heterogeneous habitats across different depth gradients. Among the identified species, *Halophila ovalis* and *Halodule pinifolia* demonstrated the most comprehensive distribution range, spanning from Landfall (Site 1), the northernmost limit, to Great Nicobar Islands (Site 66), the southernmost limit (Figure 3.1, Annexure 2). These two species collectively occurred in over 50% of the investigated meadows. Following them, *Halodule uninervis* (34.8%), *Thalassia hemprichii* (31.8%), and *Cymodocea rotundata* (19.7%) were the

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[6] https://www.R-project.org/(accessed on December 2022)

following most frequently encountered species (Annexure 2). However, the spatial spread of the remaining six species was relatively limited. An interesting finding was the rare occurrence of *H. beccarii*, observed only once at Pokkadera (Site 18) (Figure 3.1), indicating its scarcity in the studied areas. *Syringodium isoetifolium* exhibited a restricted distribution, being confined to just five sites: Jua Tekdi (Site 21) and Vijay Nagar (Site 27) in the RA, and the shallow waters of Kardip (Site 53), Trinket (Site 63), and Al-Reak (Site 64) in the Nicobar Islands (Figure 3.1, Annexure 2). Notably, *C. serrulata* was absent in the NMA sites, while *H. minor* and *Enhalus acoroides* were exclusively found in the RA and NIC regions (Annexure 2). In the Nicobar Archipelago, I observed the highest seagrass coverage and total plant biomass in the shallow subtidal meadows of Safed Balu and Kardip, respectively (Annexure 2). Shoot densities, however, were the highest in the mixed intertidal meadow of Vijay Nagar (6392.5 ± 672.5 shoots/ m^2).

Table 3.2. Island-wise summary of seagrass meadow characteristics in the Andaman and Nicobar Islands, India

Island group	**Sites**	**New Seagrass beds**	**Sampling Range**	**Species Richness**	**Species Composition**	**Water Depth Range (m)**	**Total Cover (%)**	**Total biomass (dry wt.; g/0.04m^2; mean ± SE)**	**Shoot density (shoots/ m^2; mean ± SE)**
North and Middle Andaman	18	10	13°38'7.91"N, 93° 1'50.66"E to 12°54'15.44"N, 92°54'40.50"E	8	*Hb, Hd, Ho, Hu, Hp, Cr, Th, Ea*	0.4 to 8.5	32.9	87.2 ± 51.4	1448.8 ± 212.4
Ritchie's archipelago	19	12	12°12'37.84"N, 93° 4'31.94"E to 11°47'4.81"N, 93° 4'26.94"E	10	*Ho, Hd, Hm, Hu, Hp, Cr, Cs, Th, Ea, Si*	0.2 to 21.5	28	131.8 ± 82.5	1147.9 ± 313.9
South Andaman	8	2	11°40'55.56"N, 92°43'32.12"E to 11°23'58.12"N, 92°33'21.65"E	6	*Ho, Hu, Hp, Cr, Cs, Th*	0.2 to 6.6	32.8	55.5 ± 28.5	2124.7 ± 427.3
Little Andaman	7	2	10°47'1.00"N, 92°35'23.89"E to	6	*Ho, Hu, Hp, Cr, Cs, Th*	0.1 to 0.5	35.8	158.2 ± 35.9	2556.4 ± 488.7

			10°30’49.21”N, 92°29’39.82"E						
Nicobar	14	6	8°2’21.88”N, 93°32’55.61”E to 7°0’31.25”N, 93°55’49.58"E	10	*Ho, Hd, Hm, Hu, Hp, Cr, Cs, Th, Ea, Si*	0.2 to 5	44.5	870.1 ± 306	1764.2 ± 288.9

[Cr, *Cymodocea rotundata*; Cs, *Cymodocea serrulata*; Ea, *Enhalus acoroides*; Hb, *Halophila beccarii*; Hd, *Halophila decipiens*; Hm, *Halophila minor*; Ho, *Halophila ovalis*; Hp, *Halodule pinifolia*; Hu, *Halodule uninervis*; Si, *Syringodium isoetifolium*; Th, *Thalassia hemprichii*]

3.3.2. Species distribution across depth gradients

Seagrass meadows in the study area exhibited a range of depth wise distribution trends, occurring from the littoral zone (n=17) to subtidal regimes, shallow-subtidal (n=39), and deep waters (n=10, Annexure 2). Most NMA, SA, and NIC meadows were found in shallow-subtidal areas (Annexure 2). Deepwater seagrass beds were restricted to RA, except Delgarno in the NMA (Table 3.2, Figure 3.1). In LA, seagrasses were exclusively intertidal and distributed along the island's northeastern to southern coast (Figure 3.1). No subtidal seagrasses were detected along Little Andaman's West and North coasts. Intertidal and shallow-water seagrass meadows exhibited similar species richness, with ten species each, of which nine species were overlapping between the two zones. The exceptions were *H. beccarii*, which was restricted to intertidal regions (0.4 m), and *H. decipiens*, which occurred exclusively in subtidal zones (3 to 21 m). *T. hemprichii* and *C. rotundata* were dominant species in the intertidal meadows (0 to 0.5 m), occurring with 88 % and 59 % frequency rates, respectively. However, *T. hemprichii* was observed colonizing down to a depth of 2.5 m. *E. acoroides*, *Cymodocea* spp., and *S. isoetifolium* had a downslope limit of 5 m, beyond which these species were not found. The *Halophila* spp. + *Halodule* spp. complex, excluding *H. beccarii*, dominated the depth regimes beyond 5 m, accounting for approximately 96 % of the observed occurrences, particularly within the 8-15 m (Figure 3.2, Annexure 2). In the shallow- subtidal seagrass beds, *H. ovalis* was the most frequent species (66 % occurrence rate), followed by *Halodule pinifolia* (50

%) and *Halodule uninervis* (39 %). *H. ovalis* also dominated the deepwater meadows, occurring in ~ 80 % of the sites.

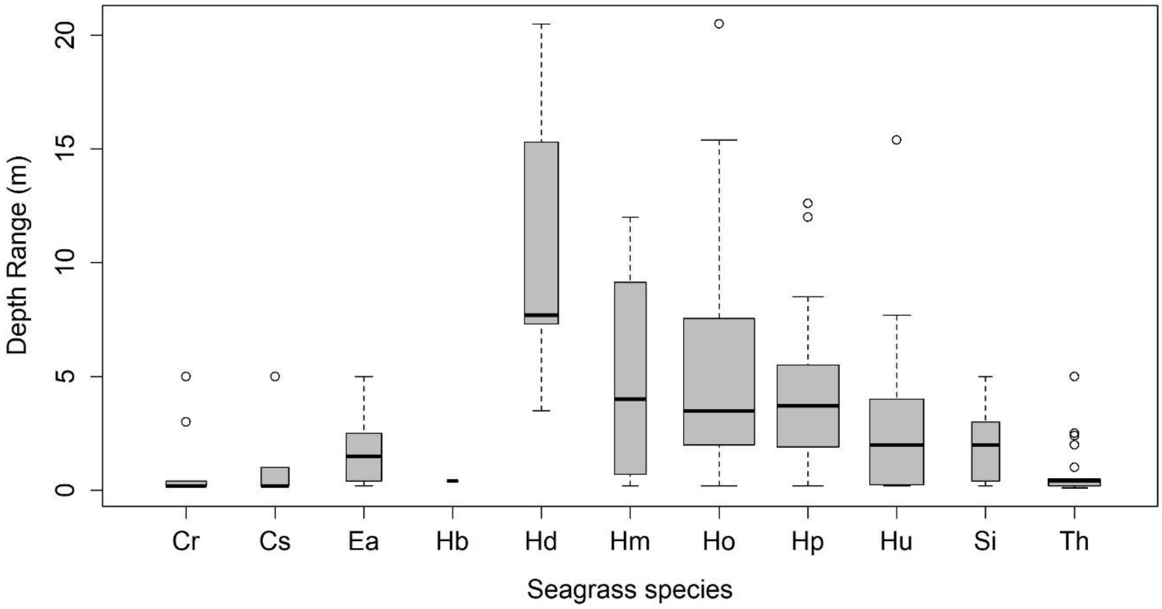

Figure 3.2: Depth specific distribution trends of seagrass species [Cr, *Cymodocea rotundata*; Cs, *Cymodocea serrulata*; Ea, *Enhalus acoroides*; Hb, *Halophila beccarii*; Hd, *Halophila decipiens*; Hm, *Halophila minor*; Ho, *Halophila ovalis*; Hp, *Halodule pinifolia*; Hu, *Halodule uninervis*; Si, *Syringodium isoetifolium*; Th, *Thalassia hemprichii*]

3.3.3. Meadow species composition and distribution trends

Based on depth profile and species composition, I classified the observed seagrass meadows into six categories; (1) Intertidal, mono-species meadows (n=4), (2) Intertidal, mixed-species meadows (n=13), (3) Shallow, mono-species meadows (n=15), (4) Shallow, mixed-species meadows (n=24), (5) Deep, mono-species meadows (n=3), (6) Deep, mixed-species meadows (n=7). Of the 66 meadows, 44 were mixed-species, while 22 were mono-specific (Annexure 2). A clear trend of decreasing seagrass species richness and coverage with increasing water depth was observed. Mixed-species beds exhibited dense coverage and were limited to intertidal and shallow waters (Annexure 2). In contrast, single species dominated all depth regimes but rarely formed dense meadows. In Category 1, *T. hemprichii* was the dominant species in the sparse to moderate seagrass beds found in the heterogeneous habitats of RA and SA (Annexure 2). In category 3, *H. ovalis* accounted for 40 % of the sparse to moderate, mono-species meadows along with *C. rotundata, H. decipiens, H. minor, H. ovalis, Halodule pinifolia,* and *Halodule uninervis*. Similarly, *H. ovalis, H. minor*, and *Halodule pinifolia* formed deep water, and mono-species stands in category 5 (Annexure 2).

The species 50richness in mixed-seagrass meadows ranged from at least two to eight species. Interestingly, I found that the probability of two co-occurring species was more frequently observed (> 50% of meadows) than a greater number of species in a single mixed-species meadow. Six species exhibited the highest co-occurring tendencies; ‘*Halophila* spp. with *Halodule* spp.’ (in all-depth regimes), ‘*T. hemprichii* with *C. rotundata*’ (in intertidal habitats), and ‘*S. isoetifolium* with *E. acoroides*’ (in intertidal habitats). Three to eight co-occurring species characterized intertidal, mixed meadows (category 2) and showed a wide range of seagrass coverage ranging from sparse to very dense (Annexure 2). Particularly within this category, I observed highly diverse (4 to 8 co-occurring species), dense, and contiguous seagrass meadows in sheltered bays such as Jua Tekdi (Site 21), Vijay Nagar (Site 27), Haddo (Site 38), Burmanallah (Site 39), and Light House-South Bay (Site 51) (Figure 3.1, Annexure 2). Except for Haddo, all other intertidal seagrass-rich sites exhibited habitat heterogeneity (Annexure 2). The mixed-species meadows of categories 4 and 6 predominantly harbored *Halophila* spp. and *Halodule* spp. complex.

3.3.4. Habitat-sediment characterization and species' affinities

Seagrasses were predominant in five habitat types: sand, rubble, dead coral with macroalgae, rock, and live coral (Figure 3.3, Annexure 2). The sediment texture consisted of fine and coarse sand, clay, and silt. Homogeneous seagrass beds exhibited high siltation and turbidity. Sites in NMA and NIC were predominantly homogeneous, while LA and SA indicated habitat heterogeneity. RA displayed a more diverse habitat profile with homogeneous and heterogeneous benthic profiles (Annexure 2). Seagrass patches in sites with fine sand were often found around dunes formed by crustacean burrows, such as Pokkadera, Dolphin, Temple, Nemo Reef, and Imli Dera (Figure 3.1). The presence of habitat heterogeneity supported highly diverse and extensive mixed-species meadows. The dominant non-epiphytic macroalgae were the *Padina* spp., followed by *Halimeda* spp. and *Caulerpa* spp. Epiphytic algal cover varied from thin or dense matt algal film over seagrass shoots. I observed the epiphyte *Melobsia* spp. on *T. hemprichii* shoots in Laxmanpur, Natural Bridge, and Burmanallah (Figure 3.1). 14 seagrass sites, mainly from NMA and RA, exhibited a high cover of mat-forming algae on shoots and the seabed (Annexure 2).

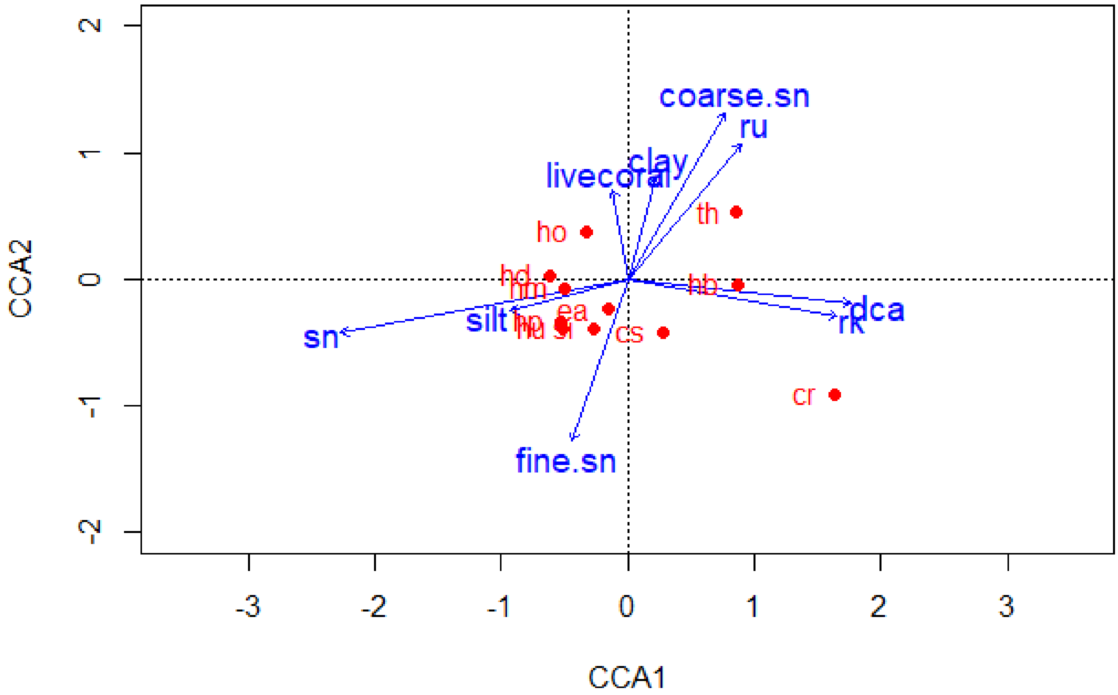

Figure 3.3: Canonical Correspondence Analysis ordination showing the influence of habitat profile and sediment texture on seagrass species' shoot densities [sn, sand; fine.sn, fine sand; rk, rock; dca, dead coral with macroalgae; coarse.sn, coarse sand; ru, rubble; cr, *Cymodocea rotundata*; cs, *Cymodocea serrulata*; ea, *Enhalus acoroides*; hb, *Halophila beccarii*; hd, *Halophila decipiens*; hm, *Halophila minor*; ho, *Halophila ovalis*; hp, *Halodule pinifolia*; hu, *Halodule uninervis*; si, *Syringodium isoetifolium*; th, *Thalassia hemprichii*]

Seagrass species' densities clustered according to their habitat and substratum preferences, with Axes 1 and 2 of the CCA plots explaining a cumulative variance of 76. 32 % (54.96 % and 21.36 %, respectively). While most species were dominant along a sediment gradient of sand, silt, and fine sand, distinct preferences for *H. ovalis*, *T. hemprichii*, and *C. rotundata* densities were observed. *H. ovalis* showed higher shoot densities in sandy substrata mixed with clay. It also occurred sparsely around the fringes of coral reefs in subtidal meadows (Figure 3.3). *H. decipiens* and *H. minor* displayed a strong preference for sandy habitats. *H. beccarii* was observed as a one-time occurrence in a muddy substratum, occupying fine sand mixed with mud near the high tide edges of Pokkadera (Site 18, Figure 3.1). *E. acoroides* and *S. isoetifolium* were positively associated with fine sand, while *Halodule* spp. was predominantly observed in silt. *T. hemprichii, C. rotundata,* and *C. serrulata* favored heterogeneous habitats of sand, rock, dead coral with macroalgae, and rubble across all sites (Figure 3.3). However, there were differences in microhabitat preferences among these species. *T. hemprichii* densities correlated with coarse sand mixed with rubble, while *C. rotundata* was found in coarse sand as random sparse stands interspersed within the rubble, dead coral with macroalgae, and rocks. Additionally, *C. rotundata* and *C. serrulata* also preferred fine sand in shallow waters or the upper edges of intertidal zones (Figure 3.3).

3.3.5. Factors influencing seagrass distribution and meadow characteristics

I used multiple regression models to examine factors influencing seagrass distribution and meadow characteristics (seagrass occurrence, cover, biomass, and shoot densities). Water depth and sand (except for shoot densities) were the key environmental variables significantly predicting all response variables. Seagrass occurrence was found to decline with water depth (*p* value = 3.72e-15), as well as the presence of dead coral with macroalgae (*p* value = < 2e-16) and rubble (*p* value = 3.88e-10) (Table 3.3, Figures 3.4A to C). However, sand positively associated with seagrass occurrence (*p* value = < 2e-16, Table 3.3, Figure 3.4D).

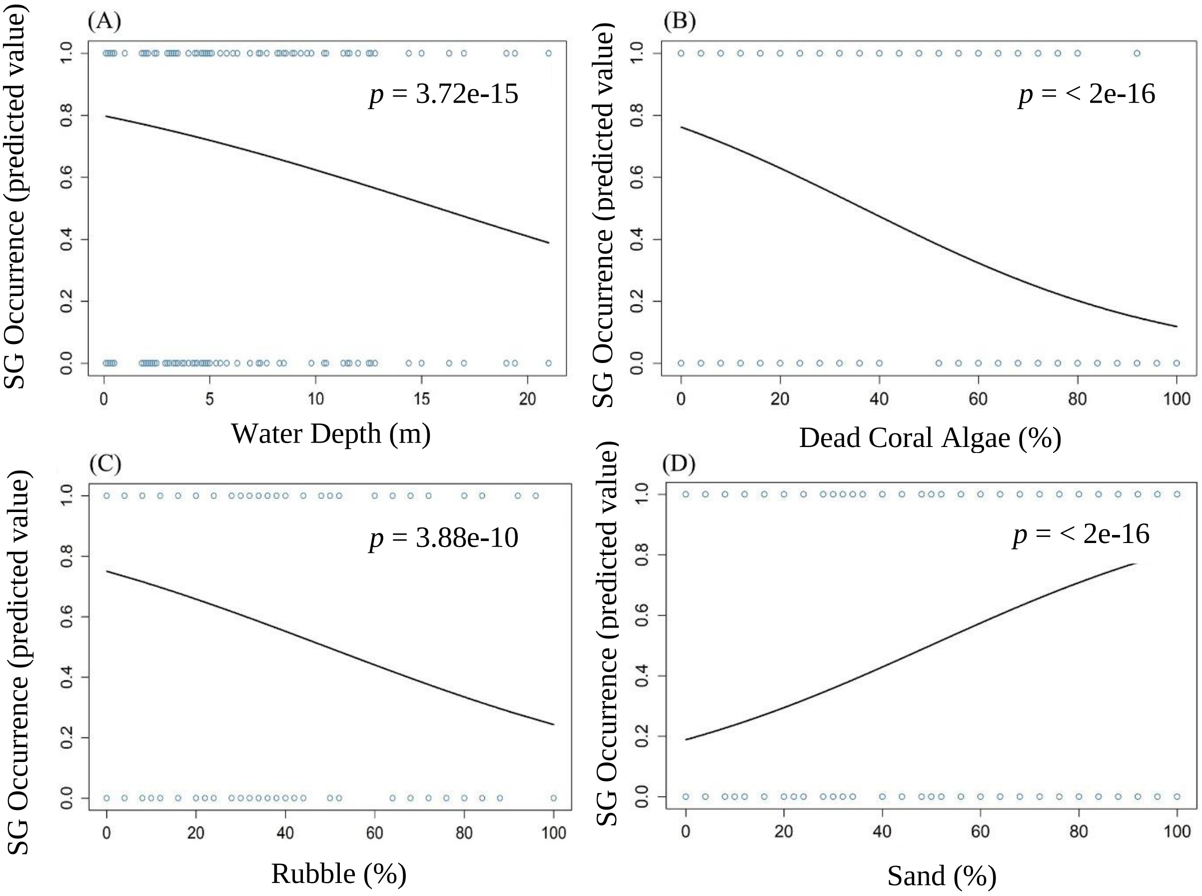

Figure 3.4: Influence and nature of the relationship between seagrass occurrence and (A) water depth, (B) dead coral with algae, (C) rubble, and (D) sand [SG-Seagrass]

Table 3.3. Summary of logistic linear models used to identify critical explanatory variables influencing seagrass occurrence in the Andaman and Nicobar Islands, India.

Sr. No.	**Model combination**	**AIC**	**LogIik**	***p* value**
1	seagrass occurrence vs. sand	1566.404	-781.1982 (df=2)	< 2e-16 ***
2	seagrass occurrence vs. dead coral algae	1682.356	-839.1738 (df=2)	<2e-16 ***
3	seagrass occurrence vs. water depth	1723.925	-859.9586 (df=2)	3.72e-15 ***
4	seagrass occurrence vs. rubble	1745.774	-870.8831 (df=2)	3.88e-10 ***
5	seagrass occurrence vs salinity	1765.806	-880.8991 (df=2)	6.12e-06 ***
6	seagrass occurrence vs pH	1767.476	-881.7339 (df=2)	1.89e-05 ***
7	seagrass occurrence vs. temperature	1781.31	-888.6509 (df=2)	0.025623 *
8	seagrass occurrence vs. epiphytic algae	1782.1	-889.0459 (df=2)	0.0454 *
9	Intercept model	1784.224	-891.1107 (df=1)	
10	seagrass occurrence vs non-epiphytic algae	1786.223	-891.1073 (df=2)	0.935

Sr. No.	**Additive Models**	**AIC**	**AIC delta**	**AIC weights**	**LogIik**	**McFadden's R**
1	**seagrass occurrence vs. water depth+ dead coral algae+rubble+sand**	**1421.8**	**0**	**0.65**	**-705.4889 (df=6)**	**0.21**

2	seagrass occurrence vs. water depth+ dead coral algae+rubble+sand+epiphytic algae	1423.0	1.5	0.30	-705.4889 (df=6)	0.21
3	seagrass occurrence vs. water depth+ ph+temperature+salinity+dead coral algae+rubble+sand+epiphytic algae	1426.4	5.2	0.05	-704.2162 (df=9)	0.21

[*Indicate significant *p* values; bold denotes selected best-fit model]

Water depth exhibited a similar correlation with seagrass cover (β = -0.2759; SE = 0.02471; *p* value = < 2e-16), shoot densities (β = -0.3556; SE = 0.1231; *p* value = 0.005) and biomass (β = -0.3526; SE = 0.1159; *p* value = 0.003). These variables decreased from littoral zones to deep waters (Table 3.4, Figures 3.5A to C). On the other hand, seagrass cover (β = 0.2924; SE = 0.03124; *p* value = < 2e-16) and biomass (β = 0.295; SE = 0.1171; *p* value = 0.01) showed a positive relationship with the availability of sand (Table 3.4, Figures 3.6A and B). Furthermore, seagrass cover and biomass exhibited a positive correlation with the presence of epiphytic algae (β = 0.136, SE = 0.0244, *p* value = < 2e-16) and water temperature respectively (β = 0.4235, SE = 0.1103, *p* value = 0.0002) (Table 3.4, Figures 3.6C and D). Lastly, I observed a peak in seagrass biomass at approximately 2.5 m depth, with the highest coverage and shoot densities recorded up to 5 m depth (Figures 3.7A to C).

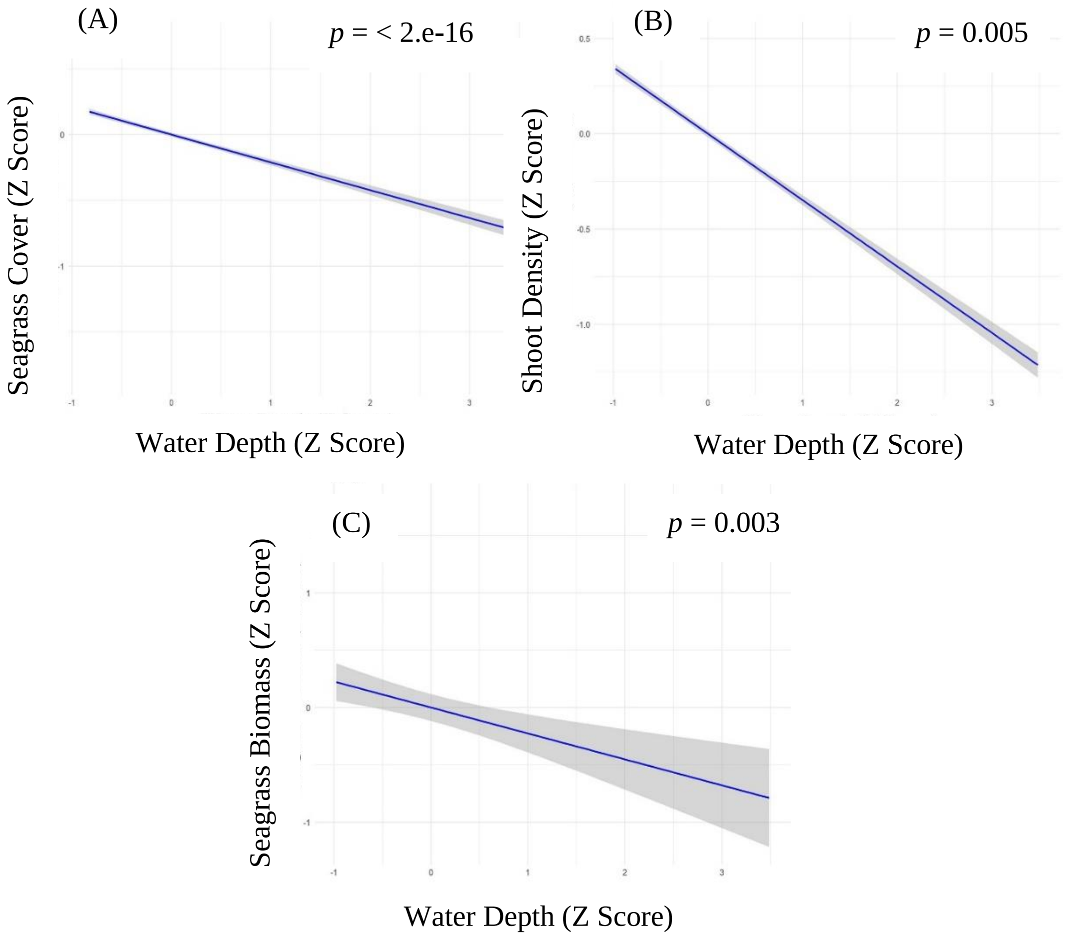

Figure 3.5: Relationship between water depth with (A) seagrass cover (Z-score values), (B) shoot density (Z-score values) and (C) seagrass biomass (Z-score values)

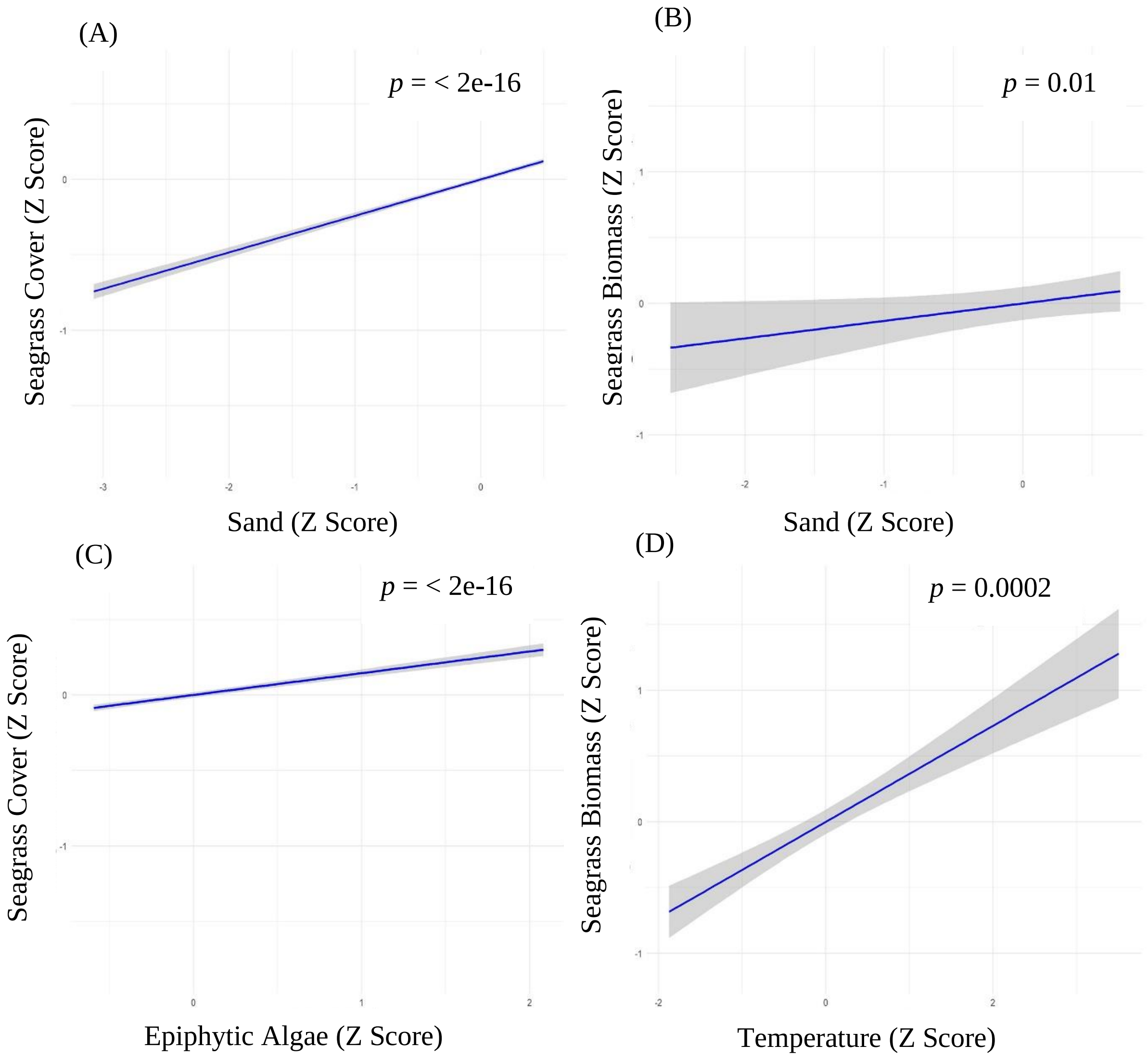

Figure 3.6: Relationship between Sand with (A) seagrass cover (Z-score values), and (B) seagrass Biomass (Z-score values), (C) Epiphytic Algae on seagrass cover (Z-score values), (D) Water temperature on seagrass biomass (Z-score values)

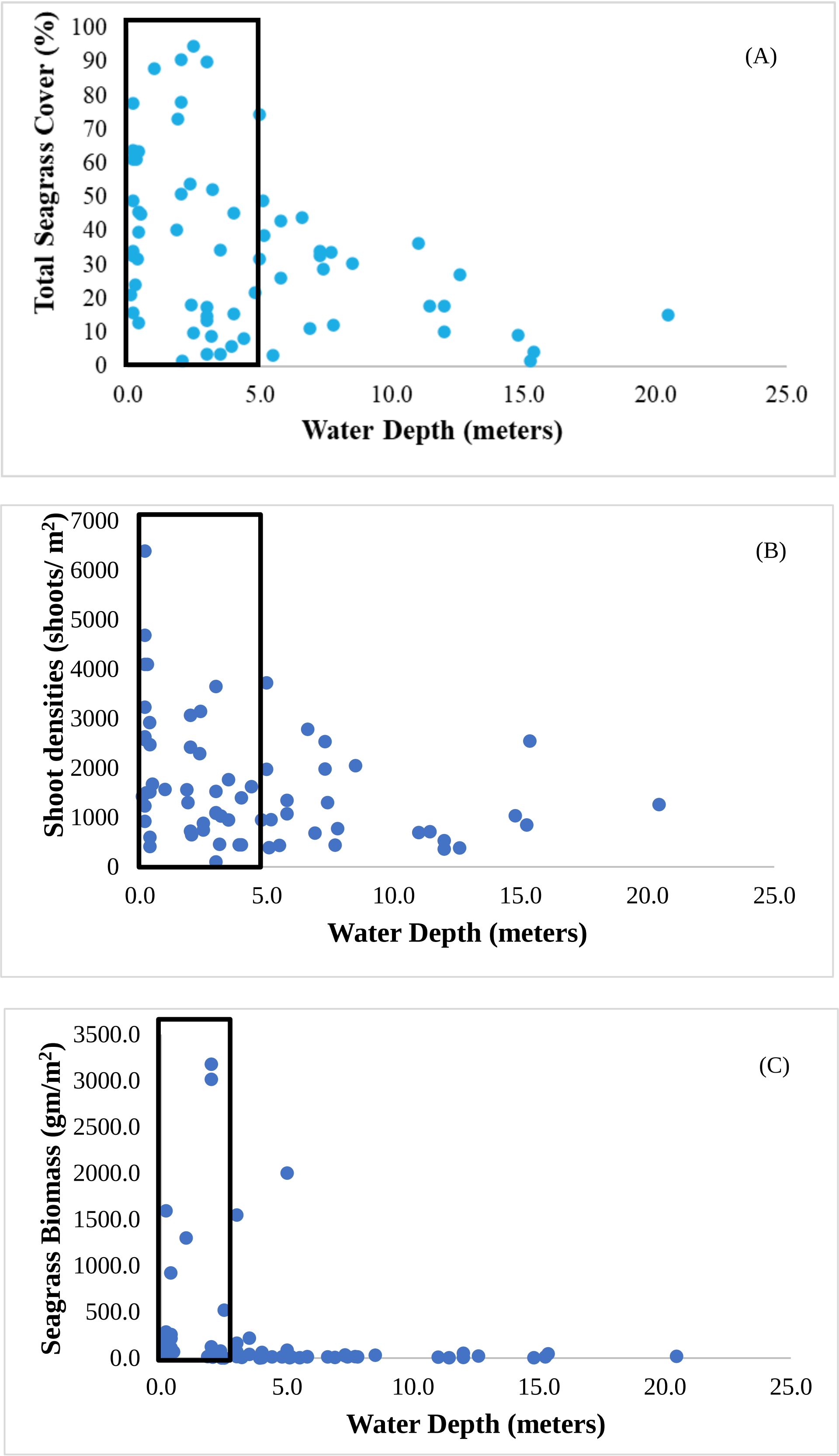

Figure 3.7: Response of seagrass growth; (A) seagrass cover, (B) shoot densities, and (C) biomass in relation to water depth; box indicates threshold depth limits with maximum values of response variables

Table 3.4. Summary of Gaussian model-averaged coefficients (full average) explaining the influence of each explanatory variable on seagrass cover, biomass, and shoot densities [Model-averaging pre-criterion= AIC delta < 2]

Quantitative response variable	**Predictor variables**	**Estimate**	**Std. Error**	**Adjusted SE**	**z value**	**Pr(>|z|)**
Seagrass cover	(Intercept)	2.13E-10	2.37E-02	2.38E-02	0	1
	Water depth	-2.76E-01	2.47E-02	2.47E-02	11.156	<2e-16 *
	Sand	2.92E-01	3.12E-02	3.13E-02	9.354	<2e-16 *
	Epiphytic Algae	1.36E-01	2.44E-02	2.44E-02	5.57	<2e-16 *
	Temperature	3.17E-02	3.05E-02	3.05E-02	1.036	0.3
	pH	3.33E-02	3.00E-02	3.00E-02	1.109	0.267
	Non-Epiphytic Algae	1.26E-02	2.16E-02	2.16E-02	0.58	0.562
	Dead Coral Algae	-1.06E-02	2.38E-02	2.39E-02	0.443	0.658
	Rubble	8.26E-03	1.98E-02	1.98E-02	0.418	0.676
	Salinity	-1.66E-02	2.48E-02	2.49E-02	0.667	0.505
Seagrass biomass		**Estimate**	**Std. Error**	**Adjusted SE**	**z value**	**Pr(>|z|)**
	(Intercept)	3.50E-11	1.08E-01	1.10E-01	0	1
	Sand	2.95E-01	1.17E-01	1.19E-01	2.47	0.013521 *

	Temperature	4.24E-01	1.10E-01	1.13E-01	3.764	0.000167 *
	Water depth	-3.53E-01	1.16E-01	1.18E-01	2.984	0.002849 *
	Epiphytic algae	2.08E-02	6.82E-02	6.92E-02	0.301	0.763477
Seagrass shoot densities		**Estimate**	**Std. Error**	**Adjusted SE**	**z value**	**Pr(>|z|)**
	(Intercept)	5.78E-11	1.16E-01	1.18E-01	0	1
	Water depth	-3.56E-01	1.23E-01	1.25E-01	2.837	0.00456 *
	Salinity	4.84E-02	9.77E-02	9.86E-02	0.491	0.62343
	Sand	3.94E-02	9.14E-02	9.24E-02	0.426	0.66981
	Dead Coral Algae	-1.13E-02	5.18E-02	5.24E-02	0.215	0.82941
	Epiphytic algae	9.00E-03	4.68E-02	4.74E-02	0.19	0.84951

[*Indicate significant p-values]

3.4. Discussion

The spatial diversity, distribution, and growth of seagrasses in the explored meadows are primarily determined by water depth, habitat heterogeneity, and substrate availability. The findings reveal significant variations in species richness between intertidal/shallow and deepwater meadows, with the former supporting higher species (10) than the latter (4). All 11 observed species were found up to a depth of 5 m in mono-species or mixed meadows. Beyond this depth, the species composition shifted towards exclusive dominance of *Halophila* spp. and *Halodule* spp. complex, with *Halophila ovalis* and *H. decipiens* marking the deepest recorded seagrasses from the study area (ANI), reaching depths of 21 m. While the general depth limits for Indo-tropical seagrasses are commonly less than 10 m (Short et al., 2007), the present findings, along with regional studies from Hervey Bay and Cape York (Queensland), the Red Sea, and the Mediterranean Sea, indicate region-specific deepwater trends (den Hartog, 1971; Lee Long et al., 1996; Short et al., 2007). *Halophila* spp. has been recorded from depths of 50 m in the tropical Atlantic region, 70 m in the Red Sea (Short et al., 2007), and 90 m in the Coral Sea (den Hartog, 1971) highlighting the species' adaptability to deeper regimes. Additionally, *H. decipiens* has been reported from 58 m in the Great Barrier Reef (Lee Long et al., 1996), while *H. ovalis* is commonly observed beyond 35 m (Coles et al., 2000). The deepest recorded seagrass sample to date is a one-time dredged sample of *H. stipulacea* from 145 m (Lipkin et al., 2003; Short et al., 2007). My findings are, thus, consistent with global evidence, supporting the notion that *Halophila* spp. and *Halodule* spp. are adaptive to depths.

Although the observed depth-scaled distribution trends are consistent with previous local and regional assessments from ANI and mainland India (Jagtap, 1996, 1998; Das, 1996; D'Souza et al., 2015), I report some stark contrast for a few species' regional colonization depths. For instance, Jagtap et al. (2003) reported *Thalassia hemprichii* and *Cymodocea serrulata* from a depth range of 0-10 m in Southeast India, as opposed to restricted littoral distribution in my study (with one-time observations from 2.5 m and 5 m, respectively). Similarly, the compensation depth of *Halodule uninervis*, one of the deepest species from the present study sites (15 m), was 3 m from Tamil Nadu (Jagtap et al., 2003). These differences may be driven by local variations in the physical environment of the two regions. Palk Bay and the Gulf of Mannar in Tamil Nadu have a shallow continental shelf, a vast seagrass expanse (often 5 to 10 km from the shore), and a tidal amplitude of around 0.3 to 0.5 m (Geevarghese et al., 2018). In contrast, in ANI habitat discontinuity, narrow shelf and sharp depth slopes (a few meters from the shore) result in irregularity in seagrass distribution (Das, 1996; Geevarghese et al., 2018). Considering the limited physical variation in Tamil Nadu, water depth likely plays a lesser role as a regulatory variable in shaping the distribution of seagrass species. Nevertheless, in ANI, I propose that water depth favors certain adaptive species over others, thus influencing the colonization depths of seagrasses (Lee et al., 2007; Short et al., 2011).

Furthermore, depth regulates the species' distribution ranges and plant growth in this study. Overall, seagrass coverage, shoot densities, and community biomass declined in deep waters (critical limit between ~ 2 to 5 m), consistent with reports from other geographic regions such as the Southeast coast and insular systems (Lakshadweep) of India (Jagtap, 1996, 1998), north-western Cuba (Buesa, 1975), and from the Mediterranean Sea (Drew, 1978). As light attenuates strongly in deeper waters, the observed variations are a possible outcome of differential traits of seagrasses to adapt to depths (Lee et al., 2007; Short et al., 2011; Minguito-Frutos et al., 2023). Seagrass depth penetration and growth are directly influenced by light availability (Ziemann, 1980; Duarte, 1991), owing to which conducive growth environment declines in the subtidal regions (Dennison and Alberte, 1987). Within similar environmental conditions, species-specific variation in colonization depths is a response to range of factors such as plant architecture, growth strategies, physiological responses, and acclimation potential (Dennison et al., 1993; Alcoverro et al., 2001; Greve and Binzer, 2004; Bité et al., 2007; Silva et al., 2013; Kilminster et al., 2015; Schubert et al., 2018; Tuya et al., 2019). A synthesis of the seagrass-water depth relationship indicates that seagrasses restrict their rhizome development in deeper regimes, with subsequent growth reduction (Duarte, 1991). This ability is highly pronounced in pioneer, small-sized species with fast recolonization rates, allowing them to cope in deeper regimes. For instance, *Halophila* spp. and *Halodule* spp. can more efficiently regulate their respiratory demands in depths than large-sized seagrass species (Fourqurean et al., 1995). Therefore, deep water colonization of *Halophila* and *Halodule* species complex in my study could be accounted for higher acclimation potentials at greater depths (Minguito-Frutos et al., 2023). Since light attenuation is not the only predictor of depth distributions (Koch, 2001), on the way forward, it would be critical to understand the fine-scale mechanisms that allow the dominance of one species over the other across variable depth regimes.

Additionally, I suggest that seagrass distribution is a product of habitat heterogeneity and substratum suitability from the sampled meadows. Heterogeneous habitats in the islands support a higher species richness (Das, 1996; Savurirajan et al., 2018). My study reveals that variabilities in substratum types and habitat heterogeneity allowed different species to dominate various spatial niches. Meadows with less substratum variability, such as those found in Little Andaman, Burmanallah, Laxmanpur, and Natural Bridge, had a vast extent but supported lower species richness. The investigation of sediment texture affinities of seagrass species partially agrees with a previous study by Savurirajan et al. (2018), which also reported high densities of *H. ovalis* in sand and clayey substrates. However, I observed *T. hemprichii*, *E. acoroides*, and *Halodule pinifolia* occupying coarse sand, fine sand, and silt, respectively, contrary to their preference for clayey sand in the previous study. It is important to note that the study by Savurirajan et al. (2018) focused on intertidal waters (< 2 m), while my study spanned depths up to 21 m. Therefore, the differences in spatial scale and sample sizes may contribute to the variations in results between the two studies. Moreover, I suggest that habitat and substratum profiles change from intertidal to deeper waters, limiting direct comparisons.

Additionally, the absence of *H. decipiens* from the intertidal regions is in line with the same report from South Andaman (Savurirajan et al., 2018). Yet, contrary to this study, I report *C. serrulata* and *Syringodium isoetifolium* from the littoral zones (0.2 to 0.4 m) of Ritchie's archipelago and Little Andaman, updating the species' distribution ranges. Lastly, despite the vast spatial scale of this study, I did not observe *H. ovata* from the ANI's seagrass checklist (12 species). Genus *Halophila*, with high taxonomic diversity, overlapping morphology, and phenotypic plasticity at local scales (Japar Sidik et al., 2010), has often led to species misidentification and systematic ambiguity (Fortes et al., 2018). The species was last reported in 2010 from ANI (Thangaradjou et al., 2010a, b). A recent study (Ragavan et al., 2016) argued that *H. ovata* is a misidentified *H. minor* from all previous assessments in ANI. A similar report from Southeast Asia pointed to taxonomic discrepancies within *Halophila* spp., where the morphological resemblance between *H. ovata* and *H. minor* was "compounding" and has led to species misidentification (Fortes et al., 2018). Since all seagrass assessments in ANI have relied only on morphological traits for species identification, including the present study, the possibility of misidentification cannot be ruled out in case of ambiguous species complexes. Thus, I recommend a more robust approach for species identification using molecular traits to resolve present inconsistencies.

In conclusion, this study has updated critical ecological information on the spatial distribution, habitat suitability, and depth ranges of seagrass meadows in the Andaman and Nicobar Islands. By conducting a comprehensive assessment across a broad spatial scale and depth gradients, this work has filled significant data gaps in previously data-deficient regions of ANI. My findings highlight key regulatory factors, such as water depth, influence seagrass growth, and species distribution. The observed differences in seagrass distribution along depth gradients can be attributed to various factors, including differences in covariates associated with water depth, species' adaptability to different depth regimes, and habitat heterogeneity and substratum availability, which also change with depth. Any alterations in the benthic habitat profile of these meadows are likely to impact species distribution patterns and overall performance. The present findings suggest that *Halodule* spp. and *Halophila* spp. are generalist species, capable of occupying suitable habitats across different depth regimes, while larger-sized species like *Enhalus acoroides, Thalassia hemprichii*, and *Cymodocea* spp. exhibit specialist characteristics. The presence of seagrasses in deepwater regions of Ritchie's archipelago further confirms the availability of conducive growth environments in deeper regimes. Replicating similar investigations in other island groups would provide valuable insights to complement the current findings. Lastly, the outcomes of this study will have significant implications for the management and conservation of seagrass habitats in the region. The findings will provide valuable baseline information for policymakers, conservationists, and stakeholders and contribute to the broader scientific understanding of seagrass ecosystems and their responses to environmental changes.

CHAPTER 4: MACROBENTHIC COMMUNITY ASSEMBLAGES AND THEIR LINKAGES WITH SEAGRASS HABITATS

4.1. Introduction

Seagrasses are highly productive marine ecosystems that support abundant macrobenthic biodiversity. Seagrass-macrofauna association is complex and determined mainly by plant architecture and environment (Heck and Orth, 1980; Orth et al., 1984). Vagile organisms with reduced mobility, such as mollusks, polychaetes, and crustaceans, derive food resources from seagrasses, their associated epiphytes, and macroalgae (Ansari et al., 1991; Heck and Valentine, 2006; Gacia et al., 2009; Sokołowski et al., 2012). Thus, seagrass presence and subsequent resource prospects are known to shape macrofaunal diversity and abundance. Furthermore, species-specific variation in seagrass spatial features, such as leaf surface area, biomass, canopies, and densities, collectively increase the structural complexity of a meadow (Stoner and Lewis, 1985; Connolly and Butler, 1996; Gambi et al., 1998; Lee et al., 2001; Gartner et al., 2013; Navarro-Mayoral et al., 2020). These micro-habitat niches act as refugia against predation and environmental extremities, resulting in a higher macrobenthic richness and abundance in vegetated areas than in bare sediments (Boström et al., 2006; Gagnon et al., 2020; Murphy et al., 2021; Hu et al., 2022).

Habitat structural complexity in seagrass meadows is additionally determined by the local environment, such as wave action, hydrodynamics, water depth, and sediment profile, which influences plant occurrence, growth, and consequently, macrobenthic communities (Fonseca et al., 1982; Gambi et al., 1998; Gacia et al., 2009; Abrogueña et al., 2021). In this mutualistic relationship, macrofauna acts as ecosystem health indicators for seagrasses and sustain habitat resilience, nutrient recycling, productivity, food web, and trophic energy transfer (Nicholson and Lam, 2005; Lee, 2008; Queirós et al., 2013; Nakaoka et al., 2014; Lamb et al., 2017; González-Duarte et al., 2020; Donaher et al., 2021). Nevertheless, the ecologically unique relationship between seagrass and macrofauna remains underestimated and poorly studied in most seagrass hotspots (Snelgrove, 1998; Leopardas, 2015).

Evaluating the seagrass-associated biological diversity is challenging yet inevitable for habitat conservation (Gamfeldt et al., 2015). Globally, most seagrass habitats are under crisis mainly due to human-induced stressors; therefore, generating ecological information about biodiversity is essential for seagrass management (Orth et al., 2006; Short et al., 2007). Since rise anthropogenic footprints in seagrass ecosystems are predicted to escalate in developing countries (Islam and Tanaka, 2004; Short et al., 2011), seagrass loss and habitat alteration ultimately will impact the associated fauna and shared socio-ecological services to the environment and coastal communities (Duarte, 2002; Boström et al., 2006; Orth et al., 2006; Unsworth, 2007; Navarro-Mayoral et al., 2023). In such a scenario, biodiversity loss from data-deficient regions lacking a detailed baseline on associated fauna would be catastrophic, and quantifying damage will be challenging. In comparison to many regions, despite supporting a diversity of seagrasses and fauna (Short et al., 2007), Indian coastal waters significantly lack ecological information on the seagrass-associated macroinvertebrates (Thangaradjou and Bhatt, 2018).

Coastal ecosystems in the Andaman and Nicobar Islands (ANI) support 62.41 % of India's total faunal species associated with seagrasses (Chandra et al., 2018). The systematic inventories from the region are intensive and include seagrass-associated foraminiferans, sponges, polyclads, sipunculans, copepods, mollusks, echinoderms, polychaetes, nematodes, brachyurans (see Chandra et al., 2018 and references therein). However, these studies are primarily taxonomic, with limited ecological information. Hence, in addition to creating a detailed quantified baseline on seagrass-associated macrofauna, my study focused on understanding how seagrass meadow architecture and environment govern macrofaunal community structure. Here, I investigated the role of vegetation (seagrass presence-absence), additional resources such as macroalgae (epiphytic and non-epiphytic), and environmental variables such as sediment profile, water depth (intertidal and subtidal), and physical variability in habitats in shaping macrofaunal densities. Additionally, I checked if seagrass species richness and vegetation type influence the macrobenthic group diversity and densities, assuming that physical differences in seagrass species may offer varied niches to communities.

4.2. Materials and Methods

4.2.1. Study site

The present study was carried out across the five island clusters such as NMA, RA, SA, LA and NIC with different depth regimes (see section 3.2.1). Macrofauna in this study was any faunal group more than 1 mm in size and further categorized as, a) epifauna- animals found on the seagrass beds (visible to naked eye on field), and b) infauna- animals associated with the seagrass sediments (hidden in soil- up to 10 cm from the surface; Leopardas, 2015). From January to April 2018 to 2022, 66 seagrass meadows were surveyed for associated macrofaunal assemblages, of which 66 were epifaunal sampling sites and 55 were infaunal (Figure 4.1). For epifaunal communities, I deployed LITs and the quadrat method (see section 3.2.2) and recorded associated fauna within a seagrass meadow. Epibenthos up to group level were noted, and abundance for each group was calculated. Densities were calculated later for each group and averaged for each transect. For infaunal assemblages, samples of the upper soil layer (up to 10 cm) were hand-scooped from a 20 × 20 cm quadrat. The infaunal samples were collected in triplicates and secured in ziplock sampling bags. Further, another replicate of samples was collected for sediment texture analysis. The infaunal samples were immediately preserved in the 4 % buffered rose Bengal solution, and sediment samples were air-dried.

Seagrass meadow features such as cover, biomass, shoot densities, and canopy height (see section 3.2.2) were the primary predictor variables in this study.

In addition, determinants, such as water depth, algal cover, habitat, and sediment profile, were used. I further classified the epifaunal groups into a) count and b) coverage. All groups with countable individuals were placed in the first group, while poriferans, ascidians, and cnidarians (corals and hydroids), spread over the substratum, were considered in the epibenthic cover category. Lastly, I placed all the epibenthic burrowing animals under the category ‘burrowers,’ where a) usage was done by multiple groups (crabs, shrimps, goby fishes; confirmed observations) or/and b) by individual groups with unconfirmed identity (active burrows confirmed using cues such as water bubbles from burrow openings, but animal not observed).

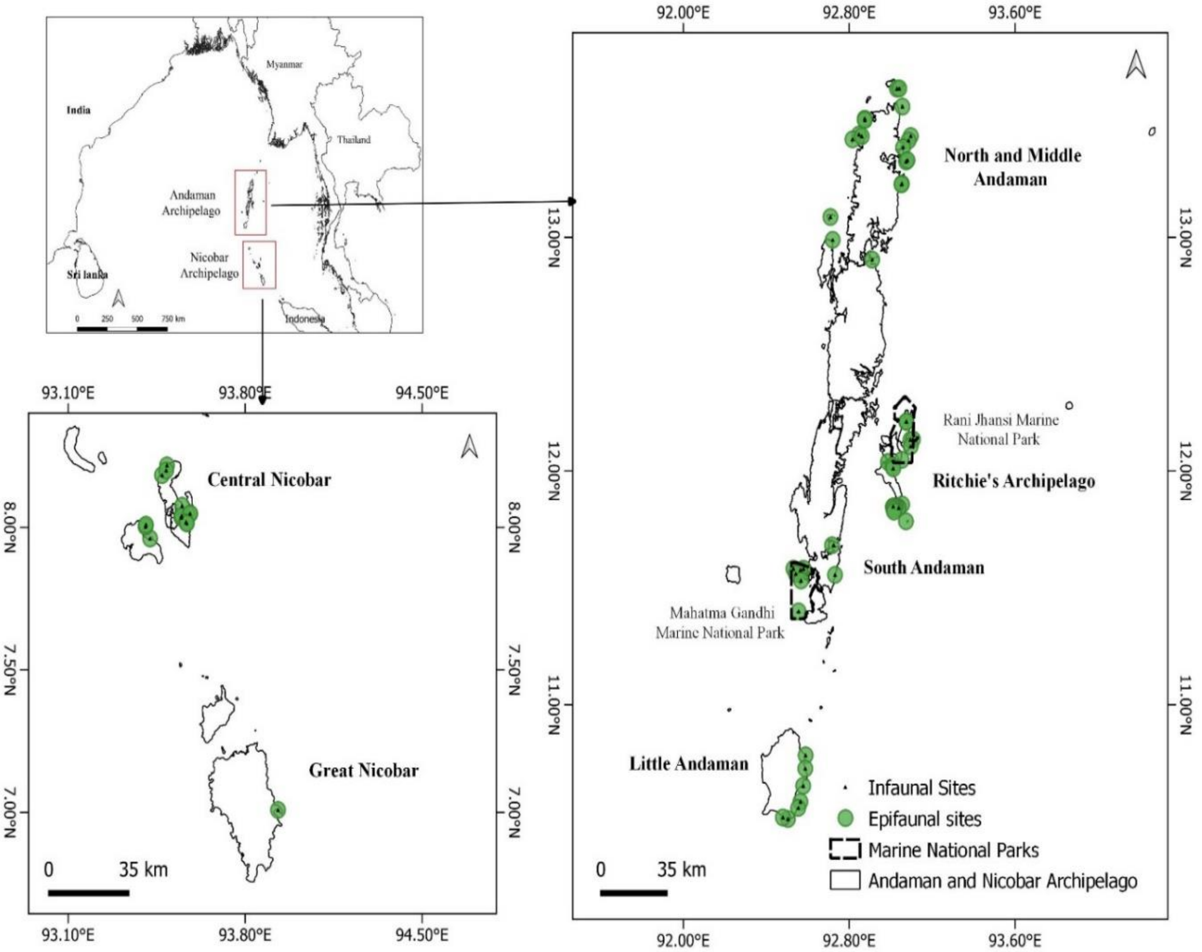

Figure 4.1: Macrofaunal sampling locations in the Andaman and Nicobar Islands, India

4.2.2. Laboratory assessments

The infaunal samples were gently sieved using a 500µm mesh to retain the macrobenthos. Each sample was sub-sampled further into four sets, sorted, and grouped using a stereo microscope (OLYMPUS SZX16 and Zeiss discovery V.8). Group validation was done using standard identification manuals (Fauchald, 1977; Keppner and Tarjan, 1989; Sturm et al., 2006; Sasaki, 2008). Further, individuals of each group were counted to estimate the group densities (ind./m^2). Lastly, sediment texture was analyzed using standard methods IS2720 (PART 4).

4.2.3. Data analysis

Group-specific and total mean densities (all groups) were calculated for each site, and Shannon's diversity and evenness indices were used to compare the diversity of benthic faunal communities across sites. Further, I used a generalized linear model (GLM) approach to understand the critical seagrass and environmental predictors that govern benthic faunal communities. In addition, I used non-parametric tests (Kruskal-Wallis followed by a post-hoc Dunn test and Man-Whitney U test), to investigate category-wise dissimilarities in faunal densities for 1) vegetation status (presence and absence), 2) species richness (mono and mixed species), 3) composition (each seagrass species with a different plant architecture), and 4) habitat heterogeneity (homogenous and heterogenous).

I collected samples from seagrass vegetation and adjacent bare sediments to examine macrofaunal dissimilarities between vegetated and unvegetated areas. Based on plant architecture, seagrass composition was further categorized as complex 1: small-sized species (*Halophila* + *Halodule* spp.; meadows with either one of the species or in combination), complex 2: large-sized species (*Thalassia* + *Cymodocea* spp.; meadows with either one of the species or in combination) and complex 3 (mixed meadows inclusive a combination of multiple species). Habitats with 100% sand cover were categorized as homogeneous, and the ones with a mix of sand and other substrata (rubble, dead coral algae, rock) were treated as heterogeneous.

4.2.3.1. Generalized linear modeling

Step 1-Data normalization and collinearity: I first checked for the data normality using the Shapiro-Wilk test for each response (total mean and group-specific faunal densities) and predictor variables. This step was similar to an analysis done for Chapter 3 (see section 3.2.4.1). Instead of Z-score normalization, I log-transformed (log10) the non-normal dataset. Further, a bivariate regression analysis was run to check for the relationship between all predictor variables. I observed that seagrass cover and shoot length significantly influenced critical variables such as seagrass densities and biomass (Pearson's correlation value r = > 0.5, Table 4.1). Similarly, coarse sand and clay were potentially collinear with fine sand. Thus, the four variables mentioned above were excluded from the further analysis. Later, I used a Generalized Linear Model (GLM) framework to elucidate the influence of 10 potential explanatory variables on total mean infaunal and epifaunal densities/cover. Group-specific analysis was conducted only on identified dominant guilds from each category (infauna and epifauna). Considering the overall low diversity and spread, this step was excluded for epibenthic cover. Before GLM, I used Variance Inflation Factor (VIF values) to assess the collinearity among ten quantified explanatory variables, namely seagrass shoot densities, seagrass biomass, water depth, rubble, dead coral algae, rock, epiphytic algae, non-epiphytic algae, fine sand, and silt. All the variables had a VIF value < 3 exhibiting less collinearity as recommended for regression analysis (Bolker, 2008).

Table 4.1. Summary of bivariate regression analysis on 14 predictor variables to assess the strength and collinearity between the variables

	SC	SB	SD	SL	WD	RU	DCA	RK	EA	NPA	C. sn	F. sn	Silt	Clay
SC	**1**	0.57*	0.33	0.69*	-0.30	-0.05	-0.15	-0.16	0.34	-0.13	-0.01	0.06	-0.09	-0.13
SB	0.57*	**1**	0.40	0.76*	-0.19	-0.07	-0.09	-0.06	0.12	-0.01	-0.11	0.13	-0.02	-0.06
SD	0.33	0.40	**1**	0.20	-0.36	0.12	0.11	0.14	-0.05	0.07	-0.05	0.12	-0.13	-0.17
SL	0.67*	0.76*	0.20	**1**	-0.15	-0.13	-0.15	-0.12	0.08	-0.13	-0.20	0.25	-0.06	-0.17
WD	-0.30	-0.19	-0.36	-0.15	**1**	-0.15	-0.37	-0.32	0.06	-0.26	0.12	-0.17	0.11	0.18
RU	-0.05	-0.07	0.12	-0.13	-0.15	**1**	-0.17	-0.11	-0.02	0.33	0.31	-0.23	-0.18	0.05
DCA	-0.15	-0.09	0.11	-0.15	-0.37	-0.17	**1**	0.22	-0.22	0.12	-0.14	0.22	-0.14	-0.13
RK	-0.16	-0.06	0.14	-0.12	-0.32	-0.11	0.25	**1**	-0.19	0.12	0.06	0.01	-0.14	0.02
EA	0.34	0.12	-0.05	0.08	0.06	-0.02	-0.22	-0.19	**1**	-0.09	0.07	-0.13	0.11	0.05
NPA	-0.13	-0.01	0.07	-0.13	-0.26	0.32	0.14	0.12	-0.09	**1**	-0.07	0.17	-0.16	-0.24
C. sn	-0.01	-0.11	-0.05	-0.20	0.12	0.31	-0.14	0.06	0.07	-0.07	**1**	-0.87*	-0.37	0.67*
F. sn	0.06	0.13	0.12	0.25	-0.17	-0.23	0.22	0.01	-0.13	0.17	-0.87*	**1**	-0.14	-0.77*
Silt	-0.09	-0.02	-0.13	-0.06	0.11	-0.18	-0.14	-0.14	0.11	-0.16	-0.37	-0.14	**1**	0.23
Clay	-0.13	-0.04	-0.17	-0.17	0.19	0.05	-0.12	0.02	0.05	-0.24	0.61*	-0.77*	0.23	**1**

[SC, seagrass cover; SB, seagrass biomass; SD, shoot densities; SL, shoot length; WD, water depth; RU, rubble; DCA, dead coral algae; RK, rock; EA, epiphytic algae; NPA, Nonepiphytic algae; C.sn, coarse sand; F.sn, fine sand) [Values expressed as r- spearman's correlation coefficient ,* indicates significant correlation]

Step 2-Regression analysis: I assumed log-transformed response variables, namely infaunal densities, epifaunal densities, and epifaunal cover (total and group-specific), to follow a Gaussian distribution. I later used the information-theoretic model averaging approach and created multiple combinations of 'dependent vs. predictor variables' models using the function *dredge* in package *Mumin* in *R* (version 4.2.1). Lastly, I averaged the models with 'lowest AIC' and 'AIC delta <2' as pre-selection criteria (Burnham and Anderson, 2002). The resultant models thus provided a more robust understanding of the influence of potential explanatory variables on faunal assemblages. All analyses were performed in *R* (version 4.2.1) with extended *CAR*, *AICcmodavg,* and *ggplot2* packages using *glm*, *AIC*, *Loglik,* and *aictab* functions (R core development team, 2019[7]).

4.3. Results

4.3.1. Site-specific diversities in macrofaunal assemblages

Ten groups of soft-bottom sediments in the investigated seagrass meadows were infaunal, while 15 were epifaunal (Figures 4.2A and B). Of these, six groups, for instance, polychaetes, gastropods, bivalves, crustaceans, cnidarians, and ophiuroids, were commonly shared between the categories. Meanwhile, four groups, such as nematodes, foraminiferans, sipunculids, and oligochaetes, were exclusively infaunal. Nine groups were exclusively epifaunal: burrowers, holothuroids, echinoids, asteroids, crinoids, chitons, platyhelminthes, poriferans,

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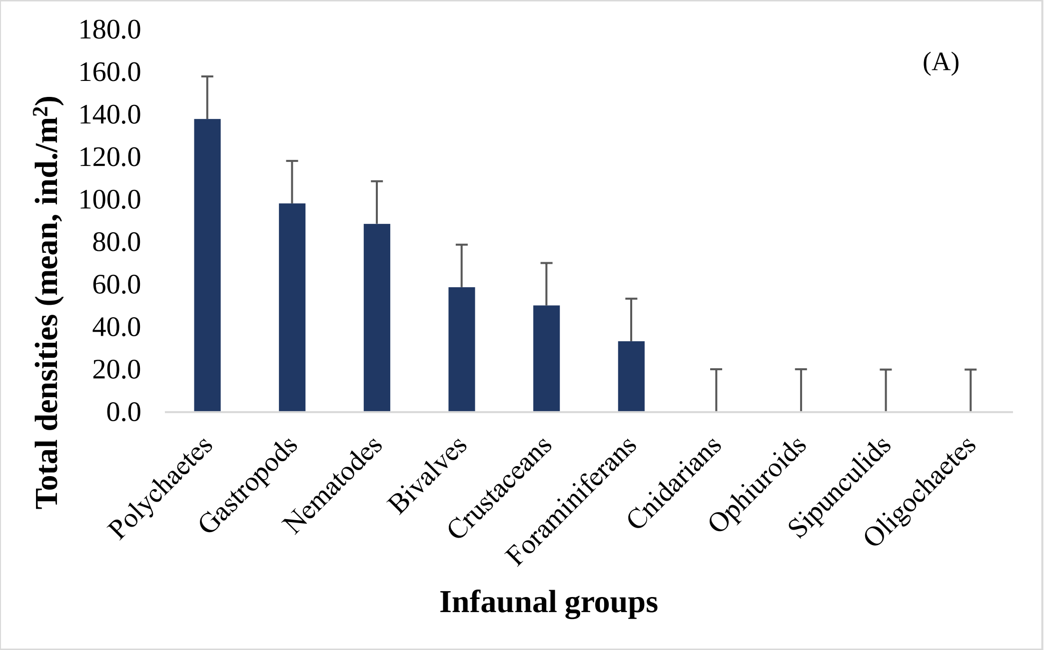
[7] R core development team 2019 (https://www.R-project.org/(accessed on December 2022)

and ascidians. Infaunal richness ranged from 2-8 co-occurring groups in seagrass sediments, while epibenthos showed a much more comprehensive range of 1-12 coinciding groups in a single seagrass meadow. Total mean infaunal and epifaunal densities varied from 42.5 ± 5.5 ind./m^2 to 48.5 ± 8.7 ind./m^2 respectively (expressed as mean ± std. error). Polychaetes (125.5 ± 19.5 ind./m^2; expressed as mean ± std. error), gastropods (89.3 ± 10.9 ind./m^2), nematodes (80.6 ± 17.3 ind./m^2), bivalves (53.5 ± 8.2 ind./m^2), and crustaceans (45.6 ± 13 ind./m^2) represented 93 % of the total infaunal population. Foraminiferans, cnidarians, ophiuroids, sipunculids, and oligochaetes comprised 7 % of the rare infaunal groups (Figure 4.2A).



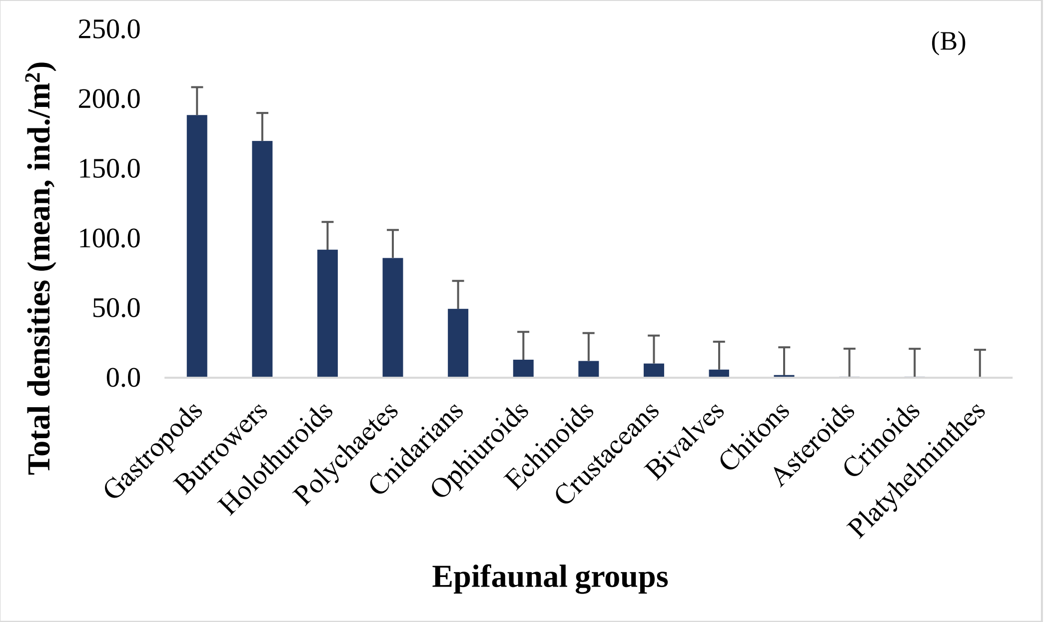


Figure 4.2: Seagrass-associated A) infaunal and B) epifaunal diversity recorded in the Andaman and Nicobar Islands [line in bars represents the standard error]

Epibenthos from the investigated sites were rich, both in terms of richness and within-group diversity. Gastropods (188.5 ± 86 ind./m^2) and Platyhelminthes (0.1 ± 0.05 ind./m^2) were the most and least numerically dominant groups, respectively. Five groups dominated the total epifaunal densities (93 %) in the following order: gastropods > burrowers > holothuroids > polychaetes > cnidarians (Figure 4.2B). Gastropod diversity was mainly composed of nudibranchs, limpets, micro-molluscs, and egg cases, along with the most abundant genera *Engina*, *Nassarius*, *Clypeomorus*, *Tridacna*, *Natica*, and *Conus*. Brachyurans (true crabs), isopods, amphipods, and shrimps formed the crustacean epibenthic group, of which crabs contributed to > 80% of the total population. Within the holothuroids, I observed five sea cucumber species: *Stichopus chloronotus* (60%), *Holothuria atra* (33%), *Synapta maculata* (5%), *Holothuria leucospilota*, and *Actinopyga mauritiana* (collectively 2%), with the first two being dominant across their spatial distribution. Lastly, echinoids comprised sea urchins, sea potato, and sand dollars, whereas cnidarians (both count and cover) included sea anemones, sea pen, corals, and hydroids.

Within the investigated island groups, infauna numerically dominated seagrass sediments in RA (88.6 ± 22.3 ind./m^2), followed by LA (62.6 ± 15.6 ind./m^2), NMA (30.1 ± 6.1 ind./m^2), NIC (29.9 ± 7.7 ind./m^2) and the lowest in SA (28.9 ± 8.7 ind./m^2, Table 4.2). The highest and lowest infaunal densities were recorded from the deep-water seagrass meadow of Imli Dera (RA, 187.5 ± 99.2.4 ind./m^2) and Trinket, NIC respectively (6.3 ± 5.1 ind./m^2, Annexure 3). Five sites namely Paget, Excelsior, Craggy, Bada Inak, and Pilpilow (Moh Ryak) were devoid of infauna (Annexure 3). Across all the Island groups, seagrass meadows of South Andaman harbored the most stable infaunal communities in terms of diversity and evenness (Annexure 3).

Epibenthos, on the contrary, was the highest in the following order: NMA (88.2 ± 23.7 ind./m^2) > SA (58.4 ± 19 ind./m^2) > NIC (31.5 ± 15.1 ind./m^2) > RA (27.8 ± 11.5 ind./m^2) > LA (25 ± 7.9 ind./m^2, Table 4.2). Overall diversity and spread showed irregular trends for epifauna, with only one highly diverse site (Burmanallah; $H > 1.5$; Annexure 4). The intertidal meadow in Kalipur, NMA harbored the highest epifaunal densities (389.4 ± 44.8 ind./m^2) while the lowest were recorded from Campbell Bay (NIC, 0.4 ± 3.9 ind./m^2; Annexure 4). Although meadow-specific group richness was higher for epifaunal communities, ~ 22 % of the seagrass meadows were dominated by only one group (Annexure 4). Group diversities (H) ranged from 0.07 to 1.92 across 64 sites, while low evenness (< 0.50) was reported from ~ 20 % of sites despite high group richness (Annexure 4). Only two sites, Patthar Nali (LA) and Pilpilow (Rai-Kin-Fimo; Kamorta, NIC), had no epibenthos. Despite the low richness, seagrass meadows in Imli Dera, Hutbay (LA), and Hypo (NIC) had complete evenness across all sites (Evenness- 1), indicating stable relative abundances (Annexure 4). Lastly, epibenthic cover that included poriferans, cnidarians, and ascidians was dominantly observed in SA and RA (Annexure 4).

Table 4.2. Summary of seagrass-associated macrofauna across the investigated island groups

Sr. No.	Island Group	Seagrass meadows	Group richness and composition	Macrofaunal densities (mean ± Std. Error)
1	North and Middle Andaman (NMA)	18	**INFAUNA: 5 groups** gastropods, bivalves, polychaetes, nematodes, crustaceans	**INFAUNA** 30.1 ± 6.1 ind./m^2
			EPIFAUNA: 13 groups gastropods, burrowers, holothuroids, polychaetes, cnidarians, ophiuroids, echinoids, crustaceans, bivalves, chitons, asteroids, poriferans, ascidian	**EPIFAUNA** 88.2 ± 23.7 ind./m^2
2	Ritchie's archipelago (RA)	19	**INFAUNA: 8 groups** gastropods, bivalves, polychaetes, nematodes, crustaceans, cnidarians, foraminiferans, ophiuroids	**INFAUNA** 88.6 ± 22.3 ind./m^2
			EPIFAUNA: 13 groups gastropods, burrowers, holothuroids, polychaetes, cnidarians, ophiuroids, echinoids, crustaceans, bivalves, chitons, crinoids, Platyhelminthes, poriferans, ascidian	**EPIFAUNA** 27.8 ± 11.5 ind./m^2
3	South Andaman (SA)	8	**INFAUNA: 8 groups** gastropods, bivalves, polychaetes, nematodes, crustaceans, oligochaetes, sipunculids, ophiuroids	**INFAUNA** 28.9± 8.7 ind./m^2
			EPIFAUNA: 11 groups	**EPIFAUNA**

			gastropods, burrowers, holothuroids, polychaetes, cnidarians, ophiuroids, crustaceans, bivalves, chitons, poriferans, ascidian	58.4 ± 19 ind./m^2
4	Little Andaman (LA)	7	**INFAUNA: 6 groups** gastropods, bivalves, polychaetes, nematodes, crustaceans, foraminiferans	**INFAUNA** 62.6 ± 15.6 ind./m^2
			EPIFAUNA: 10 groups gastropods, burrowers, holothuroids, polychaetes, cnidarians, ophiuroids, crustaceans, bivalves, chitons, poriferans	**EPIFAUNA** 25 ± 7.9 ind./m^2
5	Nicobar (NIC)	14	**INFAUNA: 5 groups** gastropods, bivalves, polychaetes, nematodes, crustaceans	**INFAUNA** 29.9 ± 7.7 ind./m^2
			EPIFAUNA: 9 groups gastropods, burrowers, holothuroids, cnidarians, ophiuroids, echinoids, asteroids, crinoids, poriferans	**EPIFAUNA** 31.5 ± 15.1 ind./m^2

4.3.2. Factors influencing macrofaunal densities

Mean infaunal and epifaunal densities did not differ significantly in response to predictor variables (Annexure 5). However, I observed noteworthy trends at a group level. Infaunal polychaete densities decreased with water depth (β estimate = -0.46, *p* value = 0.03, Figure 4.3A, Annexure 5), with mean densities of 235.4 ± 53.3 ind./m^2 in intertidal compared to 96.3 ± 38.5 ind./m^2 in subtidal. In contrast, high non-epiphytic algal cover positively influenced this group (β estimate = 0.47, *p* value = 0.02, Figure 4.3B, Annexure 5). Infaunal crustacean densities declined with silt content in sediments (β estimate = -0.71, *p* value = 0.0005, Figure 4.3C), followed by high seagrass shoot densities (β estimate = -0.84, *p* value = 0.02, Figure 4.3D). Water depth was the last negative predictor for this group, with a decline in densities from intertidal (84.8 ± 16.6 ind./m^2) to subtidal waters (35.4 ± 10.9 ind./m^2, β estimate = -0.50, *p* value = 0.03, Figure 4.3E, Annexure 5). Heterogeneity in the habitat, regarding high rubble cover, negatively impacted the infaunal gastropod densities (Figure 4.3F). Nematodes and bivalves were the only infaunal group with no significant correlation with predictors in GLM analysis (Annexure 5).

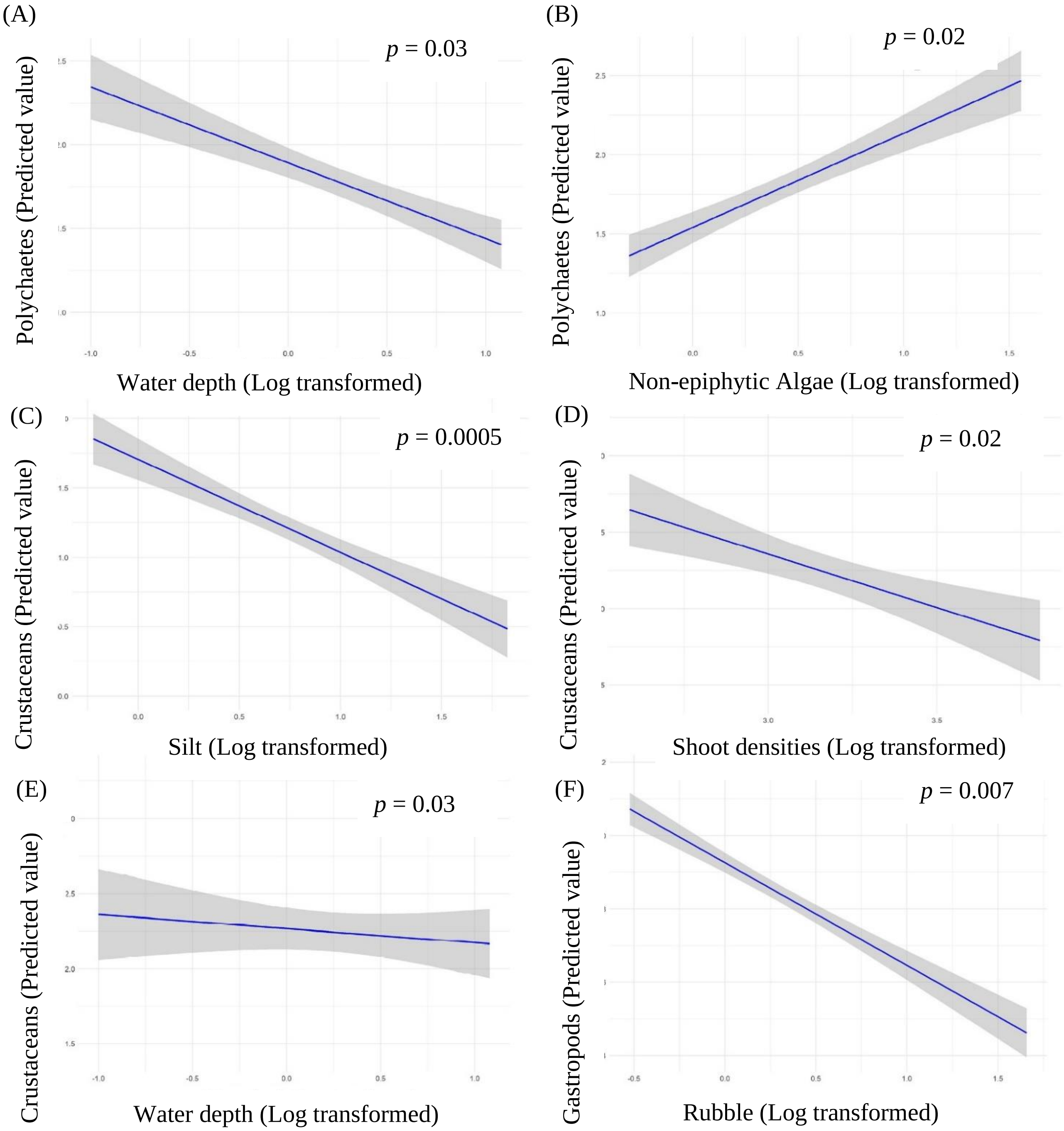


Figure 4.3: Generalized linear plots depicting the relationship between response variables and infaunal group densities, A, and B: polychaete densities; C-E: crustacean densities; F: gastropod densities

Furthermore, only epifaunal holothuroids positively correlated with seagrass biomass, while epifaunal gastropod densities reduced with water depth (Figures 4.4A and B, Annexure 5). Burrowers preferred higher sediment silt content (β estimate= 0.62, *p* value= 0.03, Figure 4.4C). On the contrary, I observed decreased epifaunal polychaete densities in response to silt and fine sand (Figures 4.4D and E; Annexure 5). The epibenthic cover was dominant in dead coral algae habitats (Figure 4.5A, Annexure 5). Nevertheless, fine sand and non-epiphytic algae negatively influenced this group (Figures 4.5B and C, Annexure 5).

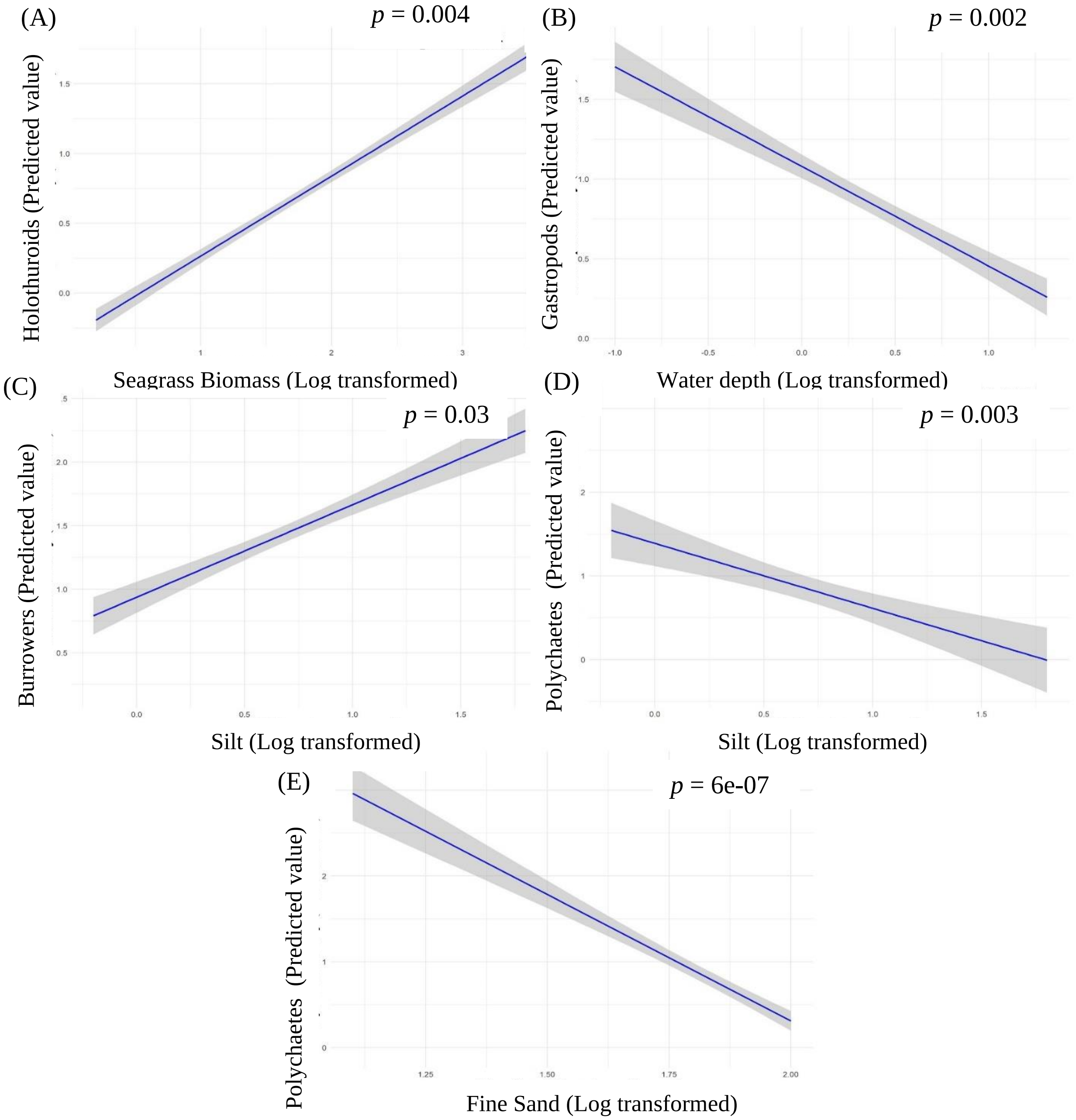


Figure 4.4: Generalized linear plots depicting the relationship between response variables and epifaunal group densities A) holothuroid densities; B) gastropod densities; C) burrowers' densities; D-E) polychaete densities

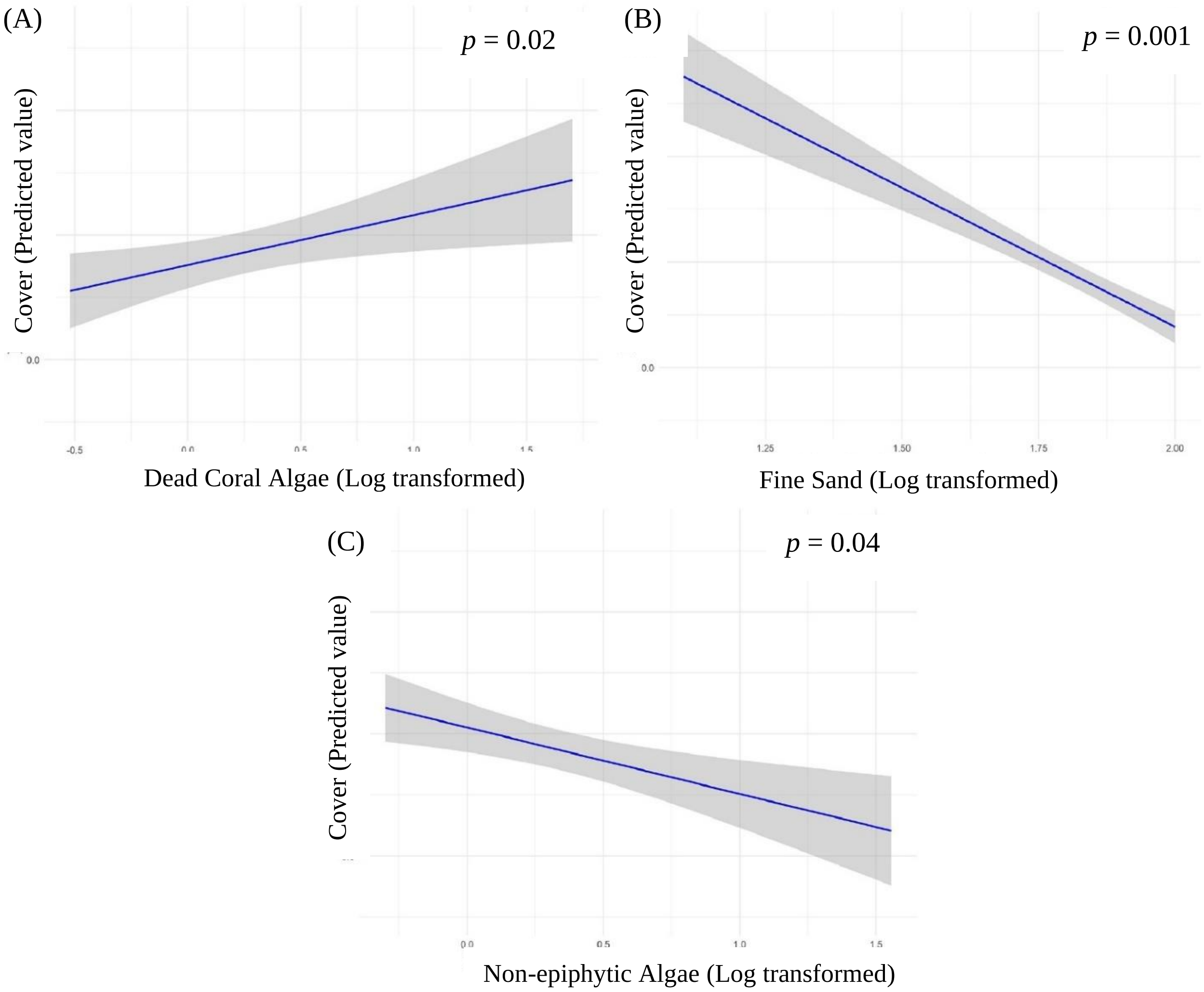


Figure 4.5: Generalized linear plots depicting the relationship between response variables and epibenthic cover

4.3.3. Vegetation status: Although statistically insignificant, I observed higher macrofaunal densities (total) in vegetated meadows than in bare sediments (Annexure 6). Aligning with a similar pattern, most dominant groups were numerically abundant in seagrass meadows. However, only three groups exhibited a significantly more robust relationship with seagrass vegetation (Annexure 6). For instance, polychaetes (both in- and epifaunal), infaunal nematodes (vegetated- 152.1 ± 63 ind./m^2; unvegetated- 53.4 ± 6.3 ind./m^2) and epibenthic burrows (vegetated- 12.7 ± 11.4 ind./m^2, unvegetated- 3.7 ± 1.5 ind./m^2, Annexure 6) had higher densities in vegetated habitats than bare regions. Epi-cnidarians and total epibenthic cover were the only exceptions to this general trend, with higher densities/ cover (except gastropods) in unvegetated sediments (Annexure 6).

4.3.4. Seagrass species richness: Total infaunal and epifaunal densities varied significantly based on the species richness of the meadow (Annexure 6). Densities of epifauna were much higher in a mixed meadow (p value = 0.05) than infaunal communities, which dominated mono-specific meadows (p value = 0.008, Annexure 6). Epibenthic coverage aligned with infaunal densities and was higher in mono-species seagrasses, yet this variation was insignificant (Annexure 6). I did not observe a fixed pattern for group densities for overall macrofauna.

4.3.5. Species composition: Total macrofaunal densities did not significantly vary across species complexes (Annexure 6). However, I report a general (not fixed) trend of higher densities in complex3 (mixed meadows) > complex2 (*Thalassia* + *Cymodocea* spp.) > complex1 (*Halophila* + *Halodule* spp.). Epifaunal holothuroids aligned with this trend, and densities were significantly lower in complex 1 than in complex 2 (post-hoc Dunn *p* value = 0.0006) and 3 (post-hoc Dunn *p* value = 0.04). On the contrary, infaunal bivalve densities were significantly higher in complex 1 than in complex 2 (post-hoc Dunn *p* value = 0.01). No influence of seagrass species composition was observed on epibenthic cover (Annexure 6).

4.3.6. Habitat heterogeneity: Habitat variability did influence dominant guilds in seagrass beds. I observed significantly higher densities of infaunal mollusks and epifaunal burrowers (*p* value = 0.004) in homogeneous sandy habitats than in heterogeneous beds (Annexure 6). Contrarily, epifaunal polychaetes (*p* value = 0.02), holothuroids (*p* value = 0.003), and benthic cover (*p* value = 0.007) were abundant in heterogeneous seagrass beds (Annexure 6).

4.4. Discussion

The present study suggests that seagrass presence positively influenced macrofaunal densities at a larger spatial scale of investigation (inclusive of all meadows). These findings corroborate several reports from different geographic regions, stressing macrofauna's preference for seagrass vegetation over plant-devoid areas (Orth, 1975; Reise, 1977; Lewis and Stoner, 1983; Ansari, 1984; Boström et al., 2006; Abrogueña et al., 2021; Murphy et al., 2021). Further, at group-level investigation, vegetation status significantly influenced infaunal polychaete and nematode densities. My observations align with a study from the United Kingdom (Webster et al., 1998), where infaunal polychaete and nematode densities reportedly declined with reduced vegetation. For polychaetes, however, densities, although significantly higher in macrophytes, were similar in seagrasses and bare regions. I cannot derive likely reasons for the existing pattern but speculate the same to be either a possible outcome of sediment granulometry if similar across both habitats (Santos and Simon, 1974) or an edge effect (Yahner, 1988). Significant outliers to the general vegetation-allied trends were epibenthic cnidarians and cover. I observed the reliability of these two groups more on substratum availability, such as bare sand (sea anemones and sea pens) and hard substrata (poriferans, ascidians, corals, and hydroids) than seagrass. Occupancy was subsequently impacted for these groups, especially in response to other biological groups, such as macroalgae, possibly due to competition for similar spaces.

Despite not being significant for all groups, I report seagrass biomass and shoot densities as negative determinants for infaunal group densities. Infauna was abundant in homogeneous, mono-species habitats, which declined with sediment profile (fine sand and silt). These observations contradict studies from Hong Kong (Lee et al., 2001), Mozambique (Paula et al., 2001), and the Gulf of Oristano (Como et al., 2008), which demonstrated the importance of above and below-ground seagrass features such as rhizome complexity, shoot densities and canopy height in infaunal protection from predators. However, the present findings align with those of Webster et al. (1998) and Leopardas (2015), which inform the small role of seagrasses as critical habitats for infaunal assemblages. The underground root-rhizome network is a product of seagrass species and growth, which increases sediment stability and favors infaunal diversity and abundance (Orth, 1975). Contrary opinions advise sediment stability as not a dependent outcome of seagrass but a function of the physical environment (Young and Young, 1982). Despite these differing arguments, sediment stability is critical for infaunal assemblages. For instance, loose sediments facilitate excavation by predators; hence, this sediment form is unstable for infauna (Reise, 1977), which is also supported by my observations of decreased densities in silt and fine sand.

Moreover, coarse-grained sediments are difficult to penetrate and offer more protection to within-sediment faunal groups (Reise, 1977). Additionally, studies have proposed the negative effect of seagrass biomass on macrofauna such as polychaetes (Stoner, 1980) and bivalves (van Houte-Howes et al., 2004), indicating little function of growth and root-rhizome measures for infauna. Considering supportive literature and present observations, I speculate that meadows with high seagrass richness and growth are unsuitable for most infauna. Higher species richness and meadow attributes (cover, densities, biomass) create a complex under-soil root-rhizome network, which, coupled with habitat heterogeneity (hard substrata such as rubble, rock, and dead coral algae), could hinder space availability for infauna. Primarily being burrowing animals, such habitat conditions could inhibit digging activities for infauna, subsequently impacting their densities (Brenchley, 1982; Skilleter, 1994).

For epifauna, my results imply a collective role of sediment profile, water depth, seagrass species richness, and habitat heterogeneity in governing densities. However, I report no effect of plant biomass and shoot densities on epifaunal abundance, except for holothuroids. Thus, present findings are notwithstanding with numerous studies that report a positive correlation between seagrass growth and epifauna (Lewis and Stoner, 1983; Ansari et al., 1991; Edgar and Robertson, 1992; Vonk et al., 2010; Satumanatpan et al., 2011; Navarro-Mayoral et al., 2023). Noteworthy is the positive response of holothuroids to most of the seagrass variables, such as biomass, species richness, vegetation type, and habitat structure, collectively implying strong seagrass dependency of this group. Holothuroid-seagrass affinity and observed habitat preferences are well documented at local and regional scales (Flammang and Conand, 2004; Tanita and Yamada, 2019; Gole et al., 2022b). Moreover, sea cucumbers derive indirect food sources from seagrasses (Hartati et al., 2019). Considering this affinity, I speculate that meadows with extensive vegetative diversity and plant size (complexes 3 and 2) potentially boost available food resources, resulting in high holothuroid densities. Two dominant species in the present study, *Stichopus chloronotus* and *Holothuria atra*, are known to inhabit sandy substrata in seagrasses (Flammang and Conand, 2004). Remaining semi-cryptic species, such as *H. leucospilota*, *Actinopyga mauritiana*, and *Synapta maculata*, are reported from seagrass beds in Sri Lanka (Dissanayake and Stefansson, 2012) and underneath the rocks and crevices from Japan (Tanita and Yamada, 2019) and ANI (Gole et al., 2022b). Accordingly, the observed holothurian affinity towards heterogeneous seagrass habitats with high vegetative diversity could be attributed to the species-specific micro-niche preferences (Gole et al., 2022b), which potentially offers more food resources and refugia.

Notably, based on comparisons between infauna and epifauna, I propose that seagrasses play a more regulatory role in shaping epifaunal assemblages than infauna (Leopardas, 2015). I further propose that vegetation type is not a strong predictor for macrofauna. My observations contradict the reports from elsewhere suggesting differences in benthic diversity and abundances owing to seagrass species composition (Cebrian et al., 2001; Como et al., 2008). However, supporting assessments from the southern Philippines (Leopardas et al., 2014) and Singapore (Fong et al., 2018) have demonstrated little role of seagrass species type on macrofaunal communities. Consistent with these reports, I imply that macrofaunal assemblages are positively influenced by seagrass presence and richness but show little seagrass host-specificity and could be more responsive to the local environment in which they reside (Edgar, 1990).

Water depth was another critical variable in the present study, negatively influencing dominant groups such as polychaetes, crustaceans, and gastropods. This variation could be a response of seagrass habitats to the local environment, which varies with substrate and water depth (Arrivillaga and Baltz, 1999). Beyond resources offered by seagrasses, sediment stability (Young and Young, 1982), chemistry (Brito et al., 2005), substrate and microstructures availability (Bologna and Heck, 2000; Syukur et al., 2021), predation (Young and Young, 1982; Orth et al., 1984), sediment and nutrient profile (Gambi et al., 1998) and biological traits of faunal groups (Bell and Westoby, 1986) are critical in governing community structure. For the latter trait, the epifaunal polychaete affinity towards heterogeneous habitats and negative correlation with fine sand and silt could be due to this group's nature and micro-habitat requirements. Through most of their spatial spread, polychaetes primarily comprised of calcareous, hard-bottom worms attached underneath rocks or dead coral algae, explaining their preference for heterogeneous habitats. In contrast, burrowing crustaceans (burrowers), sometimes guarded by goby fishes, preferred homogenous seagrass beds with high silt content, as this sediment profile favors digging activities.

In conclusion, contrary to abundant reports on the strong influence of seagrass growth and architecture on macrofaunal groups (Heck and Wetstone, 1977; Stoner, 1980; Ansari et al., 1991; Attrill et al., 2000; Cebrián and Duarte, 2001; Lee et al., 2001), my results indicate little effect of meadow architecture, seagrass richness and composition on overall faunal assemblages, but to some degree on dominant guilds. This is more reflected in infauna than epifauna. Hence, as macrofaunal trends are group or species-specific (Edgar, 1990; Gambi et al., 1998), investigating group-level responses (or lower taxa) over an inclusive approach (all groups, including rare fauna) would be a more robust way of understanding these ecological interactions. Lastly, the findings imply that the comparison scale is critical in understanding seagrass-macrofauna interaction. Seagrass-macrofauna dynamics is complex and varies with scale of analysis (within and across sites), where macrofaunal responses are more evident at more minor scales, and patterns may not be evident at larger scales (Bell and Westoby, 1986). The present study provides the first insights from ANI on seagrass-associated macrobenthos on a local and regional scale. However, the small-scale (within-meadow) and across-site variations, in addition to the influence of diel rhythms (Vina et al., 2023), seasonality (Włodarska-Kowalczuk et al., 2014; Pullen et al., 2022) and most importantly human impacts (Claassens et al., 2020; Castellanos-Iglesias et al., 2021) on community structure are crucial where the existing patterns would vary but remain unexplored and warrant further investigation.

CHAPTER 5: SEASONALITY IN SEAGRASS MEADOWS AND ASSOCIATED MACROFAUNAL GROUPS

5.1. Introduction

Seasonal variation in the local environment governs the population dynamics of coastal marine plants and is well-documented throughout their distribution ranges. The magnitude of seagrass seasonality varies across latitudes and different climate regimes, as its strength is much more prominent in higher latitudes and temperate waters (Duarte and Chiscano, 1989; Jankowska et al., 2014). However, tropical coastal plants, too, exhibit seasonality (Short et al., 2006). Macrophyte growth and reproduction are determined by several intrinsic and extrinsic factors such as temperature, salinity, wind patterns, air exposure, hydrodynamics, tidal rhythms, light irradiance, and nutrient dynamics, all of which vary seasonally and with local environment (Ott, 1980; Harrison, 1982; Walker and McComb, 1988; Duarte, 1991; Erftemeijer and Herman, 1994; Laugier et al., 1999; Supanwanid et al., 2001; Lee, 2008; Chiu et al., 2013). In addition, seagrass response to seasonal changes is species-specific, which varies in reproductive cycles, competitive traits to survive (inter-species competition), and subsequent adaptability, such as phenotypic and physiological responses to stress (Harrison, 1982; McDonald et al., 2016). Therefore, seagrass seasonality is a shared outcome of species and their interaction with the local environment. This knowledge is essential for effective local-scale management (Harrison, 1982), given all seagrass habitats respond to the local environment variably (Ward et al., 2022).

As a foundation species, seagrass facilitates enormous biodiversity, including commercially essential and threatened fauna (Hughes et al., 2009; Waycott et al., 2009). These seagrass-associated species strongly correlate with meadow attributes as they mainly rely on vegetation for food and shelter (Hemminga and Duarte, 2000; Gullström et al., 2012; Ray et al., 2014; Unsworth et al., 2019a; Berkström et al., 2020). Seasonal alteration in seagrass resource prospects, including plant availability, structural micro-niches (change in species composition), or food sources (differential growth), consequently influence the abundance of macroinvertebrates in seagrass beds (Supanwanid et al., 2001; Boström et al., 2006). Furthermore, the reproductive cycles of prey and predator species influenced by seagrass meadows are another determinant of seasonal trends in the community dynamics (Pullen et al., 2022). Therefore, seasonal fluctuations in plant biomass, densities, and canopy structure are not limited to only seagrass but have a much more significant effect on the associated community dynamics (Vonk et al., 2010).

Additionally, fine-scale structural complexity varies within a meadow (food resources and refugia) and effects faunal abundances (Heck and Orth, 1980; Sirota and Hovel, 2006). The relative position of communities within a seagrass meadow and the distance from the meadow edges are critical factors impacting faunal densities (Tanner, 2005; Moore and Hovel, 2010). Seagrass margins, which act as 'movement corridors' for fauna (habitat-interlinkages), share resources with adjacent habitats, creating a productive niche of predation opportunities at the edges (Irlandi et al., 1995; Gullström et al., 2008; Smith et al., 2008). On the contrary, edges also make smaller animals vulnerable to predation by large, motile groups. Fishes and decapod crustaceans use these edge corridors for movement facilitation in case of which, the patch interior offers additional refugia for prey species (Unsworth et al., 2007; Gullström et al., 2008). Accordingly, the edge effect trends could be positive, where community richness and abundance are concentrated at the meadow edges than the interior (positive edge), vice versa (negative edge), or neutral (no difference, Warry et al., 2009). Since seagrass edges too fluctuate with seasons, so do the subsequent community interactions at margins (Bos et al., 2008).

Global seagrass decline demands strong management based on comprehensive knowledge of fundamental ecological patterns (Orth et al., 2006; Burkholder et al., 2007; Yarbro et al., 2023). Under such a crucial ecological context, it is necessary to understand how seagrass naturally behaves to the variation in the environmental variables induced by seasonality. However, there is a dearth of seagrass-centric seasonal studies from the Indian waters (Balasubramaniam, 1974; Govindasamy and Arulpriya, 2011; Govindasamy et al., 2013), and information furthermore critically lacks from the remote seagrass ecosystem of the Andaman and Nicobar Islands, India (ANI). Micro and macro-scale processes in seagrass habitats remain largely underexplored for the geologically vulnerable tropical ecosystem of ANI. For instance, the massive destruction caused by the 2004 tsunami altered seagrass distribution trends and the local extinction of species (Thangaradjou et al., 2010a). Here, understanding the seasonal responses of seagrasses to any change in the local environment is thus critical, especially in the wake of climate change, which critically impacts the growth patterns and physiology of seagrasses (Short and Neckles, 1999; Zimmerman et al., 2021; Yarbro et al., 2023). For instance, climate change-induced tidal changes enhance the thermal stress on seagrasses, impact salinity ranges, and, in turn, affect the seed germination potential of seagrasses (Short and Neckles, 1999). Furthermore, although a small-scale measure of community diversity, detailed trends on the edge effect can reflect information on particular habitat connectivity of seagrasses.

Nevertheless, this topic is poorly understood (Vonk et al., 2010), with no baseline from the Indian seagrass meadows. Thus, my study attempted to address these research gaps where I investigated the influence of seasonality on *Thalassia hemprichii*-dominated intertidal beds with varying local environments. Further, I examined the intricate influence of two ecological processes: seagrass seasonality and edge effect on associated macrobenthic communities. A detailed rationale and synthesis of this study is explained in Figure 5.1.

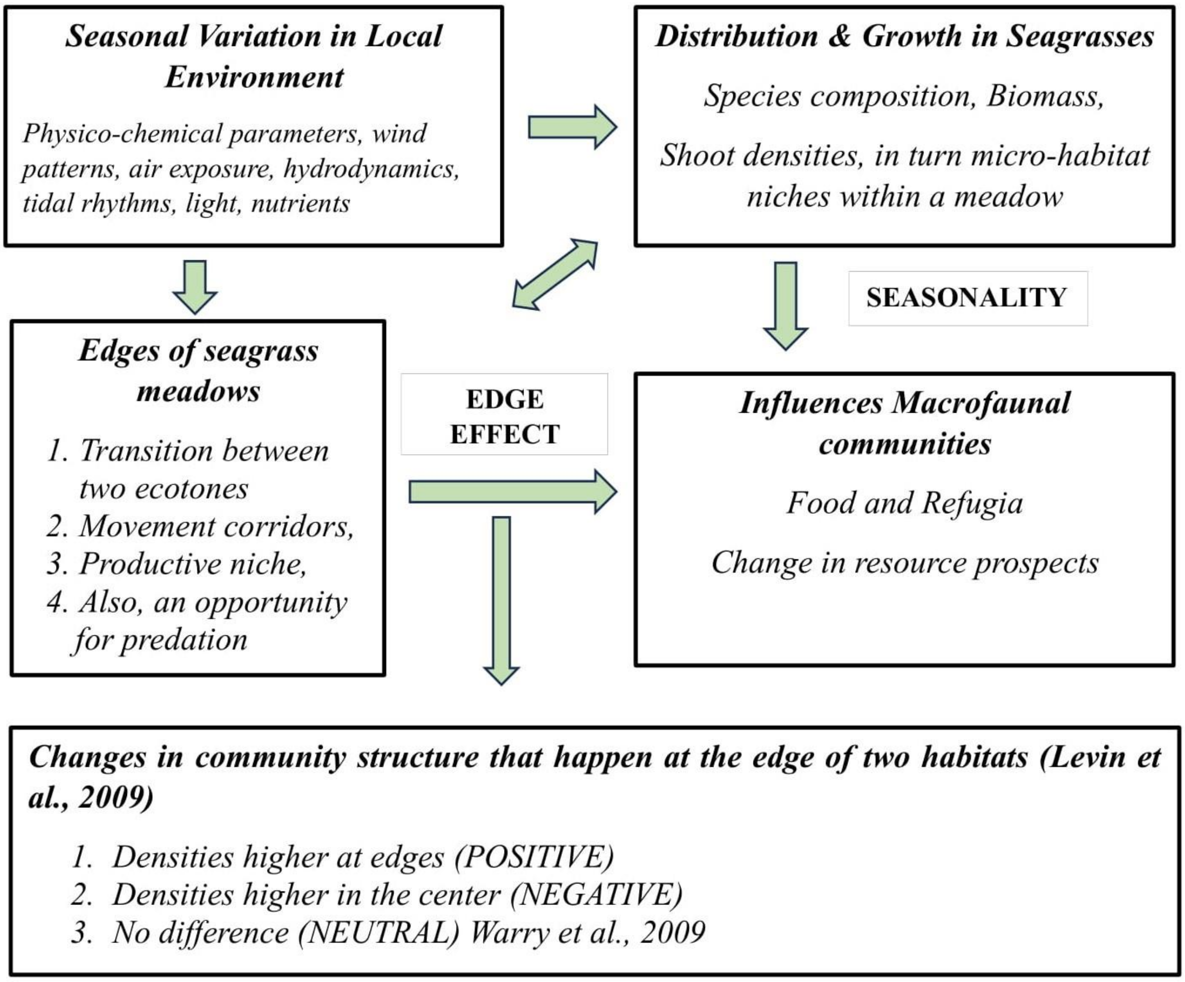


Figure 5.1: Illustrative framework of the study explaining the influence of local environment, seagrass seasonality, and edge effect on macrofauna

5.2. Materials and Methods

5.2.1. Study sites (depth gradient-[0 m (min) to 2 m (max)]

The present study was carried out in 2021, and based on the seasonal traits in the Islands, three sampling seasons were chosen: summer (April), monsoon (August), and winter (January). After the exploratory surveys (see Chapter 3), I delineated three intertidal sites in the Andaman Islands: one in South Andaman (Site 1) and two in Ritchie's archipelago (Sites 2 and 3) (Figure 5.2). Sites were selected based on 1) patch size and type, 2) local environment-variability, and 3) species composition. Additionally, factors such as replicability of seasonal study (which is logistically challenging in SCUBA-aided subtidal surveys, especially in monsoon), proximity to the research base, and logistics to move across three Islands (inter-island movement) in the same season were also considered while shortlisting study sites. Given my study's objective was to assess seagrass seasonality and edge effect, I further ensured that the chosen sites also qualified for the edge studies (distinct edge demarcation, Image 1).

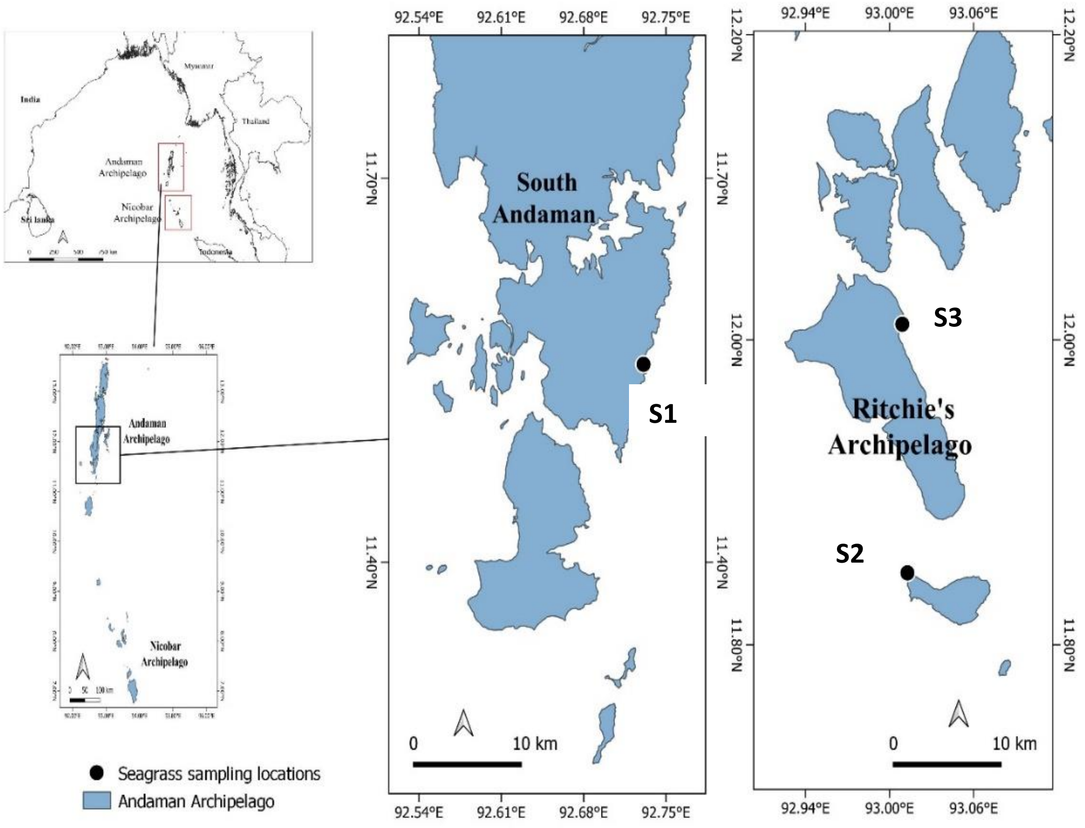


Figure 5.2: Study area map showing intertidal sampling sites in the Andaman Islands [S1- Site 1, Burmanallah; S2- Site 2, Laxmanpur; S3- Site 3, Vijay Nagar]

Image 1: Clear-cut edge demarcation in mixed-species meadow, Site 3- Vijay Nagar [Swaraj Dweep, Ritchie's archipelago, *Photo Credits: Swapnali Gole*]

All three sites experience southwest and northeast monsoon winds. Sites further showed a robust patch-size variability where the mean seagrass spread for Site 3 was 16.8 ha, followed by 4.8 ha for Site 1 and the lowest for Site 2 (2 ha).

Site 1, Burmanallah (11°40'55.56"N, 92°43'32.12"E), is a sheltered site on the eastern aspect of South Andaman (Figure 5.2). The meadow was largely heterogenous (Image 2) and protected by a mangrove edge at the fringes. The high tide edge was characterized by gravel (always dry and exposed in low tide). An inward channel, which discontinued the seagrass meadow, formed the third edge.

In contrast, hard substrata such as dead coral reefs primarily dominated the reef-ward, low-tide edge. The meadow was dominant of *Thalassia hemprichii*, which contributed to > 90 % of the spread and growth. At the same time, a pocket (1 m^2) of co-occurring *Cymodocea* spp. and *Halodule* spp. was restricted to the high tide edge near the channel.

Image 2: Seagrass meadow dominant of *Thalassia hemprichii* in heterogeneous Site 1, Burmanallah [South Andaman, *Photo Credits: Swapnali Gole*]

Site 2, Laxmanpur (11°50'53.45''N, 93° 0'45.22'' E), is located on the north-western front of Shaheed Dweep in the Ritchie's archipelago (Figure 5.2). Meadow spread here was continuous and exposed to wave action. The habitat profile was comparable with Site 1 except for less hard substrata and more fine sand at the high tide edges (Image 3). Low tide edges of the meadow were similar to Site 1.

Image 3: Continuous seagrass growth of *Thalassia hemprichii* in Site 2, Laxmanpur; meadow expansion visible till high-tide edges, vegetation submerged even in low tides [Shaheed Dweep, *Photo Credits: Sumit Prajapati*]

Site 3, Vijayanagar (12° 0'39.99" N, 93° 0'45.31" E) lies on the north-eastern coast of Swaraj Dweep, Ritchie's archipelago (Figure 5.2). Meadow spread was highly continuous-fragmented with diverse species composition. *Enhalus* *acoroides* was the dominant species, followed by *T. hemprichii* and *C. rotundata* (Image 4). The habitat here was primarily sandy. Geographically, Sites 2 and 3 were located close (~ 8 NM), while Site 1 was spaced apart from the other meadows (> 20 NM).

Image 4: Mixed-species meadow in Site 3, Vijay Nagar [Swaraj Dweep, Rithcie's archipelago, *Photo Credits: Ajay Kumar*]

Since the field sampling overlapped with the second COVID lockdown in the Islands, I could not replicate the seasonal study for Site 3 (restrictions on inter-island movement). Thus, I surveyed only sites 1 and 2 for the first component, seagrass seasonality, while all three sites were sampled for the second component (edge effect).

5.2.2. Field sampling, laboratory, and statistical analysis (group-level macrofaunal analysis)

I mapped the entire perimeter of a seagrass meadow in low spring day tides. Reference maps were created in the Google Earth engine for each season. Exploration was also done beyond the meadow margins to demarcate the correct edges (Image 1). Sampling points were randomly chosen to cover the meadow's edges equally. Sample sizes were decided depending on the patch size (seagrass spread). I sampled 40 data points for sites 1 and 2 (all three seasons) and 20 for site 3 (only winter). For the edge effect, sampling was done across three gradients: a) the edge of the meadow, b) the center of the meadow, and c) unvegetated regions. For the patch interior (center), the two longest diagonal axes from the meadow margins were created, and the intersection points were treated as the meadow's center. Similarly, 5 m outside the edges, I surveyed the bare regions to study associated faunal groups of unvegetated habitats.

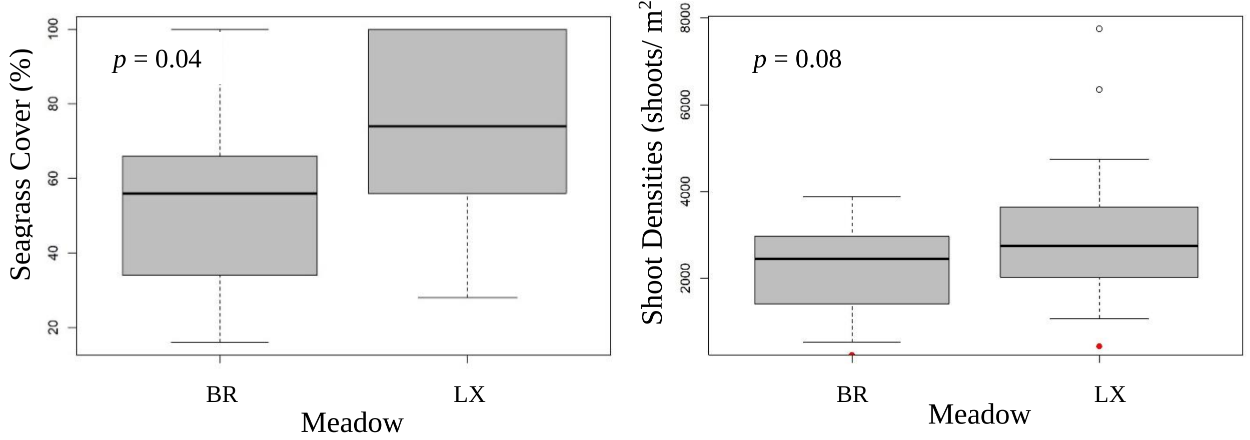
Seagrass cover (total and species-specific), habitat profile, and associated epifauna was quantified from the pre-marked sampling points using a 0.5 × 0.5 m quadrat made of a PVC pipe (Rattanachot et al., 2020). After on-field data documentation, I collected seagrass samples from a smaller 20 × 20 cm quadrat to assess total plant biomass (above and below ground), shoot densities and canopy height. Plant samples were rinsed with fresh water and cleaned of epiphyte and sediments. After cleaning, shoots were counted to estimate shoot densities (shoots/m^2), samples were air-dried, and dry weight was measured to give total plant biomass (above and below ground, gm/ m^2). Epifaunal and infaunal data collection and analysis were done using the detailed methodology mentioned in Chapter 4 (see sections 4.2.1 and 4.2.2). The macrofaunal communities were identified using standard taxonomic guides (see section 4.2.2). Epi- and infauna were identified up to group level, and later, group-specific densities (ind./m^2) or coverage (%/ m^2) were calculated.

Lastly, I checked the normality of the data using the Shapiro-Wilk test. Since the data was non-normal in distribution, I checked for between-patch seagrass variability (Sites 1 and 2) and within-patch seasonality (across seasons) using non-parametric tests such as the Man-Whitney U test and Kruskal-Wallis test. In case of significant dissimilarity, an add-on post-hoc Dunn test was performed to check for dissimilarities between the two seasons. A similar approach was used for the edge effect study across three sampling gradients: edge, center, and unvegetated niches.

5.3. Results

5.3.1. Between-patch seagrass variability and within-patch seasonality (Sites 1 and 2)

Between sites 1 and 2, seagrass growth significantly varied in cover and canopy height. The mean seagrass growth was the highest in Site 2 (exposed meadow). Coverage varied from 53.8 % to 74.2 % for Sites 1 and 2, respectively (p value = 0.004, Figure 5.3A). I also observed a similar trend for shoot densities and biomass between sites (Figures 5.3B and C). However, this difference was not statistically significant. The mean canopy height for *Thalassia hemprichii* significantly differed between Sites 1 (6.3 ± 1.5 cm) and 2 (9.2 ± 0.8 cm, *p* value = < 0.05, Figure 5.3D).


(A) Between-patches Seagrass Cover (B) Between-patches Shoot Densities

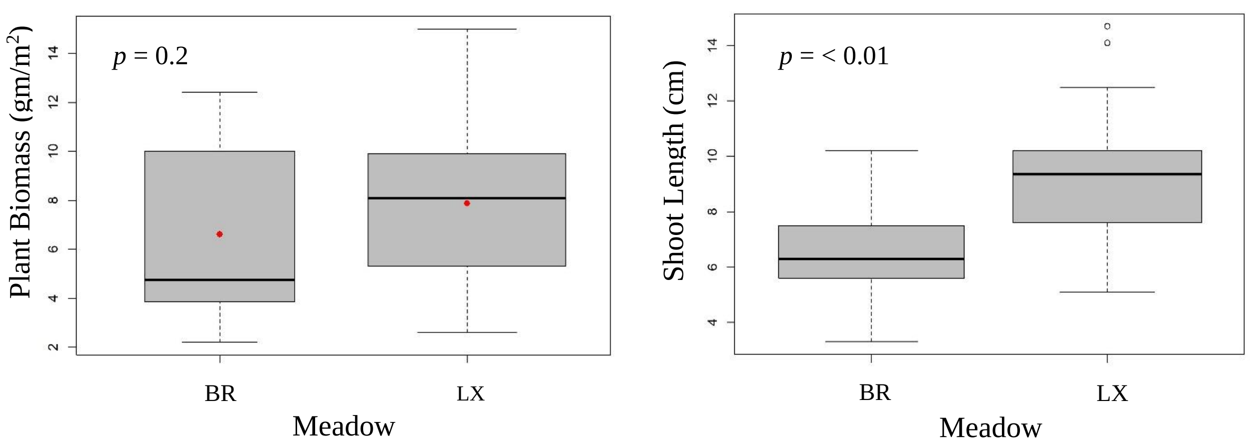

(C) Between-patches Plant Biomass (D Between-patches Shoot Length

Figure 5.3: Between-patches variation in seagrass growth in the investigated meadows, Andaman Islands [BR- Site 1, Burmanallah; LX- Site 2, Laxmanpur]

Site 1 exhibited a substantial within-site seasonal variability (Table 5.1). The spatial extent for this meadow changed in the following order: monsoon (5.26 ha) > winter (5.09 ha) > summer (3.94 ha) (Table 5.1). Summer showed less seagrass coverage than monsoon (*p* value = 0.02; Z = 2.76) and winter (*p* value =

0.05; Z = 2.25, Post-Hoc Dunn, Table 5.1). Similar trends were observed for shoot densities (*p* value = 0.005, Z = 3.13) and plant biomass (*p* value = 0.001, Z = 3.28, Table 5.1). I observed reduced canopy height in summer and the highest in monsoon (Table 5.1).

Although the meadow spread in Site 2 was much lower than in Site 1, seagrass growth was continuous and transitioned from 2.3 ha in winter to 2.1 ha in monsoon, with the lowest in summer (1.8 ha). Contrary to the monsoon in Site 1, in Site 2, I found high seagrass growth (shoot densities, total plant biomass, and shoot length) in winter (Table 5.1). However, inter-seasonal variability was observed only for plant biomass between summer (6 ± 2.4 gm/ m^2) and winter (9.9 ± 2.8 gm/ m^2, *p* value=0.01, Z =2.53). Shoot densities and canopy height showed no noteworthy variation across three seasons (Table 5.1)

Table 5.1. Seagrass meadow features and seasonality across three investigated sites in the Andaman Islands, India

Sites	**Seagrass species**	**Meadow attributes**	**Summer (April)**	**Monsoon (August)**	**Winter (January)**	***p* value (Across seasons)**
1	*Thalassia hemprichii,* *Cymodocea rotundata,* *Cymodocea serrulata,* *Halodule pinifolia,* *Halodule uninervis*	Seagrass cover (%)	36.44*#	66.22*	58.66#	0.01
sheltered		Shoot densities (shoots/m^2)	1533 ± 705.6*	2950 ± 452.3*	2272.2 ± 990.4	0.007
mixed-species		Seagrass biomass (g/m^2)	3.7 ± 1.5*	9 ± 2.9*	6 ± 3.7	0.005
patchy		canopy height (cm)	4.8 ± 2.1*	7.7 ± 2.3*#	6.4 ± 2.1#	0.001

	Seagrass species	**Meadow attributes**	**Summer (April)**	**Monsoon (August)**	**Winter (January)**	***p* value (Across seasons)**
2	*Thalassia hemprichii*	Seagrass cover (%)	64.88	80.4	77.33	0.59
exposed		Shoot densities (shoots/m^2)	2500 ± 1708.4	3100 ± 872.4	3391.7 ±1814.4	0.15
mono-species		Seagrass biomass (g/m^2)	6 ± 2.4*	7.5 ± 3.6	9.9 ± 2.8*	0.04
continuous		canopy height (cm)	9.4 ± 2.5	8.4 ± 1.6	9.9 ± 3	0.23

3	**Seagrass species**	**Meadow attributes**	**Summer (April)**	**Monsoon (August)**	**Winter (January)**
exposed		Seagrass cover (%)	x	x	62.5 ± 13

mixed-species continuous-fragmented	*Enhalus acoroides, Syringodium isoetifolium, Halodule uninervis, Cymodocea rotundata, Thalassia hemprichii, Halophila ovalis*	Shoot densities (shoots/m^2)	x	x	2080.7 ± 520.9
		Seagrass biomass (g/m^2)	x	x	10.6 ± 2.7
		canopy height (cm)	x	x	11.5 ± 2.2

[*# indicate significant differences between two categories in the posthoc Dunn test, x indicates no seasonal replicates for Site 3]

5.3.2. Influence of seagrass seasonality on macrofaunal assemblages (Sites 1 and 2; group-level)

a) Infauna

Infauna across sites comprised seven groups: bivalves, gastropods, polychaetes, nematodes, crustaceans, nemertean worms, and oligochaetes. The group richness was comparable across sites (7:6:6, Sites 1:2:3) and three seasons within sites. The sheltered meadow in Site 1 supported higher infaunal densities (96.2 ± 18.1 ind./m^2, mean ± Std. Error) than the exposed meadow of Site 2 (76.5 ± 13.4 ind./m^2). An across-sites comparative of only winter revealed the lowest infaunal densities in Site 3 (67.5 ± 26.3 ind./m^2) as compared to Sites 1 (72.2 ± 18.7 ind./m^2) and 2 (79.76 ± 11.2 ind./m^2). Polychaetes and nematodes numerically dominated Site 1, collectively contributing to > 60 % of the total abundance. Crustaceans, gastropods, bivalves, nemertean, and oligochaete worms occurred in low densities in this meadow. For Site 2, I observed a similar group richness except for the absence of oligochaetes, while crustaceans and gastropods formed the dominant fauna (Table 5.2).

In Site 1, infauna was numerically dominant in summer. Polychaete densities also exhibited seasonality (*p* value = 0.009), with higher densities recorded in summer (925 ± 75.4 ind./m^2) than monsoon (231 ± 46.6 ind./m^2, *p* value = 0.006, Z = 2.72) and winter (278.6 ± 83.5 ind./m^2, *p* value = 0.01, Z = 2.43). Although I found higher nematode densities in summer than in other seasons, the variation was insignificant. Infauna in Site 2 did not exhibit any significant trends across the three seasons (Table 5.2).

b) Epifauna

Epifaunal assemblages included polychaetes, holothuroids, gastropods, bivalves, crustaceans, chiton, burrowers, and ophiuroids. Of which, the first three groups formed the dominant fauna of Site 1 (> 75 % of the total abundance). At the same time, polychaetes, and gastropods were > 85 % contributors to the epifaunal community in Site 2. I observed all eight groups from both sites. However, bivalves, ophiuroids, and chiton were not recorded at Site 3. Across-site winter comparison revealed low group richness (8:8:5; Sites 1:2:3) and densities in Site 3. The winter epifaunal densities observed were in the following order: Site 2 (17.0 ± 13.5 ind./m^2) > Site 1 (14.6 ± 7.9 ind./m^2) > Site 3 (7.8 ± 5.8 ind./m^2).

Total epifaunal densities like infauna were higher in Site 1 (44.9 ± 21.1 ind./m^2) than in Site 2 (32.8 ± 19.7 ind./m^2). In both meadows, I observed significant seasonal differences in total epifaunal and polychaete densities (Table 5.2). Mean epifaunal densities in Site 1 varied between winter and summer (p value = 0.01, Z = 2.48), with the former supporting the highest densities. In Site 2, epifaunal densities significantly varied between 'summer and winter' (p value = 0.003; Z = 2.96) and 'monsoon and winter' (p value = 0.005; Z = 2.79, Table 5.2). Polychaete densities in both sites were high in winter (Table 5.2), while no significant seasonal trends were observed for other dominant groups (Table 5.2).

Table 5.2. Seasonal variation in macrofaunal densities with respect to seagrass seasonality in Sites 1 and 2, Andaman Islands

SITE 1: BURMANALLAH					
INFAUNA		**Summer (April)**	**Monsoon (August)**	**Winter (January)**	***p* value**
Group richness		5	6	6	
Group composition		bivalves, polychaetes, nematodes, crustaceans, gastropods	bivalves, polychaetes, nematodes, crustaceans, gastropods, nemertean	polychaetes, nematodes, crustaceans, gastropods, nemertean, oligochaetes	
Total infaunal densities (ind./m^2)		172.6 ± 57.7	43.7 ± 8.9	72.2 ± 8.7	0.06
Dominant groups	Polychaetes	925 ± 75.4*#	231 ± 46.6*	278.6 ± 83.5#	0.009
	Nematodes	213.4 ± 80	72.2 ± 17	63.9 ± 16	0.34
EPIFAUNA		**Summer (April)**	**Monsoon (August)**	**Winter (January)**	***p* value**
Group richness		6	5	8	
Group composition		gastropods, bivalves, polychaetes, crustaceans, ophiuroids, burrowers	gastropods, bivalves, crustaceans, polychaetes, holothuroids	gastropods, bivalves, chitons, crustaceans, polychaetes, holothuroids, ophiuroids, burrowers	
Total epifaunal densities (ind./m^2)		22.4 ± 9.5*	53.33 ± 8.1	116.8 ± 27.5*	0.05
Dominant groups	polychaetes	2.8 ± 1.3*#	16.7 ± 5*	50 ± 5.4#	0.001

	gastropods	0	22.2 ± 6.4	36.1 ± 5.1	0.06
	holothuroids	0	8.3 ± 7.8	8.3 ± 7.7	0.8143

SITE 2: LAXMANPUR					
INFAUNA		**Summer (April)**	**Monsoon (August)**	**Winter (January)**	***p* value**
Group richness		5	5	6	
Group composition		gastropods, bivalves, polychaetes, nematodes, crustaceans	gastropods, bivalves, polychaetes, nematodes, crustaceans	gastropods, bivalves, polychaetes, nematodes, crustaceans, nemertean	
Total infaunal densities		49.2 ± 4.6	67.9 ± 7.1	79.8 ± 11.2	0.3767
Dominant Groups	crustacean	125 ± 3.4	75 ± 5.4	120.8 ± 4.1	0.3214
	gastropods	22.2 ± 5.8	45 ± 5.4	33.3 ± 4.5	0.5604
EPIFAUNA		**Summer (April)**	**Monsoon (August)**	**Winter (January)**	***p* value**
Group richness		5	4	7	
Group composition		bivalves, polychaetes, crustaceans, ophiuroids, burrowers	polychaetes, crustaceans, ophiuroids, gastropods	bivalves, polychaetes, ophiuroids, burrowers, gastropods, chiton, holothuroids	
Total epifaunal densities		25.1 ± 9.8*	59.4 ± 11.7#	187.8 ± 14.3*#	0.004
Dominant Groups	polychaetes	8.3 ± 5*	5.6 ± 1.7#	108.3 ± 17.5*#	0.0007
	gastropods	0	13.9 ± 1.1	19.4 ± 2.8	0.64

[*# indicate significant differences between two categories in the posthoc Dunn test, values expressed as mean ± Std. Error]

5.3.3. Influence of Edge effect on macrofaunal assemblages (Sites 1, 2 and 3)

Total macrofaunal densities showed no significant edge effect in Sites 1 and 2. In addition, I did not find any difference in infaunal densities (total and dominant guilds) with respect to position in the meadow (Table 5.3). However, epifaunal trends were site, season, and group-specific. For instance, in Site 3, epifaunal densities in winter were the highest at edges (43 ± 6.4 ind./m^2) and further decreased towards the center (28 ± 7.4 ind./m^2, *p* value = 0.01) and unvegetated sediments (7.3 ± 6.4 ind./m^2, *p* value = 0.03). At a group level, polychaetes in Site 1 exhibited a neutral edge in winter (Table 5.3). Contrary in Site 2, polychaete densities, in summer, were more concentrated in the bare sediments, but the dominance shifted to edges in the monsoon season (Table 5.3). The only group with a consistent trend across sites and seasons was holothuroids, where densities were concentrated in the interiors of the patch and further decreased towards edges and plant-devoid regions (Table 5.3). Other dominant guilds, such as epifaunal gastropods, infaunal nematodes, and crustaceans of all three sites, exhibited no edge effect.

Table 5.3. Macrofaunal responses to edge effect in the investigated intertidal seagrass meadows, Andaman Islands

EPIFAUNA- Site 1				
	CEN	**EDG**	**UNV**	***p* value**
Total densities (Epifauna)	53.1 ± 8.1	76.7 ± 7.7	83.5 ± 6.6	0.66
Polychaetes (total densities)	16.7 ± 3.1	26.2 ± 6.4	6.3 ± 4.9	0.38
Summer	0	3.6 ± 1.4	0	0.65
Monsoon	0	25 ± 6.2	18.8 ± 3.9	0.38
Winter	50 ± 0*	50 ± 4.7#	0*#	0.03
Gastropods (total densities)	16.7 ± 9.7	20.8 ± 8.4	29.2 ± 7.8	
Summer	0	0	6.3 ± 2.5	0.32
Monsoon	33.3 ± 8.9	16.7 ± 2.4	75 ± 19.02	0.63
Winter	16.7 ± 2.9	45.8 ± 8.1	6.3 ± 2.5	0.61

INFAUNA- Site 1				
	CEN	**EDG**	**UNV**	***p* value**
Total densities (Infauna)	70.6 ± 11.0	131.1 ± 19.5	104.0 ± 11.6	0.07
Polychaetes (total densities)	277.8 ± 85.1	380.6 ± 77.9	250 ± 51.1	0.91
Summer	683.3 ± 175.6	737.5 ± 935.6	200 ± 185.9	0.27
Monsoon	25 ± 3.3	141.7 ± 29.4	343.7 ± 31.3	0.35
Winter	125 ± 26.5	262.5 ± 78.7	206.2 ± 51.5	0.39
Nematodes (total densities)	102.7 ± 43.6	110.8 ± 43.9	108.3 ± 66.2	0.7
Summer	287.5 ± 94.5	192.8 ± 39.8	81.3 ± 17.9	0.44
Monsoon	116.7 ± 22.1	50 ± 21.2	81.3 ± 9.4	0.97
Winter	116.7 ± 11.2	37.5 ± 11.8	18.8 ± 2.5	0.78

Holothuroids (total densities)	16.7 ± 14.0*#	0*	0#	7E-04
Summer	0	0	0	0
Monsoon	25 ± 25.1*#	0*	0#	0.02
Winter	25 ± 25.1*#	0*	0#	0.02

EPIFAUNA- Site 2				
	CEN	**EDG**	**UNV**	***p* value**
Total densities (Epifauna)	61.2 ± 24.7	57.1 ± 16.4	52.1 ± 15.5	0.81
Gastropods (total densities)				
Summer	0	33.3 ± 14	12.5 ± 4.4	0.46
Monsoon	16.7 ± 8.7	57.1 ± 4.6	106.25 ± 80.7	0.75
Winter	0	50 ± 6.2	56.4 ± 5.5	0.58
Polychaetes (total densities)	158.3 ± 25.2	269.7 ± 29.5	208.33 ± 29.58	0.07
Summer	0*	279.2 ± 72.8*#	375 ± 58.8#	0.04
Monsoon	0*		18.8 ± 3.9	0.04

INFAUNA- Site 2				
	CEN	**EDG**	**UNV**	***p* value**
Total densities (Infauna)	47.8 ± 9.6	105.2 ± 7.5	112.8 ± 7.6	0.08
Gastropods (total densities)				
Summer	0	33.3 ± 24	12.5 ± 4.4	0.46
Monsoon	16.7 ± 8.9	57.1 ± 14.6	106.2 ± 18.7	0.75
Winter	0	50 ± 5.2	56.3 ± 1.5	0.24
Crustaceans (total densities)	11.1 ± 8.5	53.9 ± 6.2	37.5 ± 5.3	0.12
Summer	0	41.7 ± 6.5	12.5 ± 4.4	0.46
Monsoon	0	21.4 ± 9.3	37.5 ± 4.1	0.39

		289.3± 22.8*		
Winter	475 ± 11.6	273.5 ± 26.2	231.3 ± 81.9	0.64

Winter	33.3 ± 7.7	104.2 ± 4.1	62.5 ± 7.9	0.18

EPIFAUNA- Site 3 (Only Winter)				
	CEN	**EDG**	**UNV**	***p* value**
Total densities (Epifauna)	28 ± 7.4*	43 ± 6.4*	7.33 ± 6.4	0.04
Holothuroids	24 ± 7.4*	10.5 ± 5.7#	0*#	0.01
Gastropods	1.3 ± 1.3	18 ± 8.5	0.7 ± 0.5	0.36

	INFAUNA- Site 3 (Only Winter)			
	CEN	**EDG**	**UNV**	***p* value**
Total densities (Infauna)	94.7 ± 8.6	57.3 ± 5.9	55 ± 6.5	0.75
Polychaetes	36 ± 3.2	23.3 ± 7.9	21.3 ± 4.8	0.8
Nematodes	40 ± 4.5	13 ± 2.8	18 ± 6.5	0.65

[CEN- Centre, EDG- Edge, UNV- Unvegetated, *# indicate significant differences between two categories in the posthoc Dunn test, values expressed as mean ± Std. Error]

5.3.4. Environmental Data

Mean pH values for sites 1 and 2 were 7.2 ± 0.7 and 6.9 ± 1.1, respectively. Ambient temperature was comparable between sites, ranging from 27.2 °C in monsoon (August) to 34.3 °C in summer (April). Mean salinity was lower (28.8 ± 1.4 ppt) in site 2 (Laxmanpur) than in site 1 (Burmanallah, 31.2 ± 2.8 ppt), with the highest recorded values from site 1 in summer (33.5 ± 1.2 ppt). I observed low salinity and temperature for sites 1 and 2 in monsoon and winter, while the highest values for these variables were in summer. Contrarily, the highest pH was recorded in summer for Sites 1 and 2. The seasonal differences across sites are given in Table 5.4.

Table 5.4. Seasonal variation in environmental variables across sites

	Summer (April)	**Monsoon (August)**	**Winter (January)**
pH	Site 1: 7.8 ± 0.6 Site 2: 7.7 ± 0.4 Site 3: X	Site 1: 6.8 ± 0.8 Site 2: 6.2 ± 0.8 Site 3: X	Site 1: 7.1 ± 0.7 Site 2: 6.9 ± 0.7 Site 3: 7.2 ± 0.7
Temperature (°C)	Site 1: 34.3 ± 1.6 Site 2: 33.5 Site 3: X	Site 1: 20.8 ± 1.2 Site 2: 28 ± 1.2 Site 3: X	Site 1: 30.9 ± 1.1 Site 2: 28 ± 1.1 Site 3: 30.9 ± 1.1
Salinity (ppt)	Site 1: 33.5 Site 2: 29.9 Site 3: X	Site 1: 28.1 Site 2: 28 Site 3: X	Site 1: 32.2 Site 2: 28 Site 3: 30.1

[X- indicates not sampled for Site 3]

5.4. Discussion

5.4.1. Seagrass Seasonality (Sites 1 and 2)

Seagrass seasonality in the investigated meadows was influenced more by variability in the local environment than the species type. For instance, the same species, *Thalassia hemprichii*, exhibited a strong seasonality in Site 1 but showed a weaker influence in Site 2. Furthermore, patch size did not positively correlate with seagrass growth. Comparatively between Sites 1 and 2, the meadow extent in Site 1 (Burmanallah) was vast but supported low seagrass growth. In contrast, Site 2 (Laxmanpur) had high seagrass growth despite a much smaller spread. I attribute these between-sites patch-size differences to the habitat variability of both meadows. For instance, the reef-ward edges of both sites were hard-bottomed, limiting the down-slope expansion of *T. hemprichii*.

Furthermore, in Site 1, the high-tide boundaries were characterized by gravel, wholly exposed at low tides and devoid of plants. Thus, space availability was limited in Site 1, where seagrass distribution was restricted in the interstitial mosaic of sandy spaces created by dead coral algae and rubble, which retained water at low tides (Image 2). Under such a scenario, the vegetative colonization could be space-limited since hard substrata may restrict horizontal rhizome expansion, causing species to form a patchy yet spread-out distribution (high spread but dispersed low growth). On the contrary, the habitat in Site 2 showed more substratum continuity and optimum water depth to support submerged vegetation even during low tides. Inshore edges (high tide) in this meadow supported rhizomeelongation till shoreward limits, resulting in continuous, high seagrass growth even in limited spaces (small patch size but high growth, Image 3).

A common seasonal trend observed for both sites was reduced growth in summer. At the same time, the highest observed growth was in monsoon and winter for both sites. These findings align with a study from Palk Bay, southern India, where high and low growth was observed in monsoon and summer, respectively (Govindasamy et al., 2013). In line with this study, I observed low temperatures and salinity in monsoon and winter, indicating a high influx of fresh water and reduced evaporation rates in wet seasons, which are intense in summers. A key stressor for intertidal seagrasses is air exposure at low tides, which is even more critical in the daytime (Erftemeijer and Herman, 1994). For both the investigated meadows, sampling overlapped with prolonged air exposure to daytime spring tides (~ 3 hours), and observations in summer included burning and desiccation of leaves (brown shoots), also reported from South Sulawesi, Indonesia (Erftemeijer and Herman, 1994).

Summers are harsh in the Andaman and Nicobar Islands, with reports of coral bleaching in response to heat stress (Marimuthu et al., 2013). Heat stress impacts photosynthesis and resource accumulation in intertidal seagrasses (Shafer et al., 2007; Jiang et al., 2013). Additionally, air exposure affects below-ground tissue reserves, which are critical for *T. hemprichii*. A physiological study from Xincun Bay, China, reported low starch and high soluble sugar content from below-ground tissues of *T. hemprichii* as a response to the stress of lengthy exposure periods (Jiang et al., 2013). The present observations corroborate a recent local study on varied tolerances of intertidal species to air exposure in low tides (Rao et al., 2023). This assessment from North Andaman reported the strategy of *T. hemprichii* to avoid exposed microhabitats (less tolerance to heat stress) and the species' preference for submerged niches in the exposed meadow. Therefore, the observed seagrass seasonality could be attributed to environmental factors (pH, temperature, salinity, air exposure, and thermal stress) and spatial heterogeneity between sites, the effects of which are evident at low tides in the tropics (Laugier et al., 1999; Short et al., 2007).

5.4.2. Seagrass seasonality and macrofauna

Seagrass seasonality induced a differential effect on infauna and epifauna. In addition, the trends further varied between sites and dominant guilds. Although not statistically significant for all groups, in Site 1, I observed infaunal dominance in summer, aligning with the lowest seagrass growth. However, no fixed trends were observed for Site 2. Studies have argued over the influence of seagrass structure on infauna. While some supporting studies suggest that seagrass biomass, canopy structure, and shoot densities positively affect infaunal densities (Lee et al., 2001; Paula et al., 2001; Como et al., 2008), contradicting research implies otherwise (Stoner, 1980; Webster et al., 1998; van Houte-Howes et al., 2004; Leopardas, 2015). Howard et al. (1989) suggested that the influence of seagrass meadow structure is more evident on epifauna than infauna, as the latter is primarily buried in the sediment. Thus, the findings imply that infauna prefers seasons with low seagrass growth (summer), as a reduced root-rhizome network may provide more space for burrowing, resulting in differing relative seasonal abundances in sediment fauna (Skilleter, 1994).

Epifaunal densities (total and polychaetes) were high in winter, while the lowest observed values were in summer. In shallow coastal seagrasses, epifaunal communities are governed by the structural complexity in seagrass habitats (Moore and Hovel, 2010). In the present study, the seasonal dominance of epifauna is in line with productive seagrass growth, which can offer more spatial diversity and resources to epifauna. Despite high seasonal growth in monsoon for Site 1, maximum epifaunal densities were observed in winter. This trend could be caused by the harsh rainy season, impacting macrofaunal communities due to enhanced wave action. Vonk et al. (2010) reported large-scale echinoderm mortality from Indonesia in the rainy season caused by storms, which are frequent in the islands and more pronounced in the wet season. Comparatively, winter in the Islands is generally marked by calmer seas, and seagrass productivity is comparable with the wet season. Therefore, my observations suggest that epifaunal assemblages, which are critically influenced by seagrass growth (Heck and Wetstone, 1977; Connolly and Butler, 1996; Webster et al., 1998; Lee et al., 2001; Leopardas et al., 2014), showed a preference for the most conducive and less stressful season (i.e., winter), further reflected in their densities. These observations are coherent with studies that reported higher epifaunal diversity and abundances within more developed seagrass meadows (Scipione et al., 1996; Gambi et al., 1998).

Besides, multi-species seagrass meadows offer different phenological attributes (habitat complexity) to macroinvertebrates, influencing their abundances

(Stoner and Lewis, 1985; Attrill et al., 2000; Lee et al., 2001; Nakaoka et al., 2001), yet my observations from Site 3 suggest otherwise. The mixed-species meadow (Site 3, Image 4), with a much larger spread of all three sites, harbored the lowest macrofaunal densities in winter. I suggest two possible explanations for the observed trend: 1) fragmented habitat caused uneven across-site relative abundances and 2) more developed meadow enhanced predation risks. Meadow in Site 3 is a vast, continuous-fragmented bed with a montage of sand interspersed with seagrass. Although I do not present a metric on habitat fragmentation, multiple factors may have caused habitat alteration. Site 3, adjacent to the local settlements, is an intensive gleaning site in ebb tides (field observations). Secondly, fragmentation by boat anchorage has been reported previously, with resultant meadow scarring (Gole et al., 2023b). In addition, meadow 3 is an active herbivory ground (direct herbivory marks on shoots), confirmed for dugong grazing (feeding trails) by field observations and drone surveys (Wildlife Institute of India, unpublished data).

Megaherbivore grazing potentially results in patchy and fragmented meadows (Christianen et al., 2013), which may be of poor quality for macrofauna, impacting faunal densities (Boström et al., 2011; Yarnall et al., 2022). An alternative hypothesis to the observed trend is higher predation rates in developed meadows since high growth rates and canopy structure attract potential prey in diverse meadows (Orth et al., 1984). Predation pressure increases in vegetated regions and is further induced by seasonal changes in seagrasses owing to different life cycles of prey and predators (Young and Young, 1982; Summerson and

Peterson, 1984). Thus, macrofaunal response towards competitive interactions, prey-predator dynamics, and habitat fragmentation needs further investigation to understand the underlying patterns.

5.4.3. Edge Effect and macrofauna

Lastly, I suggest no clear-cut response of edge effect on infauna but little on epifauna. At a small-scale investigation such as the edge effect, this study implies that 1) seagrass structural variability (growth) did not vary concerning distance in the meadow. In other words, seagrass growth at the center of the meadow and edges was comparable; 2) the effect of edges on faunal densities was variable across sites, seasons, and investigated groups. Contrary to the observed variability in seagrass structures across the distance gradient (Moore and Hovel, 2010), resource availability offered by seagrasses was comparable within the patch interior and edges. Hence, I suggest that seagrass structural variability played little role in faunal densities. Although associated with the same seagrass species (*Thalassia hemprichii*), epifaunal polychaetes responded inversely between Sites 1 and 2. In Site 1, for instance, polychaetes showed a neutral edge in winter (comparable densities in the interior and at the edges), signifying equal resource opportunities across both gradients. However, for site 2, polychaete densities were concentrated at the edges and bare regions in summer and rainy seasons, suggesting possible interlinkages with adjacent habitats or high settlement rates at the edges (Eggleston et al., 1998; Moore and Hovel, 2010).

On the contrary, holothuroid abundance exhibited a consistent negative edge, where densities increased towards the interior from the edge, as Vonk et al.

(2010) reported for macrofauna. Sea cucumbers show strong seagrass dependency for food and shelter (Hartati et al., 2019; Tanita and Yamada, 2019; Nishihama and Tanita, 2021). Their avoidance of the edges indicates enhanced food opportunities inside the meadow (Boström et al., 2006). Noteworthy, I observed juveniles of sea cucumbers in winter from Sites 1 (*Holothuria atra*) and 3 (*Synapta maculata*), mainly as epiphytes on seagrass blades/ macro alga or seeking shelter under the canopy (field observations, Image 5). Under such a scenario, holothuroids' usage of patch interiors could be as safe shelters (Shulman, 1985) and more food (Nagelkerken et al., 2000); a strategy to avoid prey-predator encounter rates which are more pronounced at the edges, especially in lower shoot densities/ fragmented meadows (Peterson et al., 2001; Norbury and Overmeire, 2019).

These observations are congruent with previous assessments from the Islands, which reported sea cucumber aggregations in seagrasses, including juveniles (Gole et al., 2022b), highlighting winter as a critical reproductive period for holothurians where seagrasses act as potential nursery grounds. Present findings differ from studies from other geographic regions (except polychaetes from site 2), which reported higher epifaunal densities at the patch edges than interiors (Bologna and Heck, 2002; Tanner, 2005; Moore and Hovel, 2010; Vonk et al., 2010). However, based on observed trends, I suggest that site-specific variations in the local environment influence epifauna more than seagrass identity (Edgar, 1990).

In conclusion, seagrass seasonality is a product of the local environment rather than the species type from the investigated meadows. Further, seagrass seasonality substantially influenced macrofauna more than the edge effect. I suggest that infauna vastly preferred seasons with low seagrass growth (summer). In contrast, epifauna preferred calm seasons with high seagrass growth (winter). In addition, group-specific responses of dominant guilds towards ecological processes, seasonality, and edge effect are consistent with global studies (Edgar, 1990; Gambi et al., 1998; Nakaoka et al., 2001). Further, I suggest the investigation of critical determinants causing fundamental patterns on community assemblages, such as reproductive cycle, migration, prey-predator dynamics, habitat requirements, and inter-patch fragmentation dynamics which vary for taxa and sites are potential future research prospects (Nelson, 1979; Jernakoff et al., 1996; Toyohara et al., 1999; Nakaoka et al., 2001; Bos et al., 2008; Yarnall and Fodrie, 2020; Yarnall et al., 2022). This is the first ecological baseline to study community responses towards seasonality and edge effect from Indian waters. Hence, the present study has filled an ecological lacuna in seagrass research and highlights the importance of conserving this habitat in the Andaman and Nicobar Islands.

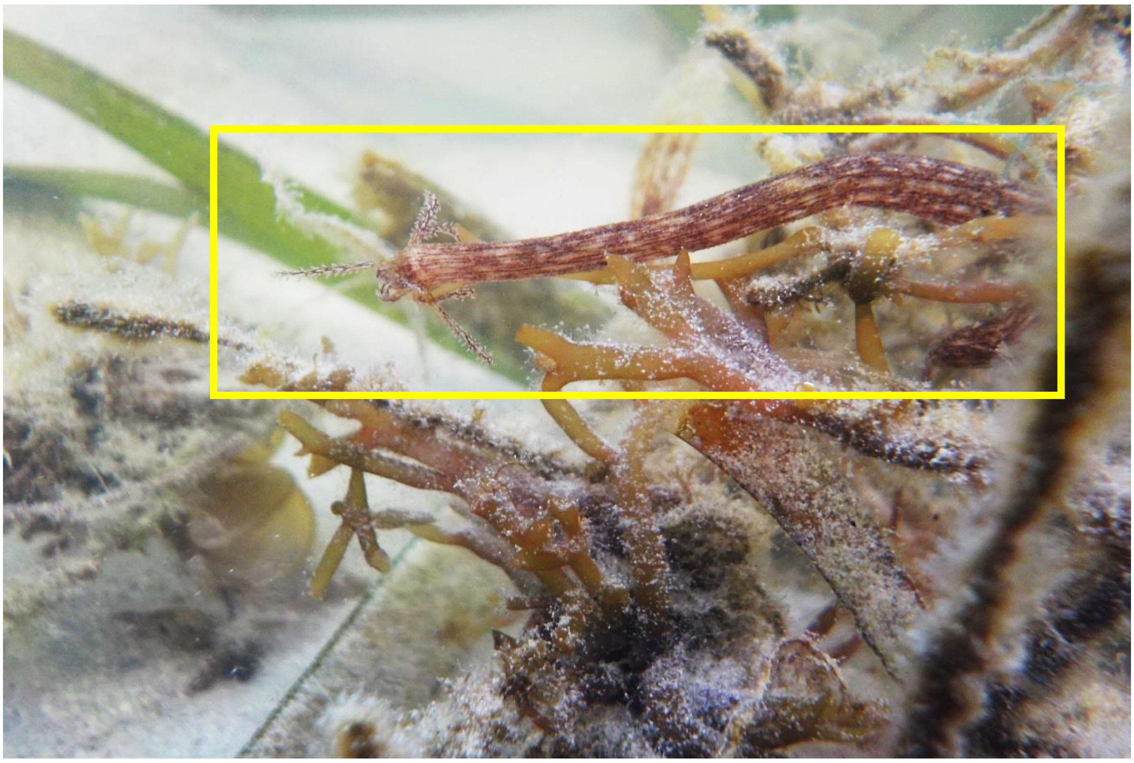


Image 5: Juvenile of *Synapta maculata* (in yellow box) in mixed-species meadow of Site 3 [Vijay Nagar, Swaraj Dweep; *Photo Credits: Swapnali Gole*]

CHAPTER 6: COMMUNITIES AND SEAGRASS- PEOPLE'S AWARENESS AND PERCEPTIONS TOWARDS SEAGRASS ECOSYSTEMS

6.1. Introduction

Seagrass is a critical coastal marine ecosystem globally recognized for the rich biodiversity it supports (Hemminga and Duarte, 2000). With a fundamental recognition in world fisheries, seagrasses provide high commercial services and food security to the coastal populace (Unsworth and Cullen, 2010; Campagne et al., 2015; McKenzie et al., 2021). The well-known ecological function of seagrass as nursery grounds serves commercially important fishes and marine invertebrates, thus contributing to recreational, subsistence, and commercial fisheries (Nordlund et al., 2018; Unsworth et al., 2018). From a fisheries perspective, the resources from these habitats are not solely seagrass-derived, but also an outcome of the intricate habitat connectivity seagrass share with mangroves and coral reefs, resulting in collective rich diversity. For instance, depending on the life cycle and biological traits, fishes migrate between seagrasses, corals, or mangroves either for feeding, spawning, or recruitment, with the former acting as primary nurseries (Unsworth et al., 2007; Berkström et al., 2013). Thus, seagrass ecosystem is a highly productive and dynamic resource provider in fisheries.

Seagrass, also acts a crucial blue carbon ecosystem that addresses challenges posed by climate change, thus, benefiting the coastal peoples' food security and economy (de los Santos et al., 2019; Jones et al., 2022a). Hence, human interactions with seagrasses on multiple levels have boosted socio-economic growth, livelihood, and well-being of communities living by the Sea (de la Torre-Castro et al., 2004; Nordlund and Gullström, 2013; Campagne et al., 2015). The local societies which rely on resources in and around seagrasses, engage in either traditional gleaning for domestic consumption (Unsworth and Cullen, 2010; Bandeira and Paula, 2014) or through commercial fisheries that contribute to their monetary means of support (Nordlund et al., 2010, 2018; Mtwana Nordlund et al., 2016). Despite the varied nature of interface, the coastal populace tends to have more accumulated information on the seagrass and environment, which could be used in coastal management (Pilgrim et al., 2007).

The inherited environmental information, also known as Local Ecological Knowledge (LEK), is gained over generations through hands-on training experience and observations of surroundings (Olsson and Folke, 2001). Marine scientists have successfully tapped into this information to address species ecology, habitat use, connectivity, migration, and management (Le Fur et al., 2011). Furthermore, reports on coherence of the LEK with Conventional Scientific Knowledge (CSK) highlights the reliability and potential use of local knowledge repository in addressing management issues (Le Fur et al., 2011; Berkström et al., 2019). This approach could provide more robust information on the socio-ecological dynamics of marine habitats. For instance, using LEK, a thorough dependency of fishers on seascapes could be charted for the fishery benefits while proposing Marine Protected Areas (Berkström et al., 2019). Thus, putting LEK into management perspective along with scientific knowledge (CSK) could provide a road map for community-based management of marine biodiversity (Crona, 2006; Begossi et al., 2016).

Including local communities in addressing research gaps, policy-making, and management is particularly critical in developing countries that often lack resources and logistics for robust scientific studies (Davis and Ruddle, 2010; Taylor et al., 2011; Thornton and Scheer, 2012). Nevertheless, the socio-ecological drivers of the human-seagrass relationship require more focused studies from the tropics (Herrera et al., 2022). Understanding local knowledge on seagrass is not only important to address research, but also to present mitigation measures. Owing to the community dependency on coastal habitats, reports of seagrass loss due to commercial and destructive fishing practices have surfaced (de los Santos et al., 2019), which requires immediate policy intervention (McKenzie et al., 2020). Most importantly, a multi-stakeholder approach in policy making requires substantial input from all actors; scientific community, managers, policymakers, and most importantly local communities. In addition, for effective seagrass management, a pre-requisite is to recognize the needs and rights of local communities, who substantially rely on these ecosystems for their livelihood. Thus, the socio-ecological dynamics of seagrass ecosystem is complex, and its implications in management and conservation can be achieved only with an in-depth analysis on the degree of awareness, utility, and perception of local communities.

With this background, I carried out the present research in a data-deficient, ethnographically unique social system of the Islands, which has diverse timelines of settlements, and therefore would present an expected variance in the ecological information on seagrasses across varying strata.

Ethnographic background of ANI and research rationale:

The Andaman and Nicobar Islands as a social system is unique, with the oldest narratives dating back to 1050 AD in the Tanjore Inscriptions of the Chola Dynasty, in memoirs of Marco Polo, and in several anecdotes of travellers and merchants using the Islands as trade routes (Chablani, 1949; Meenakshisundararajan, 2009). All the versions had one thing in common: the exaggerated stories revolving around the six indigenous tribes of the Islands: the Great Andamanese, the Jarawas, the Onges, the Sentinelese, the Shompens, and the Nicobarese. However, it was only after the British invasion of India (1857- 1947) that the strategical positioning of the Islands, trade potential, and natural harbors served as an apt location for penal settlement for mainland India's freedom fighters, giving the Islands, its first 'settler' communities in 1857 (Anderson, 2003). Since then, the islands have experienced a high immigration rate under the ambit of several socio-political-economic systematic expansion policies, making settlers the dominant communities in ANI. At present, the main ethnicities in the Islands are the settler populace from Mainland India, immigrants from Sri Lanka and Bangladesh, tribal settlers of Burma (Karens), and those, as mentioned above, six indigenous communities of the Islands (Sircar, 2004).

From the fisheries *per se*, expansion of the Islands was undertaken by the Government of India from 1955 onwards (Dorairaj and Soundararajan, 1985; Whittingham et al., 2003) to harness the fisheries potential of the region, as ANI contributes to 29.70 % of the country's Exclusive Economic Zone (Andaman and Nicobar Fisheries Policy, 2018[8]). Since then, the Islands have seen a rise in fishers along with transformation of indigenous and artisanal fisheries (Advani et al., 2013). Noteworthy, the settler history of the Islands, which predominantly forms the fishing population, is only a century deep-rooted. Even younger are the fisher settlements (5 to 6 decades old), with the early fleets established in the 1950s (Advani et al., 2013). The present fishing community in the Islands thus, had ancestors belonging to mainland India, especially Andhra Pradesh (south India) or West Bengal (east India), who did not share a robust connection with seagrass ecosystems, given the lack of seagrass distribution in these states (Thangaradjou and Bhatt, 2018).

Consequently, local fishers' knowledge is principally young and accumulated over three or fewer generations, unlike other case studies on seagrass allied LEK (Felger and Moser, 1985; de la Torre-Castro and Rönnbäck, 2004). Owing to this lack of long-term traditional percolation of knowledge system towards coastal habitats, understanding fishers' ecological perceptions in ANI, towards seagrasses, their utility and value system is particularly important. Therefore, primary aim of this study was to understand the nature of LEK, possessed by these comparatively newer generations of small-scale fishers on

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[8] http://www.and.nic.in/pdf/policydocument.pdf. (accessed on December 2023)

seagrass ecosystems. With this background, I explored the socio-ecological dynamics of the fishers and seagrass habitats in ANI. I attempted to understand how the local fishers in the islands perceived seagrasses, and if they were aware of their ecological and economic importance, the latter mainly revolving around fisheries.

The focal questions for this chapter entailed awareness, utility, and perception as follows;

1) How much LEK do the local fishers have towards seagrass ecosystems (awareness)?

2) Do the local communities derive benefits from seagrass habitats (utility)?

3) Do the small-scale fishers perceive seagrasses as important enough to be safeguarded (perception)?

6.2. Study Site and Methods

6.2.1. Registered fishers in ANI

In 2017-2018, the total number of licensed fishers in ANI was 7034, with 85 mechanized boats, 1353 motorized, and 1346 country crafts (non-mechanized) users (Andaman and Nicobar Fisheries Policy, 2018).

6.2.2. Methods

To study perceptions and value systems of seagrass habitats, I carried out semi-structured surveys with small-scale fishers in the Andaman and Nicobar Islands (Figure 6.1). Information on updated fishing localities, population, registered vessels, and crafts/ gear types was obtained from the Directorate of Fisheries, Port Blair. Around 4 to 10 % of the total fishers were interviewed from each surveyed Island, the degree of which varied based on data saturation and repeatability of answers. Interviews were conducted in Hindi, the most commonly spoken local language. Help was taken from translators for two communities, namely Nicobarese (Nicobar archipelago) and Karen (North Andaman). To begin informal interactions, I initially targeted fishers' hotspots on each Island, such as fishing jetties or marketplaces. After identifying a potential respondent, I requested a feasible time when a comparatively longer interaction was possible, and the interviews were conducted accordingly (interview places varied). Each interview lasted for ~ 30 to 45 mins.

Further, a snow-bowling approach was used to identify other respondents from the village (Goodman, 1961). Photo guides were used for questions about identifying seagrass species or the difference between seagrass and seaweed. Printed Google maps of the Andaman and Nicobar Islands were used for fishers to point out seagrass distribution sites. Most of these sites were known, owing to the seagrass exploratory surveys I did for my work (see Chapter 3). In case of unfamiliarity with the distribution sites (since fishers used local names), I took help from local contacts, such as forest department frontline staff, to delineate sites. Informed verbal consent was obtained from the respondents before the interview. For the only indigenous tribe interviewed, the Nicobarese, verbal consent was obtained from the village head first, before approaching the interviewees (Annexure 1).

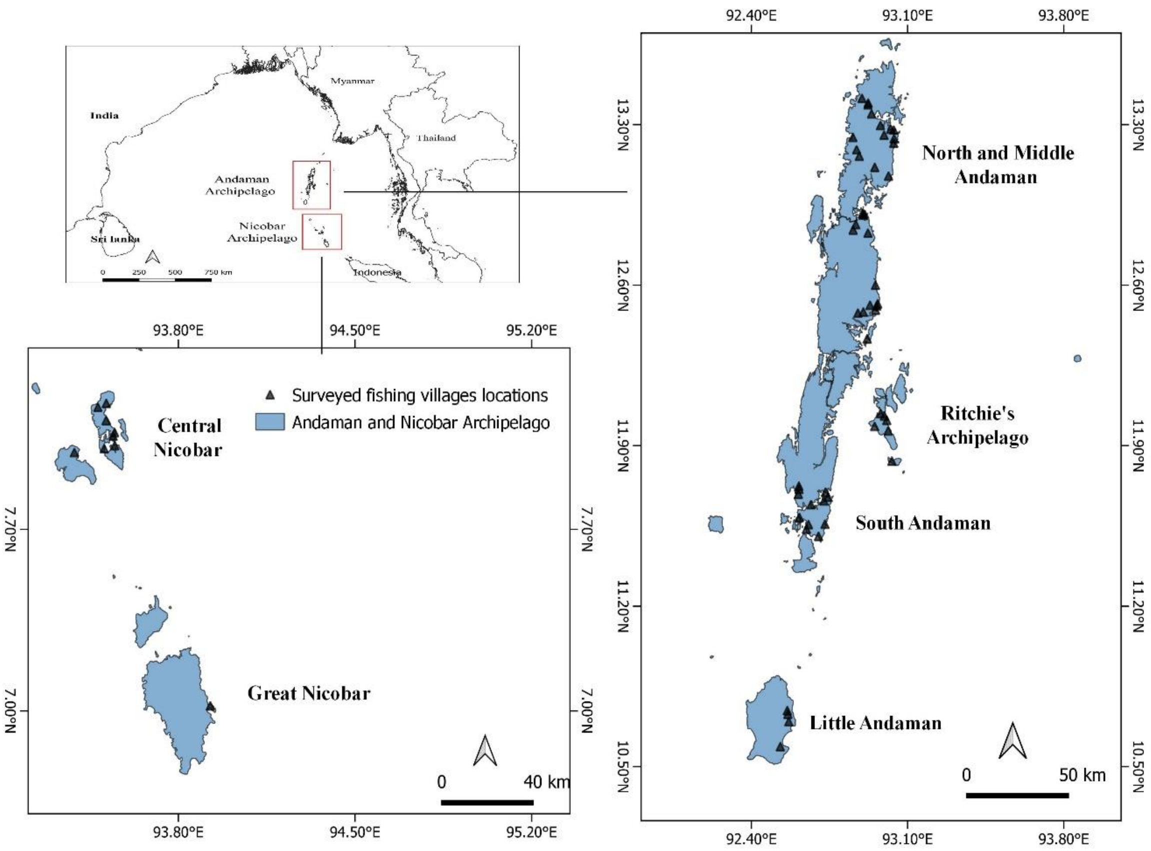


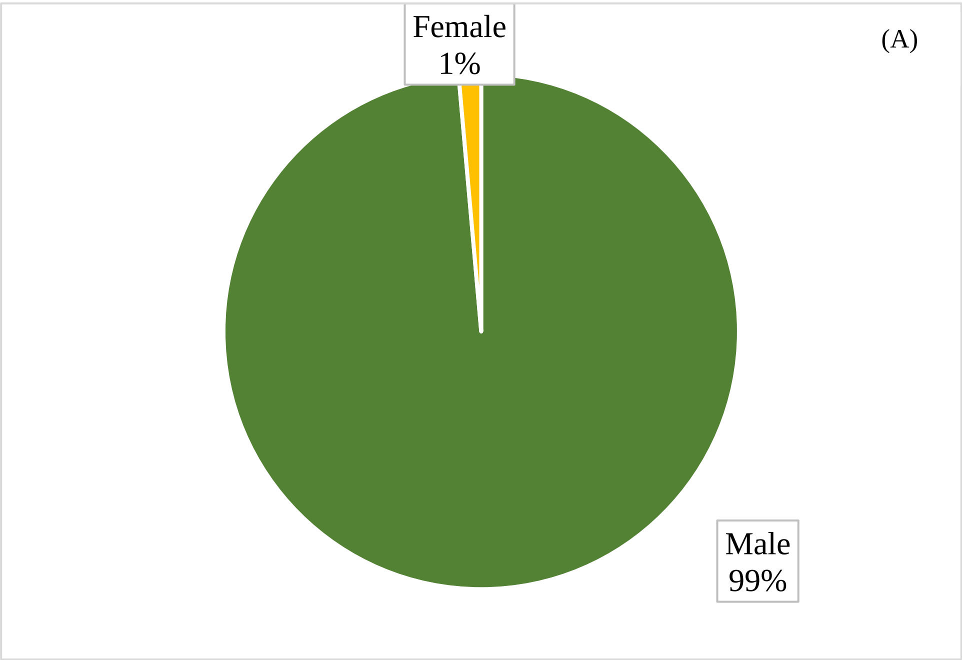
Figure 6.1: Fishing villages surveyed to understand socio-ecological dynamics of seagrass ecosystems in the Andaman and Nicobar Islands

6.3. Results

6.3.1. Respondent Profile

6.3.1.1. Age and Gender Distribution

223 small-scale fishers from 60 fishing villages were interviewed across various strata such as fishers' age classes, experiences, genders, crafts, and gears used. Of these, 99 % of fishers were males, and only 1 % were females (Figure 6.2A). The age class of respondents ranged from 20 to 70 years, with 54.7 % falling between 30 to 50 years (Figure 6.2B). The proportion of young (20 to 30 y, 27.3 ± 11 y) and retired fishers (60 to 70 y, 65.1 ± 12 y) were 14 % and 7.5 %, respectively (Figure 6.2B).



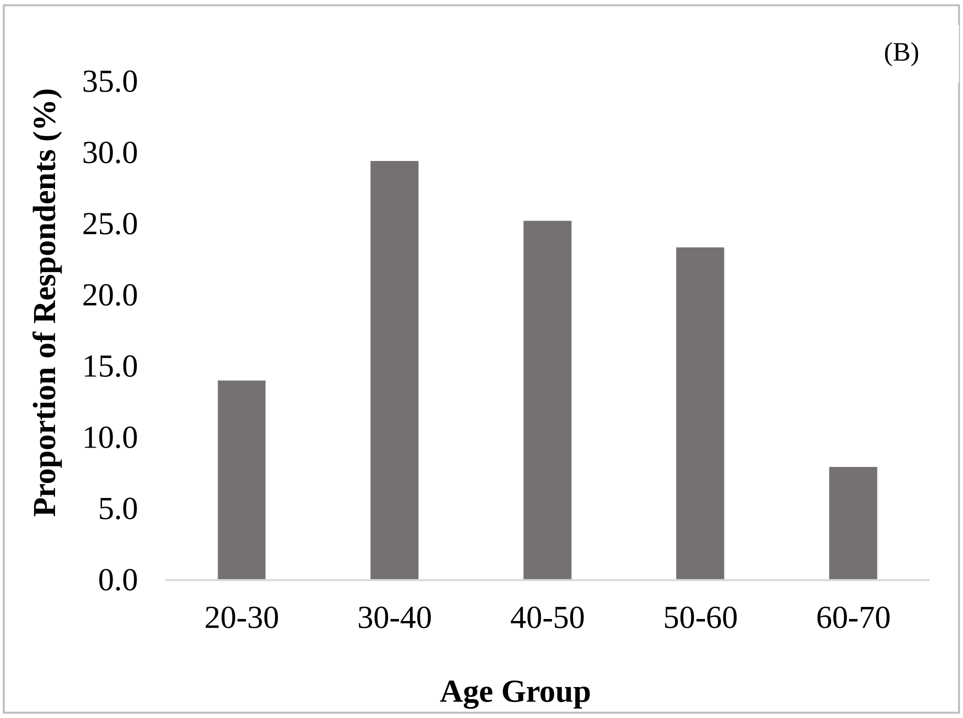


Figure 6.2: A) Gender and B) Age distribution profile of the respondents

6.3.1.2. Fishing history and experience

Majority of the fishers interviewed (~ 65 %) had a prior fishing background and belonged to either the second (14.5 %) or third generation of fishers in the family (50 %, Figure 6.3). However, 36 % of the fishers were the first in the families to opt for fishing as a livelihood option (Figure 6.3).

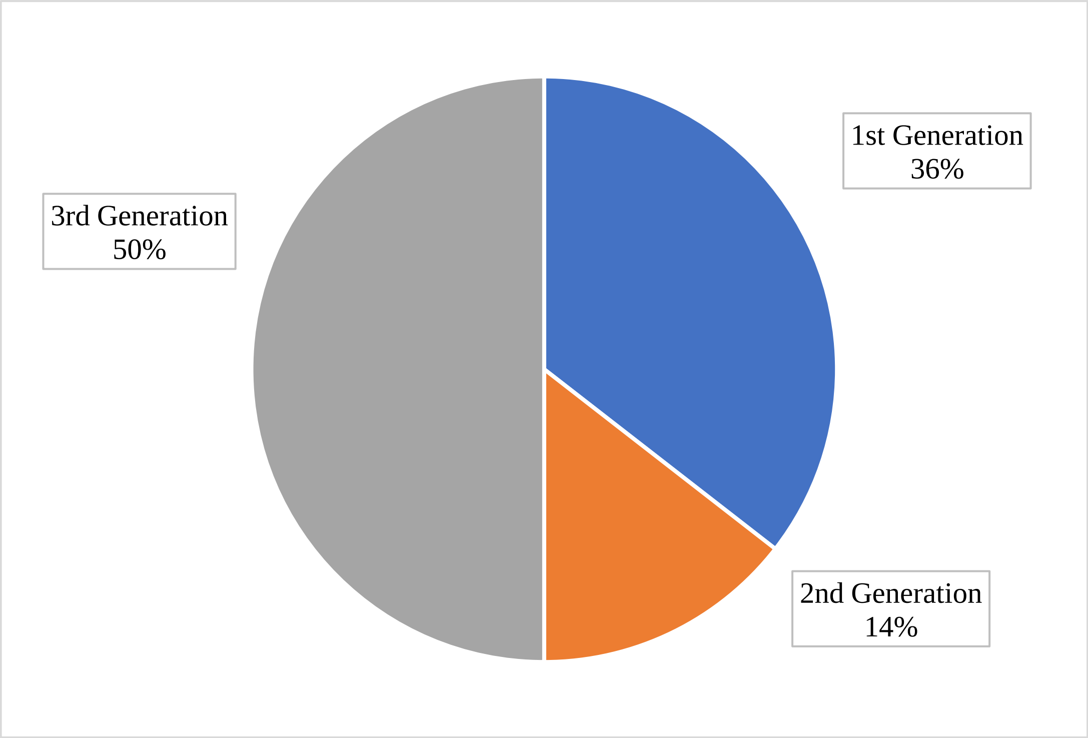


Figure 6.3: Fishing history of the respondents

Most respondents had 10 to 30 years of fishing experience (~ 50 %), while young fishers comprised 18.7 %. Elderly and retired fishers with 40 to 50 years of experience included 7.5 % of the respondents (Figure 6.4A). In total, fishing was the only source of livelihood for 37.4 % of fishers, while ~ 50 % had alternatives (Figure 6.4B). For the latter, 39 % were dependent on agriculture, followed by daily wagers in the Forest Department (6 %), tourism-allied sectors (5 %), or other jobs inclusive of service in defence.

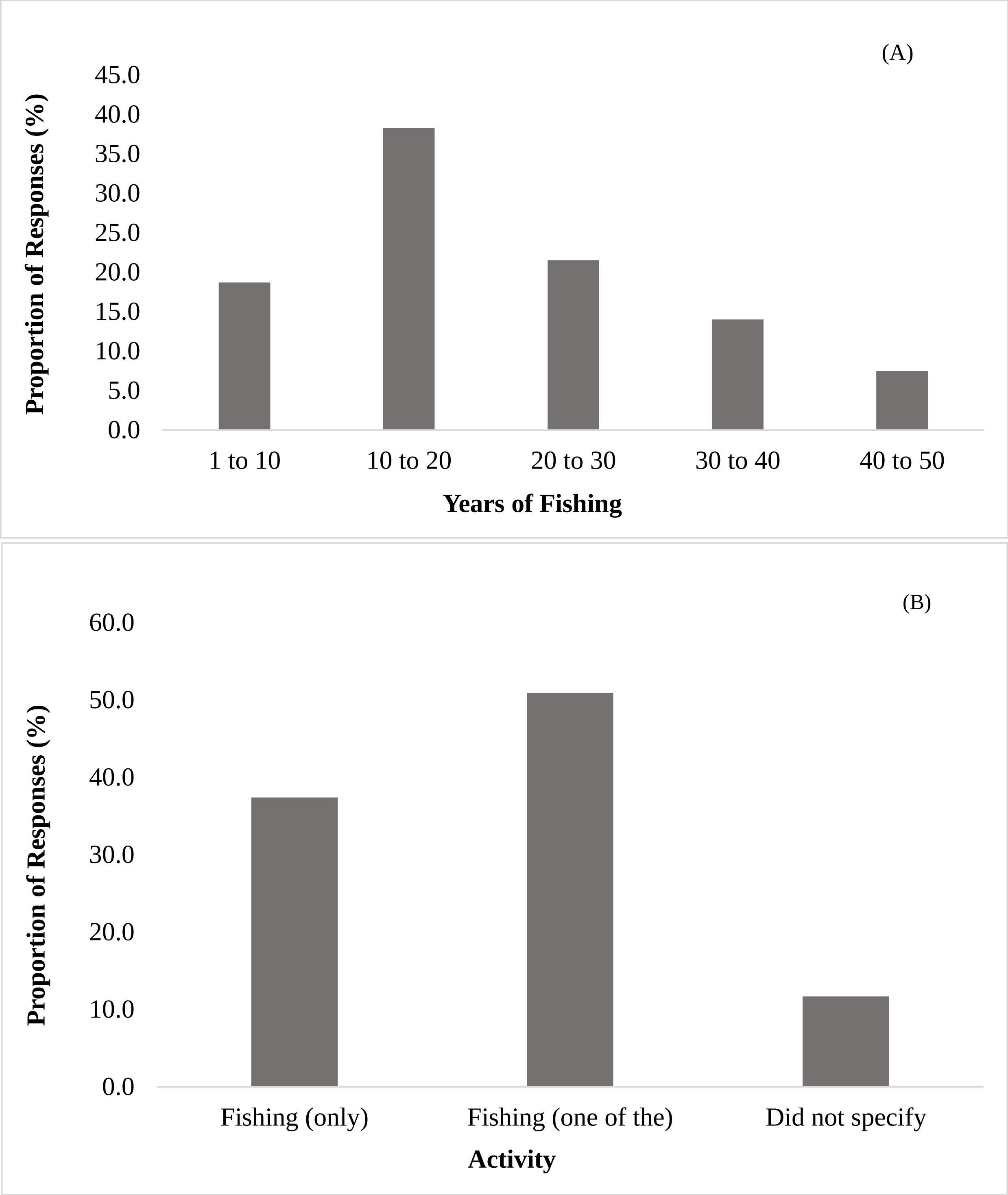


Figure 6.4: A) Years of occupation as a fisher, B) Fishing as livelihood

6.3.2. Fishing activities, Crafts and Gears

January to April months were ideal fishing seasons for the majority of respondents. However, activities continued throughout the year. Fishers largely depended on motorized boats (‘*dinghies’* in Hindi, 68 %). At the same time, non-motorized operators used dugout canoes (‘*Haleej,’* Hindi, or ‘*Hodi*’ Nicobari) for traditional fishing purposes (19 %). A smaller proportion of fishers (8 %) used a combination of both non-motorized (*Haleej*) and motorized boats. In addition, hook and line, gill net, and long line users comprised 88 % of the respondents—the remaining relied on cast nets, purse seines, and rod/spearfishing.

6.3.3. LEK: Awareness of seagrasses

Overall, 91.4 % (n=192) agreed to know what seagrasses are, yet only 50.3 % could tell the difference between seagrass (locally known as ‘*Samundri Ghaas’*: *Samundar*- Sea, *Ghaas*- grass, Hindi) and sea algae (locally known as ‘*Patthar Phool’*: *Patthar*- Stone, *Phool*- Flower, Hindi). Concerning the ages of fishers and their experience in the sea, 63.7 % of respondents (n= 102) within the age group > 40 y perceived seagrasses to be different from seaweeds. However, almost a comparable proportion of fishers with 10-20 years of experience agreed (39.2 %) and disagreed (37.5 %). 47 % of young fishers (age group 20 to 40 y; 33 ± 11 y) with an experience of only 5-10 years could barely tell the difference between both.

In general, fishers possessed observational LEK only on the most commonly found seagrass species in the ANI, such as *Thalassia hemprichii* (18.4 %), followed by *Halophila ovalis* (16.3 %), *Cymodocea rotundata* (11.7 %), *C. serrulata* (10.8 %) and *Enhalus acoroides* (10.5 %, Figure 6.5). Fishers were further aware of seagrass occurrence in ‘*Baalu*’ (sand, Hindi). Usage of local names for different types of seagrasses was common, based on their morphological differences—for instance, the entire *Halophila* spp. complex was addressed as 'goal patti' (round leaves), while 'lamba patti' was commonly used for long/ cylindrical leaved grasses (*Halodule* spp., *Cymodocea* spp., *Thalassia hemprichii*, *Enhalus acoroides*, and *Syringodium isoetifolium*). For the genus *Halophila* spp., *H. ovalis* was commonly differentiated from *H. decipiens* based on leaf shape (*H. ovalis*- oval, *H. decipiens*- elongated). In addition, fishers could roughly identify the species based on the differing width of the seagrasses.

The source of information mainly came from direct observations underwater or while fishing (74.8 %), followed by encounters when seagrasses were caught in fishing gears (nets or anchors, 7.9 %). Nevertheless, 11.7 % (n=25) fishermen did not remember how this knowledge was acquired, while 5.6 % reminisced about seeing stranded seagrass shoots on the beach due to wave action or after cyclones.

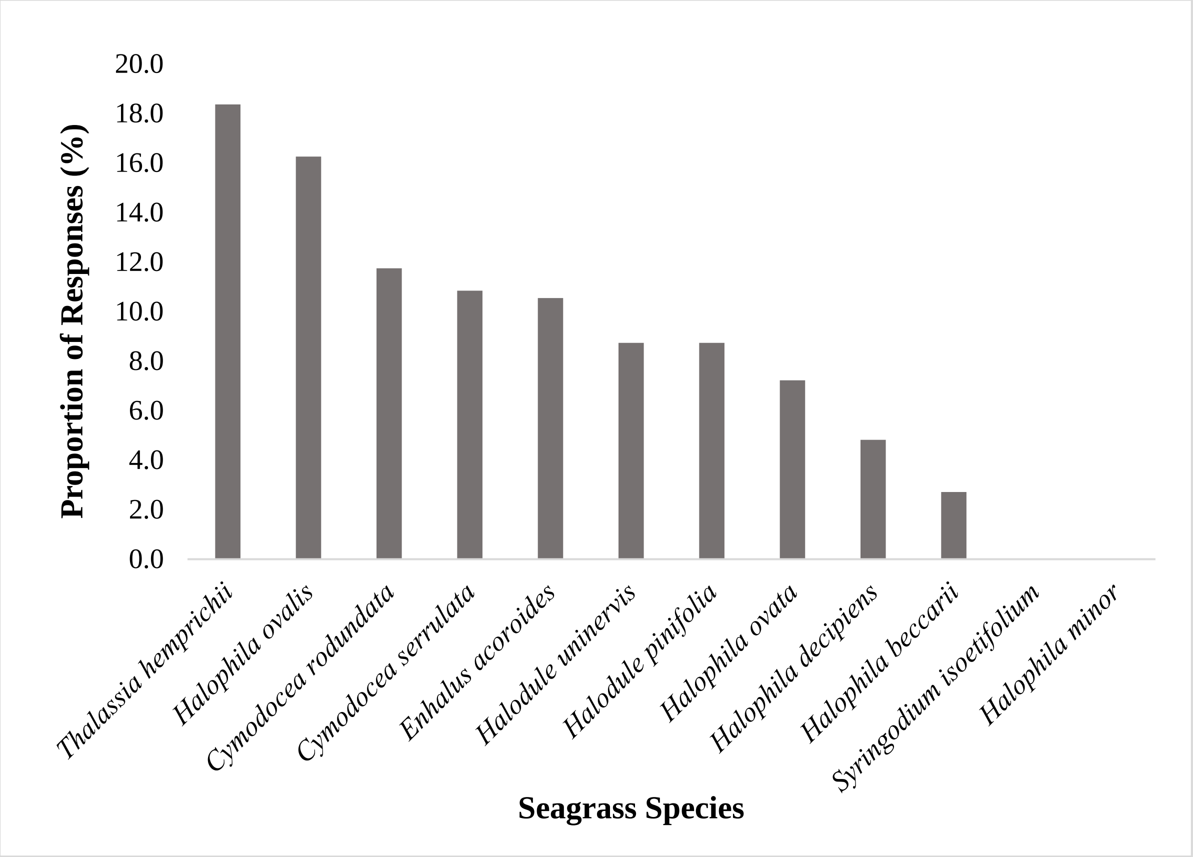


Figure 6.5: Level of awareness of seagrass species

6.3.4. LEK: Seagrass Distribution

Through the LEK, 113 potential seagrass distribution sites were given by fishers spanning across North Andaman to the Nicobar group of Islands (Table 6.1). Of these, maximum sites were reported from North and Middle Andaman (n=30), followed by Ritchie's archipelago (n=25 including Rani Jhansi Marine National Park), South Andaman (n=22 including Mahatma Gandhi Marine National Park), Nicobar (n=15), and Little Andaman (n=14, Table 6.1). The lowest observed meadows were from Middle Andaman and the Jarawa Tribal Reserve, the latter a tribal protected zone barring entry of civilians, where fishers had taken sheltered transit from bad weather (n=9, Table 6.1).

Table 6.1. Seagrass distribution sites derived through Local Ecological Knowledge (LEK) along with Conventional Scientific Knowledge (CSK) validation status [Sources for CSK: Present study (Chapter 3), D'Souza et al., 2015; Savurirajan et al., 2018]

Sr. No.	Island	LEK sites	CSK status
1	NMA	Landfall-East	Seagrass present
2	NMA	Mayabunder (Jetty)	Seagrass present
3	NMA	Durgapur	Seagrass present
4	NMA	Delgarno- Excelsior	Seagrass present
5	NMA	Aerial Bay	not surveyed
6	NMA	Sound	Seagrass present
7	NMA	Stuart Island	not surveyed
8	NMA	Karmatang	not surveyed
9	NMA	Aves	not surveyed
10	NMA	Reef	Seagrass present
11	NMA	North Reef	Seagrass present
12	NMA	Pokkadera	Seagrass present
13	NMA	Snake	not surveyed
14	NMA	Interview	Seagrass present
15	NMA	Hara Tikri (Opposite Interview)	not surveyed
16	NMA	Paget	Seagrass present
17	NMA	Radhanagar (Diglipur)	Seagrass present
18	NMA	Rampur	not surveyed
19	NMA	Paschim Sagar	not surveyed
20	NMA	Plastic Tikri	not surveyed
21	NMA	Suar Tikri	not surveyed
22	NMA	Ross & Smith	Seagrass present
23	NMA	20 Family	not surveyed

24	NMA	Ramnagar (Diglipur)	not surveyed
25	NMA	Thailand Tikri	not surveyed
26	NMA	Kishorinagar	not surveyed
27	NMA	Shibpur	not surveyed
28	NMA	Point	Seagrass present
29	NMA	Kalipur	Seagrass present
30	NMA	Shaitan Tikri	not surveyed
31	JTR	Hiran Tikri	not surveyed
32	JTR	Jarawa Tribal	not surveyed
33	JTR	Hans Puri	not surveyed
34	MA	Long Island	not surveyed
35	MA	Kadamtala	not surveyed
36	MA	Nimbu Dera	not surveyed
37	MA	Strait	Seagrass present
38	MA	North Passage	not surveyed
39	MA	Yeratta	not surveyed
40	MA	Amkunj	not surveyed
41	MA	Cuthbert Bay	not surveyed
42	MA	Shoal Bay	Seagrass present
43	SA	Burmanallah	Seagrass present
44	SA	Wandoor	Seagrass present
45	SA	Baratang	not surveyed
46	SA	Tirur	not surveyed
47	SA	Chidiyatapu	Seagrass present
48	SA	Guptapara	not surveyed
49	SA	Bada Balu	not surveyed
50	SA	Bamboo Nali	not surveyed
51	SA	Rutland	Seagrass present
52	SA	Balu Dera	not surveyed
53	SA	Pathan Tikri	not surveyed
54	SA	Cinque	not surveyed

55	SA	Brijgunj	Seagrass present
56	SA	Manjery	not surveyed
57	SA	Marina Park	Seagrass present
58	SA	North Bay	Seagrass present
59	SA	Dhani khadi	not surveyed
60	SA	Palmer Point	not surveyed
61	SA	Collinpur Beach	not surveyed
62	MGMNP	Jolly Buoy	not surveyed
63	MGMNP	Tarmugli	Seagrass present
64	MGMNP	MGMNP	Seagrass present
65	RA	Outram	not surveyed
66	RA	Dolphin	Seagrass present
67	RA	Silver Sand	not surveyed
68	RA	Elephant Beach	Seagrass present
69	RA	Neil's cove	not surveyed
70	RA	Char Nariyal	not surveyed
71	RA	Kalapatthar (Havelock)	Seagrass present
72	RA	Ramnagar (Neil)	Seagrass present
73	RA	Bharatpur	Seagrass present
74	RA	Laxmanpur	Seagrass present
75	RA	Neil Kendra	Seagrass present
76	RA	Sitapur	not surveyed
77	RA	Natural Bridge	Seagrass present
78	RA	Chota Neil	Seagrass present
79	RA	Maharaja Tikri	not surveyed
80	RJMNP	Jua Tikri	Seagrass present
81	RJMNP	Inglis	Seagrass present
82	RJMNP	Chand Balu	Seagrass present
83	RJMNP	Henry Lawrence	Seagrass present
84	RJMNP	John Lawrence	Seagrass present
85	LA	Brother-Sister	not surveyed

86	LA	Lighthouse (Little Andaman)	Seagrass present
87	LA	Dugong Creek	not surveyed
88	LA	Butler's Bay	Seagrass present
89	LA	VK Pur	Seagrass present
90	LA	Hutbay	Seagrass present
91	LA	Sukha Nali	Seagrass absent
92	LA	Magar Nali	not surveyed
93	LA	RK Pur	Seagrass present
94	LA	Patthar Nali	Seagrass present
95	LA	Harminder Bay	Seagrass present
96	LA	Junction	not surveyed
97	LA	Mahua Dera	not surveyed
98	LA	Kalapatthar (Little Andaman)	Seagrass present
99	NIC	Campbell Bay	Seagrass present
100	NIC	Katchal	Seagrass present
101	NIC	Trinket	Seagrass present
102	NIC	Safed Balu	Seagrass present
103	NIC	Champin	not surveyed
104	NIC	Munak	not surveyed
105	NIC	Al Riyak	Seagrass present
106	NIC	Bada Inak	Seagrass present
107	NIC	Bandar Khadi	not surveyed
108	NIC	Tapong	not surveyed
109	NIC	Hitui	Seagrass present
110	NIC	Atkona	Seagrass present
111	NIC	Katchal Jetty	not surveyed
112	NIC	B Quarry	Seagrass present
113	NIC	Little Nicobar	not surveyed

[NMA, North and Middle Andaman; JTR, Jarawa Tribal Reserve; MA, Middle Andaman; SA, South Andaman; MGMNP, Mahatma Gandhi Marine National Park; RA, Ritchie's archipelago; RJMNP, Rani Jhansi Marine National Park; LA, Little Andaman; NIC, Nicobar]

6.3.5. LEK: Temporal Changes and Perceived Reasons

Seagrass habitats were reported to have declined temporally by 33.6 % of fishers (n=72), while the same proportion of respondents (33.6 %) did not perceive any changes in the meadows. Only a small share of respondents (6.1 %) supposed a likely increase in the seagrass cover, while 26.6 % (n=57) were unsure of any changes. Of the fishers who perceived a decrease in seagrass habitats, > 70 % attributed the Indian Ocean Tsunami of 2004 as the primary cause of habitat decline (Figure 6.6).

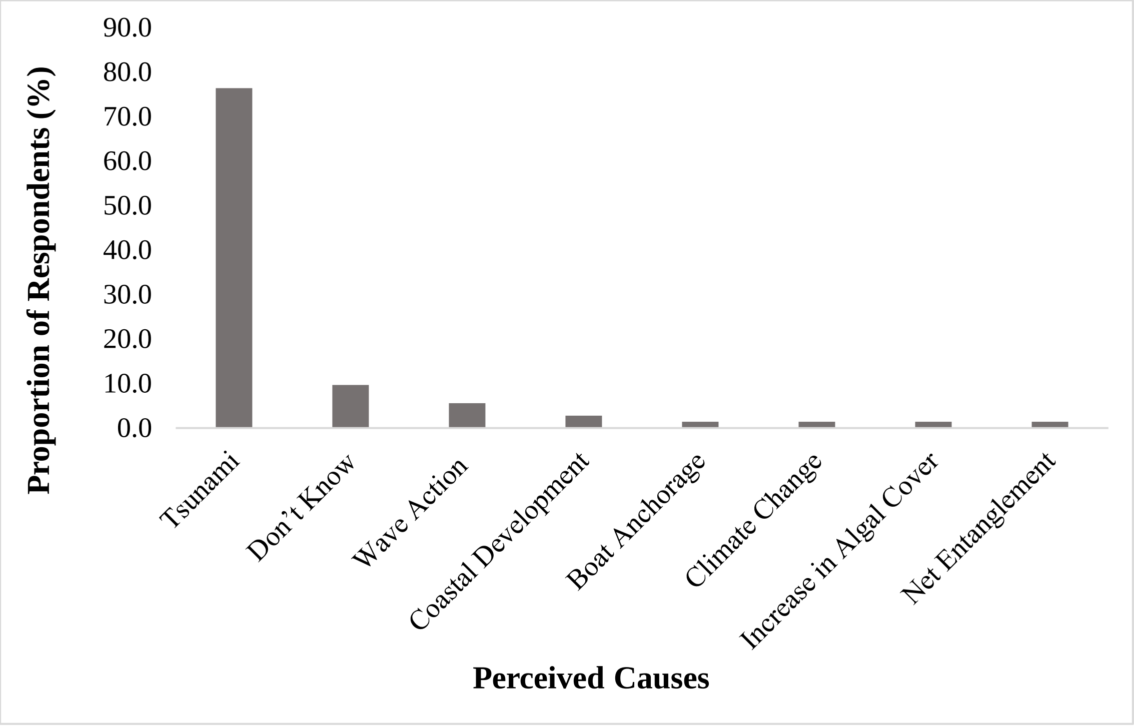


Figure 6.6: Perceived reasons for seagrass decline in the Andaman and Nicobar Islands (n=72)

6.3.6. LEK: Usage and value system

Seagrasses formed primary fishing grounds for only a small proportion of fishers (14 %). Meanwhile, 60.6 % (n=117) of the respondents fished in coral reefs or deep seas. Utility of seagrasses was mainly restricted to bait-fishing, local-scale consumption, and gleaning. Collectively, for bait fisheries and local-scale consumption, fishers extracted around 23 fish species (Table 6.2, Image 6). Further, bait fisheries were not targeted, as fishers extracted small fishes such as sardines (*Tarni*, Hindi) and others opportunistically, using cast nets (*Feka* or *Khevla Jaal*, Hindi) or gillnets- monofilament nylon net (*Current jaal*, Hindi). 21 % of the respondents were gleaners who relied for subsistence on intertidal meadows primarily for crustaceans. Gleaners either used cast nets (*Feka* or *Khevla Jaal*, Hindi), or at times improvised mosquito nets at home (Image 7). The majority of the gleaning activities were carried out in North and Middle Andaman (65 %), followed by Little Andaman (11.6 %), Ritchie's archipelago (9.3 %), and South Andaman (9.3 %). The lowest proportion of gleaners was reported from Rangat, Middle Andaman (4.7 %), while none from the Nicobar region.

The vast majority of respondents listed seagrass meadows as critical habitats for threatened species such as dugongs and sea turtles (> 70 %). However, only 23.1 % of respondents (n=33) agreed that seagrass is an essential ecosystem that must be protected. At the same time, the remainder of the respondents (26.6 %, n=38) did not know the ecological and economic importance of seagrasses. Noteworthy, ~ 50 % (n=72) of respondents perceived no significance of seagrass habitats for human well-being in the Andaman and Nicobar Islands.

Table 6.2. Seagrass-targeted fisheries in the Andaman and Nicobar Islands

Sr. No.	Local name	Common name
1	Farsa	Mullet
2	Chitra	Batfish
3	Gobra	Grouper
4	Suar Macchi	Triggerfish
5	Kukari	Trevally
6	Tota Macchi	Parrot fish
7	Lal Betki	Red Snapper
8	Rui	Jobfish
9	Jeevan	Snapper
10	Tarni	Oil Sardine
11	Catla	Sweet Lips
12	Chanda	Pony fish
13	Potti	White Snapper
14	Changochi	X
15	Maya	Anchovy
16	Tikli	X
17	Safed Katla (Kushal)	Skilfish
18	Bada Ankhi	Big Eye Tuna
19	Tehar Pili	X
20	Dariyal	Goat fish
21	Khori	Sardine
22	Girgit	X
23	Kawa Macchi	Halfbeak

[X; Could not confirm common name]

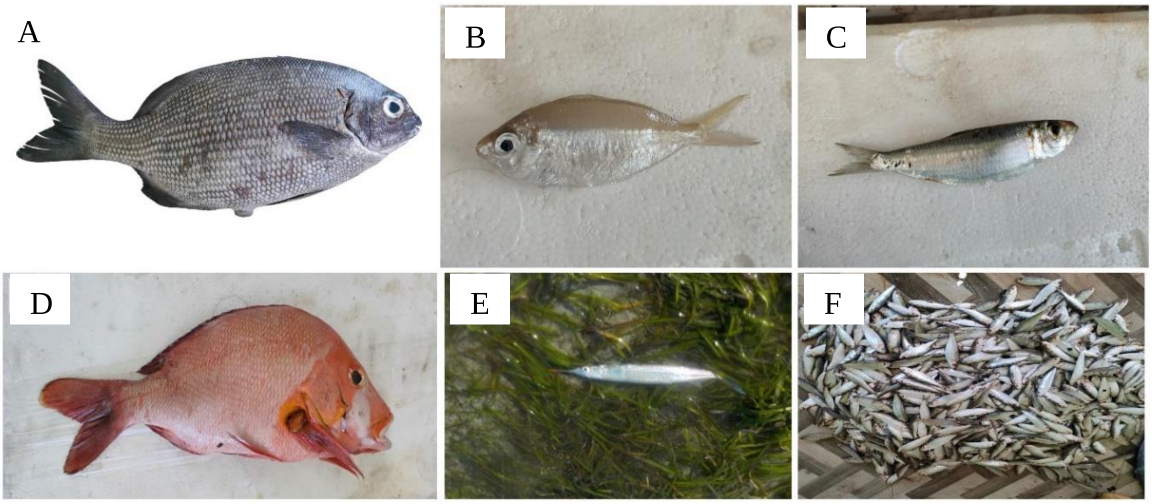


Image 6: Fishes extracted from seagrass meadows; A) Catla, B) Maya, C) Tarni, D) Lal Betki, E) Kawa Macchi, F) Tarni sold as bait-fish in local market [See Table 6.2 for common names; *Photo Credits: Sagar Rajpurkar*]

Image 7: Female gleaner with improvised mosquito handmade nets for crustacean gleaning [Swaraj Dweep, *Photo credits: Sumit Prajapati*]

6.4. Discussion

Seagrass is an example of a socio-ecological system where humans are essential beneficiaries of ecosystem services (Unsworth et al., 2019b). Therefore, coastal communities' attitudes and perceptions are integral to effective conservation (McNeill et al., 2018). Earlier studies have proven that community involvement and their perception, values, and seagrass dependency boost a holistic regional seagrass management (Bennet et al., 2021). Research initiatives to tap the local knowledge on marine species and understanding fishers' aspirations for better management are limited in ANI (Patankar, 2019; Nazareth et al., 2022; Gole et al., 2023a). However, these studies were crucial to reflect upon the vital role fishers can play in filling the region's critical marine research and management gaps. Nevertheless, given the scarcity of a seagrass-centric approach in engaging local communities, the present study provides the first insight into the diverse cognitive narratives on seagrass-human dynamics in ANI.

The findings suggest three vital trends; 1) interface of fishers with seagrass habitats is mainly opportunistic, 2) fishers possess a sound knowledge on occurrence, distribution, spatio-temporal changes, and importance of these critical habitats for threatened species, 3) However, fishers hold a minimalistic dependency on these ecosystems from utility and value system *per se*. Despite coral reefs being their primary fishing grounds, the present interactions reflected a mixed narrative of fishers on seagrass awareness. Although only 50 % of fishers were truly aware of seagrass, beyond awareness, fishers were informed about local spatio-temporal changes in seagrass meadows, which concurred with detailed conventional scientific surveys (CSK). General first-hand memory of species such as *Thalassia hemprichii*, *Cymodocea* spp., *Enhalus acoroides*, and *Halophila ovalis*, occupy intertidal or shallow subtidal waters which was further confirmed through systematic research surveys (Annexure 2). In a few instances, fishers also recognized *Halophila* spp. as a deep-water seagrass pulled out by boat anchors while fishing in deep seas. These observations aligned with the present study's deepest *Halophila* spp. record (*H. ovalis* and *H. decipiens*- 21m, Annexure 2).

However, the complexity of seagrass identification was restricted largely to morphological interpretations through sight, as opposed to several other sensory perceptions (taste, smell, touch) reported from elsewhere (Newmaster et al., 2011). Also, information on ecological aspects such as species-specific niche environment was limited. For instance, fishers were aware of different substrata seagrass (*Baalu*, sand, Hindi) and algae occupy (*Patthar*, rock or hard substrata, Hindi) in shallow waters. But not on type of sand each seagrass species prefers, different species type or depth gradients for that say. This observational, percolated memory on shallow-water seagrasses, is a possible outcome of clear waters in ANI (vertical visibility ~ 5 to 10 m or more) largely used as fishing transits/boat anchorage where the interface is highly pronounced.

Further, I suggest that while LEK is a widely used tool in marine research (Hashim et al., 2017; Idris et al., 2020; Cheng et al., 2021; Ternes et al., 2023), for taxonomically ambiguous seagrasses, information should be validated through CSK surveys. As explained in Chapter 3, *the Halophila* genus is systematically complex, where even focused scientific studies have misidentified species (Fortes et al., 2018). From the checklist of 12 species in ANI, uncertainty still exists between *H. ovata* and *H. minor* (Ragavan et al., 2016), which also resembles *H. ovalis*. Similarly, for morphologically similar genera, such as '*Cymodocea* spp. and *Thalassia* sp.' or '*Halodule* spp. and *Syringodium* spp.,' possible misidentification cannot be denied. Similar findings were reported by Newmaster et al. (2011), from southern India, where LEK system contributed to fine-scale classification system of seagrass, which did not align with scientific surveys. Under such a scenario, relying only on LEK could be misleading and should be validated through CSK in case of contrasting perceptions.

Noteworthy, fishers' LEK on seagrass distribution strongly overlapped with scientific surveys, with almost 100 % precision for the meadows explored by marine researchers. Seagrass presence was confirmed collectively at 56 meadows through the present study (see Chapter 3) and previous scientific explorations in ANI (D'Souza et al., 2015; Savurirajan et al., 2018). Only one site, namely Sukha Nali in Little Andaman, had no seagrasses when ground-truthed in the present study. The remaining sites (49.6 %, n=56, Table 6.1) have not been scientifically explored yet. In addition, the spatio-temporal changes in seagrass occurrence, distribution, and potential causes were well perceived. For example, the seagrass decline caused by the Indian Ocean Tsunami of 2004 was rightly reported by the respondents, which was further confirmed through scientific studies (Thangaradjou et al. 2010a, Geevarghese et al. 2018). Thus, the information generated through LEK could complement conventional scientific studies, especially from data-lacking regions, to apprise research gaps and better management policies (Dilling and Lemos, 2011; Claudet et al., 2020).

In terms of utility, the findings suggest low usage of seagrass habitats in the form of local-scale fisheries (sale and consumption) and gleaning. A biased gender role in participation was unsurprising since fishing is a male-dominated sector in India (Sivakumar and Nair, 2013). However, females did engage as gleaners to some level in recreational/subsistence activities in seagrass habitats (*Pers. comm.*). For instance, female gleaners (primarily wives of fishers) in Swaraj Dweep, Ritchie's archipelago, designed special nets to catch shrimps (locally known as '*Zhinga*') from meadows near their settlements. Group participation led by females, sometimes accompanied by children, generally involved weaving handmade nets and gleaning activities were carried, mostly at dawn or dusk. Thus, to these communities' seagrasses offered some recreational and subsistence value. Further, the absence of gleaning from the Nicobar region could be a possible outcome of subsidence of the intertidal sites caused by the tsunami of 2004 (Malik et al., 2006). Pre-tsunami scientific surveys reported highly diverse, intertidal seagrass meadows from Nicobar (Das, 1996), which at present have transitioned to shallow-subtidal waters due to land subsidence (see Chapter 3). Therefore, I suggest that the nature of gleaning activities in ANI are Island-specific and restricted to certain pockets, primarily driven by availability and proximity to intertidal seagrass meadows.

Notable is the contrasting opinions fishers had on the seagrass-value system. Over 70 % of fishers value seagrass habitats to sustain dugongs and sea turtles, aligning with similar reports from southern India (Newmaster et al., 2011). However, a stark contradiction was seen in how seagrasses were perceived for human well-being. Despite providing rich fisheries with tropical seagrasses (Unsworth et al., 2014; Jones et al., 2021), three-fourths of the respondents found seagrasses insignificant to their livelihoods or were unaware of any importance. The direct seagrass dependency of fishers was restricted to boat anchorage, fishing transits, bait fishery, and gleaning. Furthermore, these activities were opportunistic, carried out in pockets throughout the islands, and only sometimes seagrass-centric. These narratives differ from those documented from southern India, Sri Lanka, Cambodia, Indonesia, the Philippines, Sri Lanka, Tanzania, and Chwaka Bay (Zanzibar), to name a few, where utility and value-system seagrass ecosystems are highly pronounced (Felger and Moser, 1985; de la Torre-Castro and Rönnbäck, 2004; Newmaster et al., 2011; Jones et al., 2022b). For instance, seagrasses are used in treating ailments and diseases in Zanzibar (de la Torre-Castro and Rönnbäck, 2004), Tamil Nadu, India (Newmaster et al., 2011), and in Mexico by the Seri Indians (Felger and Moser, 1985). Few reports suggest the use of seagrass seeds as nutritional supplements to humans and livestock from Mexico, Phillipines, and India (Felger and Moser, 1973; Montaño et al., 1999; Newmaster et al., 2011). Noteworthy in these studies, is the prolonged connection coastal society has shared with seagrass ecosystems for generations. Contrary, the fisher populace in the Islands share a comparatively younger interface with seagrasses in ANI (~ 5 to 6 decades), with some fishers having no prior experience in fishing (Jaini et al., 2017), possibly generating a fresh LEK repository on seagrass habitats which do not form their primary fishing grounds.

In conclusion, the values and perceptions documented in this study draw two critical deductions: a) Fishers in the Islands have observational knowledge on seagrass occurrence and distribution but not on their value system for human well-being, and b) Seagrass habitats do offer a low degree of household food security which largely is opportunistic, yet there is a strong need of seagrass *per se* socio-economic evaluation in small-scale fisheries. The first point reflects the need for 'Education and Awareness' towards community-based seagrass management in ANI. Thus, future sensitization programs should emphasize the importance of seagrass habitats, especially their role in breeding fish, shore protection, ecotourism, ecological recycling, etc. Secondly, in the wake of elevating pressures, largely human-induced (Halpern et al., 2015, 2019), the potential consequences of seagrass loss would be many, including compromised food security and livelihoods of millions of coastal people in the future (Jones et al., 2022a). Since seagrasses in ANI are vulnerable to unprecedented natural and anthropogenic stressors, it is critically important to evaluate the economic chain generated from seagrass-centric small-scale fisheries. Additionally, the seagrass habitat linkages, is under-explored in the Indo-Pacific tropics (Jones et al., 2022b), including ANI, and must be a focal research topic.

CHAPTER 7: MANAGEMENT RECOMMENDATIONS FOR SEAGRASS HABITAT CONSERVATION IN THE ANDAMAN AND NICOBAR ISLANDS

Worldwide, seagrass ecosystems are threatened due to increasing anthropogenic footprints. Some of the attributed causes for seagrass decline are coastal infrastructure development, pollution, nutrient loading, decline in water quality, and physical damage through destructive fishing practices and boat anchorage (seagrass watch[9]). At a local scale, plastic litter is sourced mainly from tourism, and damages caused by boat anchorage in the seagrass meadows have been reported from the Andaman and Nicobar Islands, though the intensity of which varied across the spatial scale (Gole et al., 2021, 2023b). A recent study on the dietary preferences of dugongs from mainland India reported microplastics from the gut of stranded dugongs (Prajapati et al., 2022), indicating pollution load in seagrasses and further bio-magnification. Since these habitats form the only foraging grounds of dugongs, the reported plastic pollution load will significantly impact dugong physiology and other seagrass-dependent threatened species such as the green sea turtles. Furthermore, I observed the increased sedimentation and subsequent mass die-off of coral reefs and enhanced turbidity in the seagrass beds from Shaheed Dweep and meadow-scarring in Swaraj Dweep as a response to bottom dredging (for jetty construction) and boat anchorage respectively (personal

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[9] www.seagrass.watch (accessed on December 2023)

observations). Nevertheless, these observations are mainly descriptive, needing more quantitative details of the damage or loss incurred.

Given this scenario, it is essential to link research and management to strengthen seagrass conservation in ANI; therefore, based on my findings, I propose the following recommendations for the effective management and conservation of seagrass ecosystems in the Andaman and Nicobar Islands (ANI):

Top-down management recommendations

7.1. Enhance legislative measures: The limited legislative measures safeguarding seagrass ecosystems (Ramesh et al., 2018) in India include;

1) protection under the Wildlife (Protection) Act (WLPA), 1972 and,

2) recognition as an ecologically sensitive habitat under the Island Coastal Regulation Zone (ICRZ- IA) of the Island Protection Zone (IPZ) (notified by the Union Ministry of Environment, Forest, and Climate Change; ICRZ, 2019[10]).

However, the former measure protects seagrass falling only within the ambit of Marine Protected Areas (MPA), rendering seagrasses outside MPAs vulnerable to exploitation. Secondly, for the latter legislation, concerning are the recent revisions in the IPZ 2019 Notification, where the previously specified ‘No Development Zone’ was 200 meters landward from the high tide line for all the Islands (IPZ 2011[11]). Alarmingly, the same has been reformed, depending on the

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[10] https://environmentclearance.nic.in/writereaddata/SCZMADocument/ICRZ_Notification2019.pdf (accessed on November 2023)

[11] http://www.indiaenvironmentportal.org.in/files/IslandProtectionZoneNotification2011.pdf (accessed on November 2023)

island size, to only 20-50 meters within the High tide line (ICRZ, 2019), boosting more coastal development prospects, which will stress nearby seagrass meadows in case of rampant infrastructure development and possible land reclamation.

Thus, seagrass habitats in ANI critically need a 'habitat level' conservation approach. Since the present study has demonstrated seagrass meadows are substantial foraging grounds for Dugongs and also inhabit rich benthic biodiversity, I thus recommend a top-down revised approach, by reverting to a 200 m safe zone wherever seagrass meadows are present, to strengthen the existing legislative framework and more robust protection for seagrass ecosystems. Other activities like eco-tourism, navigation, etc., can be allowed through proper spatial planning of marine resources.

7.2. Expand the Marine Protected Area (MPA) Network: Less than 20% of the seagrass meadows are protected as MPAs. On the contrary, a recent review of the South-east Asian seagrasses (Sudo et al., 2021) suggests that the subtropical Ryukyuan archipelago in Japan, with a coastline of 650 km (one-third of ANI) and half the geographical expanse (~ 4600 km^2) still protects more than 99 % of their seagrass beds within its MPAs. The denoted figures shed light on the under-representation of seagrasses as valuable ecosystems that need protection in ANI. Within the remaining 80 % of unprotected seagrasses in the present study, which also includes the critical dugong habitats, the geographical remoteness of the islands (from human settlements) offers some level of natural protection.

However, these beds still fall on the geological fault lines of ANI, exposed to natural threats such as frequent cyclonic storms, earthquakes, and tsunamis, all known to impact seagrasses (Adulyanukosol and Poovachiranon, 2006; Sachithanandam et al., 2014). The rise in coastal development prospects in ANI is another matter of concern. It is likely to change seagrass ecosystems in the future, possibly with an aligning fate as reported by China (Jiang et al., 2020), Vietnam (Luong et al., 2012), Malaysia (Japar Sidik et al., 2018), and Europe (de los Santos et al., 2019), to name a few. Thus, there is a need to extend the network of MPAs to encompass a more significant portion of seagrass beds, ensuring the conservation of these critical ecosystems.

I suggest increasing the coverage of Marine Protected Areas (MPAs) and enforcement, following a potential NEOLI approach (No take, Enforced, Old, Large, and Isolated; Edgar et al., 2014). A critical aspect of an effective MPA and derived conservation benefits revolve around the NEOLI approach, where the five features above are decisive of the success an MPA would yield. This measure primarily revolves around regulation in illegal harvesting (No take), regulatory measures to implement the law (Enforcement), age of the MPA (Old; > 10 yrs.), size of the MPA (> 100 km^2), and continuity of habitats allowing faunal movement (Isolation; Edgar et al., 2014). The only two MPAs in the islands, Rani Jhansi Marine National Park (Ritchie’s archipelago) and, Mahatma Gandhi Marine National Park (Wandoor, South Andaman), currently need to implement this approach. Thus, to include a more significant proportion of seagrass meadows, especially those identified as critical dugong habitats, as highlighted in my study (see section 7.5), could be considered as potential MPAs towards seagrass conservation and management.

Bottom-up management recommendations

7.3. Promoting seagrass-centric research

a) Assess socio-ecological-economic services**:** I recommend a comprehensive research approach to evaluate the socio-ecological-economic services seagrass ecosystem provides (Rahman and Yaakub, 2020). Understanding the socioeconomic dynamics will inform policy and decision-making (de la Torre-Castro et al., 2014; Campagne et al., 2015; Kilminster et al., 2015), along with developing sustainable management strategies that align with the needs and aspirations of local communities. Further, it is recommended that the Marine Biodiversity Register be prepared by the local fishing village panchayats of ANI as per the Biological Diversity Act, 2002, with the help of the State Biodiversity Authority and the National Biodiversity Authority. Further, other non-fishing village biodiversity registers should also contain marine biodiversity records if they are located in coastal areas, for the local community to understand their biodiversity's status, threats, values, and use, including seagrasses around them.

b) Quantification of seagrass-centric threats**:** A detailed study is required to quantify the threats faced by seagrass meadows in ANI to inform policy-makers (Rahman, 2017). Assessment of the impacts of anthropogenic activities, such as dredging and boat anchorage, on seagrass health will help identify and develop targeted management strategies to minimize or mitigate these threats.

c) Increased awareness of the value system of seagrasses: Researchers play a pivotal role in community-based marine conservation as their interactions with local communities are more pronounced. I thus recommend researcher-led sensitization programs with communities about the importance of seagrass meadows and their conservation implications. These programs should be targeted towards sensitizing the key stakeholders, as well as local masses and school children, towards the importance of seagrass ecosystems and the need to safeguard them. Especially for the fisher populace, the programs should be directed towards the interconnectivity of the seagrass and coral habitats (their fishing grounds), emphasizing the nursery role of seagrasses.

Collaborative multi-stakeholder approach

7.4. Seagrass Garden for education, research, and conservation

Consider establishing a seagrass garden comprising all species in one location, depending on the conduciveness of the environment. This garden will study and develop artificial seagrass regeneration techniques or nursery techniques for all the species. This garden can also be used for education, research, and conservation activities.

7.5. Management of seagrass habitats using dugong as flagship species

Dugong, the Andaman and Nicobar Islands' state animal, is listed in Schedule I of the Indian Wildlife (Protection) Act, 1972, which offers the highest national legislative measure to the species, prohibiting its hunting and trade. Seagrasses, their only foraging grounds, are a critical component of dugong conservation. Thus, dugongs could be used as a flagship species to protect the critical seagrass habitats in ANI. The IUCN Task Force declared South Andaman an Important Marine Mammal Area in 2018, including 16 marine mammal species, counting dugongs (IMMA, 2018). IMMA, as defined by the IUCN task force, is "discrete portions of habitat, important to one or more marine mammal species, which have the potential to be delineated and managed for conservation" (IMMA, 2018). This proposed biocentric region includes the coastal stretch from Middle Andaman to Little Andaman in the South, encompassing the southwestern aspect of South Andaman.

Moreover, through the present study, which is a part of the CAMPA-Dugong Recovery program of the Wildlife Institute of India (WII), the outcome has delineated 13 high, 7 medium, and 34 low-priority seagrass meadows which are critical dugong habitats, many of which fall under the designated IMMA in 2018 (Sivakumar et al., 2021; Gole et al., 2023a). The characterization of sites by WII is carried out owing to the importance of these meadows to dugongs and threats to both seagrass and dugongs. In addition, the WII has delineated several earlier data-deficient sites as critical dugong habitats (Figure 7.1). The identified meadows are used by solitary individuals, adult pairs, calves, and, most importantly, dugong herds (Table 7.1, Figure 7.1). For the latter, a recent study reported dugong herds in ANI after ~ 4 decades and suggested that seagrass resource concentration in the Andaman Islands supports calving dugong herds, which calls for immediate management intervention in the region (Gole et al., 2023a). Furthermore, three photo-identified WII dugongs have been showing site fidelity towards the seagrass beds of Shaheed Dweep (Gole et al., 2021). Thus, the delineated dugong habitats may be considered a 'Conservation Reserve' that would cover some of the critical seagrass habitats of Andamans and help India enhance its MPA coverage concerning Sustainable Development Goals 14.

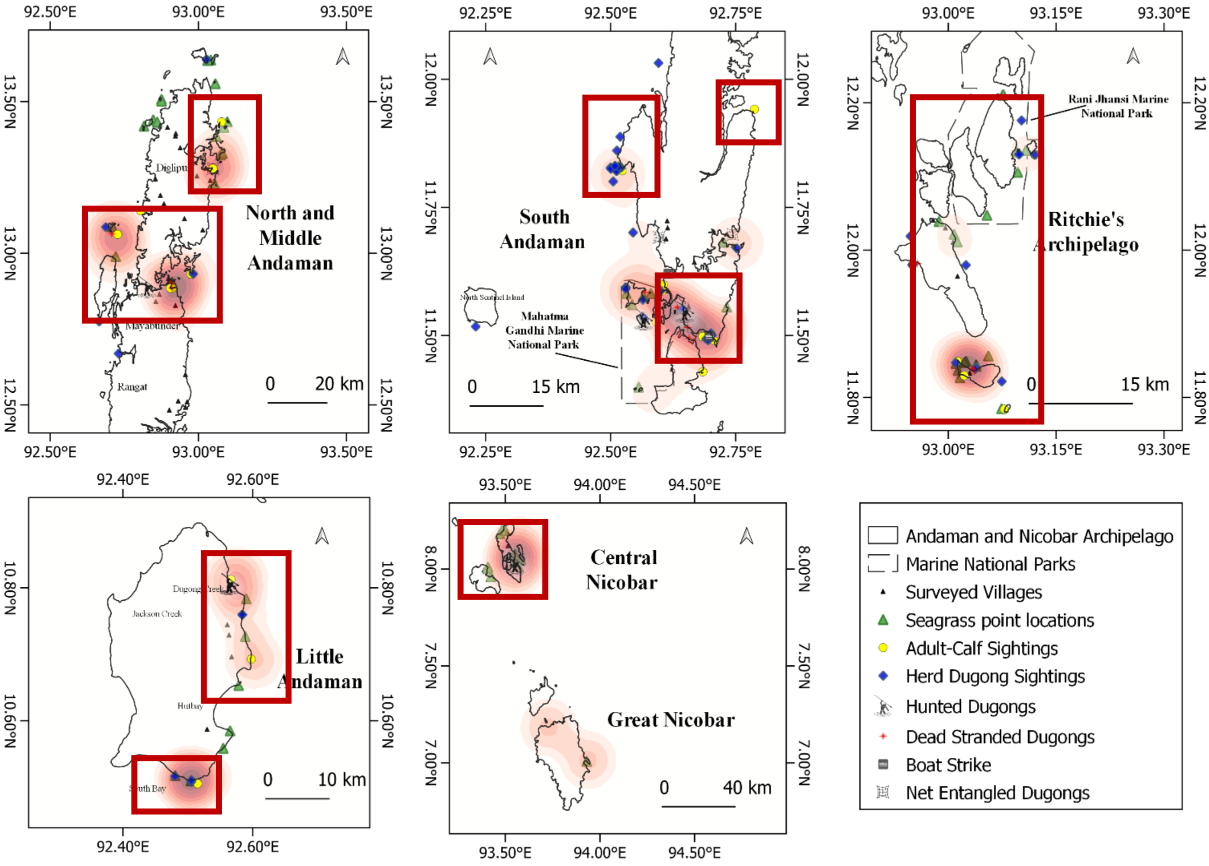

Figure 7.1: Identified critical dugong habitats in the Andaman and Nicobar Islands [highlighted in red box]

13 meadows from Ritchie's archipelago and South Andaman require immediate management intervention using both, a top-down and bottom-up approach. The high tourism pressure, subsequent heavy boat traffic (high-speed vessels), water and plastic pollution, and physical damage are detrimental to dugongs and their habitats. In a top-down approach, strict implementation of rules about sustainable tourism, such as boat speed and ensuring waste disposal, could be an immediate role for the administration. Further, seagrasses are enduring meadow scarring by boat anchorage in Swaraj Dweep, primarily along with high-speed boat traffic. To minimize threats posed by boat anchorage, I suggest installing eco-moorings (Pioch and Leocadie, 2017) on an experimental basis to check their efficiency. This could be a collaborative initiative undertaken by the relevant departments (Fisheries and Forests) to financially aid artisanal fishers and mitigate threats to intertidal seagrass meadows critical for dugongs. Further, seagrass meadows and adjoin sea around Swaraj Dweep and Shaheed Dweep islands may be considered as the Buffer Zone or Eco-Sensitive Zone of the existing Rani Jhansi Marine National Park of Andaman as dugongs use these areas extensively.

Frequent sensitization and consultation with actors such as fishers, dive schools, and tourism-allied operators is highly recommended in a bottom-up approach. Durgapur, Kalipur, Ross and Smith, and Pokkadera from the North and Middle Andaman are critical in the rest of the medium and low-priority value meadows. Although most of the meadows are not threatened at present, considering the changing scenario and tides in the Islands, these meadows need to be regularly monitored, patrolled, and considered for long-term surveys by the scientific community. Most importantly, a unique approach needs to be adopted to discuss and understand the aspirations of the indigenous communities indulged in hunting dugongs, such as in Nicobar, as they are exempted from the Wildlife Protection Act yet form a critical stakeholder in managing species and habitats.

By implementing these recommendations, a robust framework for the 'habitat-level' management and conservation of seagrass ecosystems can be drafted in the Andaman and Nicobar Islands. Drawing from regional case studies (Fortes et al., 2018) and considering the unique context of ANI, these measures could be comprehensively put into a local-scale management perspective to create a roadmap for seagrass conservation for ANI.

Table 7.1. Critical seagrass habitats used by dugongs and nature of threats [See Annexure 2 for site codes]

Island Category	**Seagrass meadows**	**Dugong occurrence**	**Threats to dugongs and seagrasses**	**Intensity**
North & Middle Andaman	Landfall (South-East)	Herd	Patrolling boats	Low
North & Middle Andaman	Landfall-East (Channel)	Herd	Patrolling boats	Low
North & Middle Andaman	Paget (North-East)	Solitary	Transit fishing boats	Low
North & Middle Andaman	Excelsior (West)	Adult pairs	Transit fishing boats	Low
North & Middle Andaman	Delgarno (West)	Adult pairs	Transit fishing boats	Low
North & Middle Andaman	Temple (West)	Herds	Transit fishing boats	Low
North & Middle Andaman	Smith (North-East)	Solitary and adult-calf pairs	Tourism	Medium
North & Middle Andaman	Smith (East)	Solitary and adult-calf pairs	Tourism	Medium
North & Middle Andaman	Kalipur	Solitary	Gleaning, Tourism, past dugong hunting, and net entanglement around Durgapur	Medium
North & Middle Andaman	Craggy	Solitary	Transit fishing boats	Low
North & Middle Andaman	North Reef (East)	Solitary, adult-calf pairs, herds	Transit fishing boats	Low

North & Middle Andaman	Jhau Nala (Interview, North)	Solitary, adult-calf pairs, herds	Transit fishing boats	Low
North & Middle Andaman	Pokkadera (Mayabunder)	Solitary, adult-calf pairs, herds	Gleaning, transit, domestic run-off, stranded dugong	Medium
Ritchie's archipelago	Imli Dera (Henry Lawrence-Shallow, North)	Herds	Transit fishing boats, patrolling boats	Low
Ritchie's archipelago	Imli Dera (Henry Lawrence- deeper, North)	Herds	Transit fishing boats, patrolling boats	Low
Ritchie's archipelago	Jua Tekdi (Henry Lawrence, East)	Herds	Transit fishing boats, patrolling boats	Low
Ritchie's archipelago	Inglis (South-West)	Herds	Transit fishing boats, patrolling boats	Low
Ritchie's archipelago	Chand Balu (Henry Lawrence, South-East)	Adult pairs	Transit fishing boats, patrolling boats	Low
Ritchie's archipelago	Nemo Reef (Swaraj Dweep, North)	Solitary, adult-calf pairs	Tourism, gleaning, boat anchorage	High
Ritchie's archipelago	Dolphin (Swaraj Dweep, North-East)	Solitary, adult-calf pairs	Tourism, gleaning, boat anchorage	High
Ritchie's archipelago	Vijay Nagar (Swaraj Dweep, North-East)	Solitary, adult-calf pairs	Tourism, gleaning, boat anchorage	High
Ritchie's archipelago	Busy Buro (Shaheed Dweep, North)	Solitary	Tourism, gleaning, boat anchorage	High
Ritchie's archipelago	Bharatpur (Shaheed Dweep-	Solitary	Tourism, gleaning, boat anchorage	High

	deep subtidal, North)			
Ritchie's archipelago	Bharatpur (Shaheed Dweep- shallow subtidal, North)	Solitary	Tourism, gleaning, boat anchorage	High
Ritchie's archipelago	Aquarium (Shaheed Dweep- deep subtidal, North)	Solitary	Tourism, gleaning, boat anchorage	High
Ritchie's archipelago	Aquarium (Shaheed Dweep- shallow subtidal, North)	Solitary	Tourism, gleaning, boat anchorage	High
Ritchie's archipelago	Laxmanpur (Shaheed Dweep, North-West)	Solitary	Tourism, gleaning, boat anchorage	High
Ritchie's archipelago	Nursery (Shaheed Dweep, North-West)	Solitary, herds	Tourism, gleaning, boat anchorage	High
Ritchie's archipelago	Natural Bridge (Shaheed Dweep, South-West)	Solitary	Tourism, gleaning, boat anchorage	High
Ritchie's archipelago	Macchi Gadda (Shaheed Dweep, South-West)	Solitary	Tourism, gleaning, boat anchorage	High
Ritchie's archipelago	Chota Neil (Sir Hugh Ross, West)	Solitary, herds	Transit fishing boats	Low
South Andaman	Haddo (Port Blair, East)	Solitary, herds	Marina development, domestic run-off, boat anchorage, past dugong net entanglement	High
South Andaman	Burmanallah (Port Blair, East)	Solitary, adult-calf pairs, herds	Gleaning, transit, domestic run-off	Medium
South Andaman	Chester (MGMNP, South-East)	Solitary, adult-calf pairs, herds	Transit fishing boats, patrolling boats	Low

South Andaman	Tarmugli (MGMNP, West)	Solitary, adult-calf pairs, herds	Transit fishing boats, patrolling boats	Low
South Andaman	Tarmugli (MGMNP, East)	Solitary, adult-calf pairs, herds	Transit fishing boats, patrolling boats	Low
South Andaman	Tarmugli (MGMNP, South)	Solitary, adult-calf pairs, herds	Transit fishing boats, patrolling boats	Low
South Andaman	Boat (MGMNP, East)	Solitary, adult-calf pairs, herds	Transit fishing boats, patrolling boats	Low
South Andaman	Twins (MGMNP, North)	Solitary, adult-calf pairs, herds	Transit fishing boats, patrolling boats, past dugong hunting in adjacent fishing villages	Low
Little Andaman	Patthar Nali (Little Andaman, East)	Solitary, adult-calf	Indigenous dugong hunting (Onges)	Low
Little Andaman	Dungi Ghat (Little Andaman, East)	Solitary, adult-calf	Gleaning, indigenous dugong hunting (Nicobarese)	Low
Little Andaman	Hutbay-Lighthouse (Little Andaman, South)	Solitary, adult-calf pairs, herds	Gleaning, indigenous dugong hunting (Nicobarese)	Low
Little Andaman	Ship Wreck (Little Andaman, South)	Solitary, adult-calf pairs, herds	Gleaning, indigenous dugong hunting (Nicobarese)	Low
Nicobar	Kardip (Kamorta, South-East)	Solitary	Busy harbor, boat anchorage, tribal fishing, indigenous dugong hunting (Nicobarese)	Medium
Nicobar	Bada Enaka (Kamorta, South-East)	Solitary	Tribal fishing, transit fishing boats, indigenous dugong hunting (Nicobarese)	Low
Nicobar	Rani Tikri (Kamorta, South)	Solitary	Tribal fishing, transit fishing boats, indigenous	Low

			dugong hunting (Nicobarese)	
Nicobar	Hypo (Katchal, East)	Solitary	Tribal fishing, transit fishing boats, indigenous dugong hunting (Nicobarese)	Low
Nicobar	Kapanga (Katchal, North-East)	Solitary	Tribal fishing, transit fishing boats, indigenous dugong hunting (Nicobarese)	Low
Nicobar	Lighthouse (Katchal, North-East)	Solitary	Tribal fishing, transit fishing boats, indigenous dugong hunting (Nicobarese)	Low
Nicobar	Safed Balu (Trinket, North)	Solitary	Tribal fishing, transit fishing boats, indigenous dugong hunting (Nicobarese)	Low
Nicobar	Trinket (West coast, South-West)	Solitary	Tribal fishing, transit fishing boats, indigenous dugong hunting (Nicobarese)	Low
Nicobar	Al- Reak (Nancowry, North)	Solitary	Tribal fishing, transit fishing boats, indigenous dugong hunting (Nicobarese)	Low
Nicobar	Hitui (Nancowry, North)	Solitary	Tribal fishing, transit fishing boats, indigenous dugong hunting (Nicobarese)	Low
Nicobar	Campbell Bay (Great Nicobar, East)	Solitary	Coastal infrastructure development, boat anchorage	Medium

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Annexure 1

Annexure 1: Statement on the Contribution of Others

- ***Funding:*** Financial support for this work was received by the CAMPA authority, Ministry of Environment, Forest, and Climate Change (MoEFCC), Government of India (Grant/Award Number: 13-28(01)/2015-CAMPA).
- ***Supervision:*** Dr. K. Sivakumar, Dr. J.A. Johnson and Dr. Himansu Das.
- ***Permits and ethics statement:*** Research permits for the work were obtained from the Department of Environment and Forests (Van Sadan, Chatham, Port Blair), including entry in forest protected areas (land and water). Boat permits to use a fishing vessel for research purpose were granted by Directorate of fisheries, Port Blair. To enter tribal protected waters, official permits were approved by the Deputy Commissioner, South Andaman. In addition, personal meetings were done with the Head of the tribal council of each island and village, and a verbal consent was obtained before entering tribal protected waters of Central Nicobar. Before all field-based surveys, the Divisional Forest officers, Station head officers of police departments, and defence patrolling agencies (Indian Navy and Indian Coastguard) based in each island, were intimated about the fieldwork using the approved protocol. For social surveys, a verbal consent of each respondent was taken.
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Annexure 2

Annexure 2: Seagrass meadow characteristics of the 66 beds investigated from the Andaman and Nicobar Islands, India [sites in bold indicate new meadow record]

Island Category	**Site code**	**Local names (English name; Coast)**	**Site locality**	**Meadow type**	**Habitat profile (Dominant substratum)**	**SG Sp.**	**WD (m)**	**Species composition**	**Seagrass cover (mean %)**	**Shoot densities (shoots/m^2, mean ± SD)**	**Total biomass (dry wt., g/m^2)**
North & Middle Andaman	**Site 1**	**Lamba Tikri (Landfall; Southeast)**	**13°38'7.91"N, 93° 1'50.66"E**	**Sparse, mixed-species, shallow subtidal**	**Homogeneous sandy (Fine sand)**	**2**	**4.8**	***Halodule pinifolia*, *Halophila ovalis***	**22.5**	**950 ± 433.01**	**14.4**
North & Middle Andaman	Site 2	Landfall-East (Channel)	13°38'12.05"N, 93° 2'30.73"E	Sparse, mono-species, shallow subtidal	Sand + Rubble (Fine sand)	1	2.4	*Halophila ovalis*	18.2	3150 ± 425.3	2.1

North & Middle Andaman	**Site 3**	**Japan Tikri (Reef; East)**	**13°30'26.93"N92°52'31.01"E**	**Moderate mixed-species, shallow subtidal**	**Homogeneous sandy** **(Fine sand)**	**2**	**7.3**	***Halophila ovalis, Halophila decipiens***	**32.7**	**1983 ± 742.18**	**25.0**
North & Middle Andaman	Site 4	Japan Tikri (Reef; South)	13°30'5.33"N, 92°52'31.30"E	Moderate, mixed-species, shallow subtidal	Homogeneous sandy (Fine sand + silt)	4	7.3	*Halodule uninervis, Halodule pinifolia, Halophila decipiens, Halophila ovalis*	35.3	2538 ± 1998.59	36.0
North & Middle Andaman	**Site 5**	**Samney Tikri (Paget Island; North-East)**	**13°26'22.85"N92°50'50.71"E**	**Moderate mono-species, shallow subtidal**	**Homogeneous sandy** **(Fine sand, > 50% epiphytic alga)**	**1**	**5.8**	***Halophila decipiens***	**42.9**	**1350 ± 648.55**	**17.3**

North & Middle Andaman	**Site 6**	**Dakshin Tikri (Point; North)**	**13°25'8.15"N, 92°48'58.86"E**	**Moderate mixed-species, shallow subtidal**	**Homogeneous sandy** **(Fine sand, > 50% epiphytic alga)**	**4**	**3.5**	***Halodule uninervis, Halodule pinifolia, Halophila decipiens, Halophila ovalis***	**36.4**	**1765 ± 199.34**	**217.8**
North & Middle Andaman	**Site 7**	**Radhanagar Channel (Opening)**	**13°25'6.17"N, 92°51'39.78"E**	**Sparse, mixed-species, shallow subtidal**	**Homogeneous sandy** **(Fine sand, > 50% epiphytic alga)**	**2**	**3.2**	***Halodule uninervis, Halodule pinifolia***	**8.9**	**458 ± 250.41**	**20.8**
North & Middle Andaman	**Site 8**	**Chota Nariyal Tikri (Excelsior; West)**	**13°25'59.16"N 93° 5' 50.64"E**	**Dense, mixed-species, shallow subtidal**	**Homogeneous sandy** **(Fine sand)**	**2**	**3.2**	***Halodule pinifolia, Halophila ovalis***	**51.6**	**1033 ± 550.18**	**6.4**
North & Middle Andaman	**Site 9**	**Nariyal Tikri (Delgarno; West)**	**13°24'51.19"N 93° 5'11.76"E**	**Moderate mixed-species, deep subtidal**	**Homogeneous sandy** **(Fine sand)**	**2**	**8.5**	***Halodule pinifolia, Halophila ovalis***	**33.8**	**2050 ± 388.90**	**32.0**

North & Middle Andaman	Site 10	Laxmi Tikri (Temple; West)	13°23'4.31"N, 93° 3'37.74"E	Dense, mixed-species, shallow subtidal	Homogeneous sandy (Fine sand, > 50% epiphytic alga)	2	1.9	*Halodule pinifolia, Halophila ovalis*	73.1	1300 ± 494.97	21.4
North & Middle Andaman	**Site 11**	**Sagar Dweep (Smith; North-East)**	**13°21'42.94"N 93° 3'45.82"E**	**Moderate mixed-species, shallow subtidal**	**Homogeneous sandy** **(Fine sand)**	**2**	**5.1**	***Halodule uninervis, Halodule pinifolia***	**49.5**	**392 ± 28.86**	**5.3**
North & Middle Andaman	**Site 12**	**Sagar Dweep (Smith; East)**	**13°19'47.03"N 93° 4'53.11"E**	**Moderate mixed-species, shallow subtidal**	**Homogeneous sandy** **(Fine sand)**	**2**	**4.0**	***Halodule uninervis, Halodule pinifolia***	**44.4**	**450 ± 155.12**	**5.1**
North & Middle Andaman	Site 13	Kohassa (Shibpur)	13°13'45.65"N, 93° 3'15.87"E	Sparse, mixed-species, shallow subtidal	Homogeneous sandy (Fine sand)	2	0.3	*Halodule pinifolia, Halophila ovalis*	10.5	438 ± 194.45	5.5

North & Middle Andaman	Site 14	Kalipur	13°13'35.16"N, 93° 3'9.30"E	mixed-species, intertidal	Sand+Rock+ Dead Coral Alga +Rubble (Fine sand + Coarse sand + Silt)	3	0.4	*Cymodocea rotundata, Thalassia hemprichii, Enhalus acoroides**	39.3	2475 ± 1947.27	213.5
North & Middle Andaman	Site 15	Kalipur Tikri (Craggy; North)	13°13'32.62"N, 93° 3'25.75"E	Moderate, mixed-species, shallow subtidal	Homogeneous sandy (Fine sand)	2	7.4	*Halodule pinifolia, Halophila ovalis**	45.6	1300 ± 476.97	13.0
North & Middle Andaman	Site 16	Battak Tapu (North Reef; East)	13° 5'12.08"N, 92°42'35.35"E	Moderate, mono-species, shallow subtidal	Homogeneous sandy (Fine sand)	1	5.8	*Halodule uninervis*	28.7	1075 ± 223.3	12.5
North & Middle Andaman	**Site 17**	**Jhau Nala (Interview, North)**	**12°59'19.59"N 92°43'14.75"E**	**Sparse, mono-species, shallow subtidal**	**Homogeneous sandy** **(Silt)**	**1**	**3.9**	***Halodule pinifolia****	**5.8**	**450 ± 110.8**	**1.5**
North & Middle Andaman	Site 18	Pokkadera (Mayabunder)	12°54'15.44"N, 92°54'40.50"E	Moderate, mixed-species, intertidal	Largely Homogeneous towards upper intertidal, heterogeneous	5	0.4	*Halodule pinifolia, Cymodocea rotundata, Thalassia*	32.2	2922.87 ± 2062.93	920.9

					towards low tides and edges (Sand+Rock+ Rubble+Live Coral (Fine + Coarse Sand)			*hemprichii*, *Halophila beccarii**, *Enhalus acoroides**			
Ritchie's archipelago	**Site 19**	**Imli Dera-Shallow (Henry Lawrence; North)**	**12°12'37.84"N, 93° 4'31.94"E**	**Moderate mono-species, shallow subtidal**	**Sand+Live Coral+Dead Coral Alga** **(Coarse + Fine Sand)**	**1**	**6.9**	***Halophila minor***	**47.8**	**683.33 ± 355.60**	**6.5**
Ritchie's archipelago	**Site 20**	**Imli Dera - Deep water (Henry Lawrence; North)**	**12°12'40.60"N93° 4'35.96"E**	**Sparse, mixed-species, deep subtidal**	**Homogeneous sandy (Coarse + Fine Sand, > 50% epiphytic alga)**	**2**	**12**	***Halophila minor*, *Halophila ovalis***	**17.8**	**533.33 ± 209.66**	**6.5**
Ritchie's archipelago	Site 21	Jua Tikri (Henry Lawrence, East)	12° 7'58.92"N, 93° 5'43.11"E	Dense, mixed-species, intertidal	Sand+Rubble+ Rock (Coarse Sand)	8	0.4	*Halodule uninervis*, *Halodule pinifolia*, *Cymodocea rotundata*,	62.9	1517.42 ± 703.62	256.5

								Halophila minor, Halophila ovalis, Syringodium isoetifolium, Enhalus acoroides, Thalassia hemprichii*			
Ritchie's archipelago	**Site 22**	**Inglis (South-West)**	**12° 8'6.78"N, 93° 6'28.17"E**	**Moderate mono-species, shallow subtidal**	**Homogeneous sandy** **(Fine + Coarse Sand, > 50% epiphytic alga)**	**1**	**5.2**	***Halodule pinifolia***	**38.5**	**958 ± 283.13**	**14.5**
Ritchie's archipelago	Site 23	Chand Balu (Henry Lawrence, Southeast)	12° 6'21.06"N, 93° 5'48.05"E	Very dense, mixed-species, shallow subtidal	Sand+Rubble (Coarse + Fine Sand)	2	2.0	*Syringodium isoetifolium, Thalassia hemprichii*	90.5	725 ± 125.6	121.5
Ritchie's archipelago	**Site 24**	**Razzak Tikri (John Lawrence, South)**	**12° 2'50.78"N, 93° 3'13.90"E**	**Sparse, mixed-species, deep subtidal**	**Homogeneous sandy** **(Fine sand, > 50% epiphytic alga)**	**2**	**15.3**	***Halophila decipiens, Halophila ovalis***	**1.6**	**850 ± 106.06**	**12.8**
Ritchie's archipelago	**Site 25**	**Nemo Reef (Swaraj Dweep, North)**	**12°2'20.00"N, 92°59'13.49"E**	**Sparse, mono-species,**	**Homogeneous sandy**	**1**	**11.4**	***Halophila minor***	**17.8**	**710.71 ± 535.38**	**3.5**

				deep subtidal	**(Fine sand, > 50% epiphytic alga)**						
Ritchie's archipelago	Site 26	Dolphin (Swaraj Dweep, North-East)	12° 1'17.58"N, 93° 0'28.48"E	Moderate, mixed-species, intertidal	Homogeneous sandy (Fine sand)	4	0.2	*Halodule uninervis*, *Cymodocea serrulata**, *Cymodocea rotundata*, *Thalassia hemprichii*	41.3	920.45 ± 1013.38	105.8
Ritchie's archipelago	Site 27	Vijay Nagar (Swaraj Dweep, North-East)	12° 0'39.99"N, 93° 0'45.31"E	Very dense, mixed-species, intertidal	Sand+Rubble+ Dead Coral Alga (Coarse + Fine Sand)	6	0.2	*Thalassia hemprichii*, *Enhalus acoroides*, *Syringodium isoetifolium**, *Halophila ovalis*, *Cymodocea rotundata*, *Halodule uninervis*	77.8	6392.5 ± 672.5	1593.8
Ritchie's archipelago	**Site 28**	**Busy Buro (Shaheed Dweep, North)**	**11°51'22.54"N 93° 3'20.81"E**	**Moderate mixed-species, deep subtidal**	**Sand+ Dead Coral Alga +Rubble+Live Coral** **(Coarse + Fine Sand)**	**2**	**20.5**	***Halophila decipiens*, *Halophila ovalis***	**36.5**	**1260 ± 283.17**	**21.0**
Ritchie's archipelago	**Site 29**	**Bharatpur-Deep water**	**11°50'38.90"N 93° 2'19.21"E**	**Moderate**	**Homogeneous sandy**	**1**	**12.6**	***Halodule pinifolia***	**34.0**	**387.5 ± 17.67**	**22.5**

		(Shaheed Dweep, North)		**mono-species, deep subtidal**	**(Coarse + Fine Sand, > 50% epiphytic alga)**						
Ritchie's archipelago	Site 30	Bharatpur shallow (Shaheed Dweep; North)	11°50'31.85"N, 93° 2'19.58"E	Sparse, mixed-species, shallow subtidal	Homogeneous sandy (Coarse + Fine Sand, > 50% epiphytic alga)	4	7.7	*Halodule uninervis*, *Halodule pinifolia*, *Halophila decipiens**, *Halophila ovalis*	22.5	442.85 ± 172.43	18.3
Ritchie's archipelago	**Site 31**	**Aquarium-deep water (Shaheed Dweep; North)**	**11°50'57.01"N 93° 1'28.31"E**	**Dense, mixed-species, deep subtidal**	**Homogeneous sandy (Coarse + Fine Sand, > 50% epiphytic alga)**	**2**	**11.0**	***Halophila decipiens*, *Halophila ovalis***	**61.7**	**695 ± 324.22**	**10.5**
Ritchie's archipelago	**Site 32**	**Aquarium-shallow (Shaheed Dweep; North)**	**11°50'50.70"N 93°1’21.09” E**	**Sparse, mono-species, shallow subtidal**	**Sand+ Dead Coral Alga +Rubble+Live Coral (Fine Sand)**	**1**	**7.8**	***Halophila ovalis***	**12.4**	**775 ± 318.19**	**13.3**
Ritchie's archipelago	Site 33	Laxmanpur (Shaheed Dweep, North-West)	11°50'53.45"N, 93° 0'45.22"E	Dense, mono-species, intertidal	Sand+ Rock+ Dead Coral Alga+ Rubble	1	0.4	*Thalassia hemprichii*	53.8	598.04 ± 412.65	111.8

					(Coarse + Fine Sand)						
Ritchie's archipelago	**Site 34**	**Nursery (Shaheed Dweep, North-West)**	**11°50'45.71"N 93° 0'38.59"E**	**Sparse, mono-species, deep subtidal**	**Sand+Rubble+ Live Coral (Coarse + Fine Sand)**	**1**	**14.8**	***Halophila ovalis***	**8.4**	**1035.71 ± 463.87**	**5.0**
Ritchie's archipelago	**Site 35**	**Natural Bridge (Shaheed Dweep, South-West)**	**11°50'1.10"N, 93° 0'51.91"E**	**Sparse, mono-species, intertidal**	**Sand+ Dead Coral Alga+ Rubble+Live Coral** **(Coarse + Fine Sand)**	**1**	**0.4**	***Thalassia hemprichii***	**12.5**	**413.2 ± 217.92**	**81.5**
Ritchie's archipelago	**Site 36**	**Macchi Gadda (Shaheed Dweep, South-West)**	**11°49'35.87"N93° 0'57.82"E**	**Moderate mixed-species, deep subtidal**	**Sand+Live Coral+Dead Coral Alga+ Rubble** **(Coarse + Fine Sand)**	**3**	**15.4**	***Halodule uninervis, Halophila decipiens, Halophila ovalis***	**41.1**	**2550 ± 847.5**	**46.8**
Ritchie's archipelago	Site 37	Chota Neil (Sir Hugh Ross, West)	11°47'4.81"N, 93° 4'26.94"E	Moderate, mixed-species,	Homogeneous sandy (Fine sand)	2	12.0	*Halodule pinifolia* *, *Halophila ovalis*	44.0	362.5 ± 88.38	52.5

				deep subtidal							
South Andaman	Site 38	Haddo (Port Blair, East)	11°40'55.56"N, 92°43'32.12"E	Moderate, mixed-species, intertidal	Homogeneous sandy (Fine sand + Silt, > 50% epiphytic alga)	4	0.3	*Halodule uninervis*, *Halodule pinifolia*, *Halophila ovalis*, *Thalassia hemprichii*	45.1	4101 ± 2381.23	67.8
South Andaman	Site 39	Burmanallah (Port Blair, East)	11°33'22.65"N, 92°43'53.01"E	Sparse, mixed-species, intertidal	Sand+Rubble+ Rock (Fine + Coarse sand)	5	0.2	*Thalassia hemprichii*, *Cymodocea rotundata*, *Cymodocea serrulata* *, *Halodule pinifolia* *, *Halodule uninervis* *	21.3	3230 ± 1201.1	242.5
South Andaman	**Site 40**	**Chester (MGMNP, Southeast)**	**11°34'55.42"N92°34'47.89"E**	**Sparse, mono-species, shallow subtidal**	**Sand+Rubble+ Rock (Coarse sand)**	**1**	**2.0**	***Halophila ovalis***	**15.2**	**650 ± 110.8**	**12.2**

South Andaman	Site 41	Taramuni (Tarmugli-MGMNP, West)	11°34'55.71"N, 92°31'52.60"E	Sparse, mixed-species, shallow subtidal	Sand+Rubble+Live Coral (Coarse Sand)	2	2.4	*Halophila ovalis, Thalassia hemprichii*	10.2	2291.6 ± 1127.04	75.9
South Andaman	Site 42	Taramuni (Tarmugli-MGMNP, East)	11°34'33.88"N, 92°33'53.56"E	Dense, mono-species, shallow subtidal	Sand+Rubble+Live Coral+Dead Coral Alga (Coarse Sand)	1	4.4	*Halophila ovalis*	52.2	1625 ± 1544.5	12.6
South Andaman	Site 43	Taramuni (Tarmugli-MGMNP, South)	11°33'36.94"N, 92°32'34.59"E	Sparse, mono-species, shallow subtidal	Sand+Rock+ Dead Coral Alga+ Live Coral (Fine + Coarse Sand, > 50% epiphytic alga)	1	2.5	*Halophila ovalis*	12.0	750 ± 565.68	1.9
South Andaman	Site 44	Cheena Pahad (Boat-MGMNP, East)	11°31'53.26"N, 92°34'5.40"E	Moderate, mixed-species, shallow subtidal	Sand+Rubble (Fine sand)	2	1.9	*Halophila ovalis, Halodule uninervis**	45.6	1562.5 ± 477.97	18.3
South Andaman	**Site 45**	**Kachua Tikri (Twins-MGMNP; North)**	**11°23'58.12"N92°33'21.65"E**	**Moderate, mono-species,**	**Sand+ Rubble Rock** **(Coarse sand)**	**1**	**6.6**	***Halophila ovalis***	**44.2**	**2787.5 ± 562.17**	**12.6**

				shallow subtidal							
Little Andaman	**Site 46**	**Patthar Nali (Little Andaman, East)**	**10°47'1.00"N, 92°35'23.89"E**	**Moderate mixed-species, intertidal**	**Homogeneous sandy** **(Fine sand)**	**3**	**0.5**	***Halodule pinifolia, Thalassia hemprichii, Halophila ovalis***	**45.1**	**1675 ± 384.87**	**69.5**
Little Andaman	**Site 47**	**Dungi Ghat (Little Andaman, East)**	**10°43'36.22"N92°35'19.07"E**	**Moderate mixed-species, intertidal**	**Dead Coral Alga+ Sand+Rock** **(Fine sand)**	**2**	**0.2**	***Cymodocea rotundata, Thalassia hemprichii***	**33.9**	**2633.33 ± 650.64**	**275.1**
Little Andaman	Site 48	Kalapatthar (Little Andaman, East)	10°39'11.40"N, 92°34'42.16"E	Moderate, mono-species, intertidal	Sand+ Dead Coral Alga+ Rock+ Live Coral (Fine sand)	1	0.1	*Thalassia hemprichii*	33.9	1425 ± 1638.25	70.4
Little Andaman	Site 49	Hutbay Breakwater Jetty (Right- Little Andaman, Southeast)	10°35'6.03"N, 92°33'54.49"E	Moderate, mixed-species, intertidal	Rock+ Sand+ Dead Coral Alga (Fine sand)	2	0.2	*Cymodocea rotundata, Thalassia hemprichii*	26.9	4100 ± 1096.02	138.8

Little Andaman	Site 50	Harminder Bay (Little Andaman, Southeast)	10°33'31.66"N, 92°33'16.58"E	Sparse, mono-species, intertidal	Sand+ Dead Coral Alga (Fine sand)	1	0.3	*Thalassia hemprichii*	24.2	1500 ± 1555.62	73.3
Little Andaman	Site 51	Hutbay-Lighthouse (Little Andaman, South)	10°30'39.91"N, 92°30'17.71"E	Dense, mixed-species, intertidal	Sand+ Dead Coral Alga+ Rock+ Rubble (Fine sand)	5	0.2	*Halodule uninervis*, *Cymodocea serrulata*, *Cymodocea rotundata*, *Thalassia hemprichii*, *Halophila ovalis*	63.9	2575 ± 1656.8	283.5
Little Andaman	Site 52	Ship Wreck (Little Andaman, South)	10°30'49.21"N, 92°29'39.82"E	Moderate, mixed-species, intertidal	Sand+ Dead Coral Alga (Fine sand)	4	0.2	*Halodule uninervis*, *Cymodocea serrulata*, *Cymodocea rotundata*, *Thalassia hemprichii*,	38.9	4686.7 ± 1290.47	196.9
Nicobar	Site 53	Kardip (Kamorta, Southeast)	8° 2'21.88"N, 93°32'55.61"E	Very dense, mixed-species, shallow subtidal	Sand+Rubble (Fine sand)	5	2.0	*Halophila ovalis*, *Syringodium isoetifolium*, *Halodule uninervis*, *Enhalus acoroides*, *Halodule pinifolia*	78.2	3068.75 ± 1532.34	3180.0

Nicobar	Site 54	Bada Inak (Kamorta, Southeast)	8° 4'33.04"N, 93°33'2.75"E	Dense, mixed-species, shallow subtidal	Homogeneous sandy (Fine sand)	4	2.0	*Enhalus acoroides*, *Halophila ovalis*, *Halodule pinifolia*, *Halodule uninervis*	50.9	2425 ± 2580.94	3014.9
Nicobar	**Site 55**	**Rani Tikri (Kamorta, South)**	**8° 2'1.34"N, 93°30'47.71"E**	**Sparse, mixed-species, shallow subtidal**	**Sand+ Dead Coral Alga+ Live Coral+Rubble+ Rock** **(Fine sand)**	**2**	**3.0**	***Halophila ovalis*, *Halophila minor***	**13.6**	**1530 ± 115.6**	**70.8**
Nicobar	**Site 56**	**Pil Pillow (Rai-Kin-Fimo; Kamorta, North)**	**8°11'0.53"N, 93°28'17.23"E**	**Sparse, mono-species, shallow subtidal**	**Sand+Rubble** **(Fine sand)**	**1**	**3.5**	***Halophila ovalis***	**3.6**	**950 ± 115.6**	**40.4**
Nicobar	**Site 57**	**Pil Pillow (Kaloweek; Kamorta, North)**	**8°13'3.38"N, 93°29'27.57"E**	**Sparse, mono-species, shallow subtidal**	**Sand+Rubble** **(Fine sand)**	**1**	**3.0**	***Cymodocea rotundata***	**17.5**	**1087.5 ± 123.74**	**162.3**
Nicobar	**Site 58**	**Pil Pillow (Moh-Ryak; Kamorta, North)**	**8°11'58.95"N, 93°29'16.45"E**	**Sparse, mono-species, shallow subtidal**	**Sand+Rubble** **(Fine sand)**	**1**	**3.0**	***Halophila decipiens***	**3.6**	**100 ± 105.0**	**17.5**

Nicobar	Site 59	Hypo (Katchal, East)	7°57'39.95"N, 93°25'27.54"E	Sparse, mono-species, shallow subtidal	Homogeneous sandy (Fine sand)	1	3.0	*Halodule pinifolia*	14.9	1100 ± 70	24.4
Nicobar	**Site 60**	**Kapanga (Katchal, North-East)**	**8° 0' 9.82"N, 93°24'22.62"E**	**Moderate mixed-species, shallow subtidal**	**Homogeneous sandy** **(Fine sand)**	**2**	**5.0**	***Halophila minor, Halodule pinifolia***	**31.8**	**3725 ± 2885.81**	**85.6**
Nicobar	**Site 61**	**Lighthouse (Katchal, North-East)**	**8° 0' 34.06"N, 93°24'28.56"E**	**Dense, mixed-species, shallow subtidal**	**Homogeneous sandy** **(Fine sand)**	**2**	**4.0**	***Halophila ovalis, Halodule uninervis***	**61.8**	**1400 ± 707.10**	**63.4**
Nicobar	Site 62	Safed Balu (Trinket, North)	8° 6' 48.68"N, 93°33'59.07"E	Very dense, mixed-species, shallow subtidal	Homogeneous sandy (Fine sand)	5	2.5	*Halodule uninervis, Halophila ovalis, Halodule pinifolia, Enhalus acoroides, Thalassia hemprichii*	94.5	885.71 ± 425.21	519.6
Nicobar	Site 63	Trinket (West coast, South-West)	8° 2' 53.33"N, 93°34'57.45"E	Very dense, mixed-species, shallow subtidal	Homogeneous sandy (Fine sand)	5	3.0	*Halodule uninervis, Halophila ovalis, Enhalus acoroides, Cymodocea rotundata,*	90.5	3650 ± 627.5	1548.5

								Syringodium isoetifolium			
Nicobar	Site 64	Al-Reak (Nancowry, North)	8° 1' 6.64"N, 93°34'0.58"E	Dense, mixed-species, shallow subtidal	Sand+ Rubble+ Dead Coral Alga (Fine sand)	8	5.0	*Cymodocea rotundata*, *Syringodium isoetifolium*, *Thalassia hemprichii*, *Halodule pinifolia*, *Enhalus acoroides*, *Cymodocea serrulata*, *Halophila ovalis*, *Halodule uninervis*	74.4	1977.70 ± 1472.48	2003.3
Nicobar	Site 65	Hitui (Nancowry, North)	8° 1' 25.78"N, 93°31'46.23"E	Very dense, mixed-species, shallow subtidal	Homogeneous sandy (Fine sand, > 50% epiphytic alga)	7	1.0	*Halophila ovalis*, *Halodule pinifolia*, *Halodule uninervis*, *Enhalus acoroides*, *Thalassia hemprichii*, *Cymodocea serrulata*, *Halophila minor*	88.2	1567.80 ± 879.36	1300.5

Nicobar	Site 66	Campbell Bay (Great Nicobar, East)	7° 0' 31.25"N, 93°55'49.58"E	Moderate, mixed-species, intertidal	Homogeneous sandy (Fine sand)	4	0.2	*Halophila ovalis*, *Halophila minor*, *Halodule pinifolia*, *Halodule uninervis*	49.1	1232.1 ± 699.2	150.0

[Sg sp., Seagrass species richness; WD, Water depth, *indicates new species distribution record for the region]

Annexure 3

Annexure 3: Seagrass-associated infaunal diversity across 55 sampled locations in the Andaman and Nicobar archipelago, India [values expressed as mean ± Std. Error]

Sr. no	**Site**	**Species complex**	**GR**	**GC**	**Shannon_ H**	**Evenness Index_e^ H/S**	**Total mean densities (ind./m^2)**	**Group-specific densities (ind./m^2)**									
								po	**gp**	**ne**	**bi**	**cr**	**fo**	**cni**	**oph**	**oligo**	**sip**
1	Landfall (South-East)	complex 1	5	gp, bi, po, ne, cr	1.3	0.7594	45 ± 23.5	116.7 ± 8.3	216.7 ± 8.3	25 ± 25	50 ± 28.9	41.7 ± 30	0	0	0	0	0
2	Landfall-East (Channel)	complex 1	5	gp, bi, po, ne, cr	1.5	0.8672	40 ± 20.3	137.5 ± 37.5	100 ± 50	37.5 ± 37.5	100 ± 100	25 ± 0	0	0	0	0	0
3	Reef (East)	complex 1	3	gp, bi, ne	1.1	0.9629	20 ± 12.3	0	50 ± 0	62.5 ± 62.5	87.5 ± 12.5	0	0	0	0	0	0
4	Reef (South)	complex 1	3	gp, bi, po	0.9	0.8201	20 ± 15	58.3 ± 22	116.7 ± 60.1	0	25 ± 0	0	0	0	0	0	0
5	Paget (North-East)	complex 1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

6	Point (North)	complex 1	4	gp, bi, po, ne	1.3	0.9473	37.5 ± 21	75 ± 63.2	80 ± 18.4	75 ± 20.9	145 ± 49.6	0	0	0	0	0	0
7	Radhanagar Channel (Opening)	complex 1	3	gp, bi, po	0.6	0.9449	9.2 ± 7.3	4.2 ± 4.2	54.2 ± 24.5	0	33.3 ± 10.5	0	0	0	0	0	0
8	Excelsior (West)	complex 1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
9	Delgarno (West)	complex 1	5	gp, bi, po, ne, cr	1.4	0.8227	26.3 ± 12.8	25 ± 25	125 ± 25	37.5 ± 12.5	50 ± 0	25 ± 0	0	0	0	0	0
10	Temple (West)	complex 1	4	gp, bi, po, ne	1.2	0.861	26.2 ± 16.6	37.5 ± 37.5	87.5 ± 62.5	25 ± 25	112.5 ± 62.5	0	0	0	0	0	0
11	Smith (North-East)	complex 1	5	gp, bi, po, ne, cr	1.5	0.8826	47.9 ± 28.5	129.2 ± 44.5	79.2 ± 18.7	54.2 ± 54.2	170.8 ± 71.7	45.8 ± 17.6	0	0	0	0	0
12	Smith (East)	complex 1	5	gp, bi, po, ne, cr	1.4	0.8138	101.7± 58	366.7 ± 159	25 ± 25	258.3 ± 134.1	116.7 ± 22	250 ± 146.5	0	0	0	0	0
13	Kohassa (Shibpur)	complex 1	5	gp, bi, po, ne, cr	1	0.8668	20 ± 14.3	20 ± 14.6	60 ± 34.1	5 ± 5	110 ± 25.7	5 ± 5	0	0	0	0	0
14	Kalipur	complex 2	4	gp, po, ne, cr	1.2	0.8379	66.3 ± 36.9	212.5 ± 212.5	187.5 ± 37.5	250 ± 50	0	12.5 ± 12.5	0	0	0	0	0
15	Craggy	complex 1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
16	North Reef (East)	complex 1	4	gp, po, ne, cr	1	0.6865	47.5 ± 29.9	300 ± 0	100 ± 16.2	50 ± 0	0	25 ± 0	0	0	0	0	0
17	Jhau Nala (Interview, North)	complex 1	5	gp, bi, po, ne, cr	1.6	0.9421	11.3 ± 4.7	12.5 ± 12.5	37.5 ± 37.5	12.5 ± 12.5	37.5 ± 37.5	12.5 ± 12.5	0	0	0	0	0

18	Pokkadera (Mayabunder)	complex 3	5	gp, bi, po, ne, cr	1.3	0.9367	23.1 ± 12.3	68.8 ± 35.8	60.4 ± 12.1	35.4 ±22.7	56.3 ± 13.8	10.4 ± 10.4	0	0	0	0	0
19	Imli Dera (Henry Lawrence-Shallow, North)	complex 1	6	gp, bi, po, ne, cr, fo	1.3	0.6106	180 ± 91.7	50 ± 0	125 ± 11.3	800 ± 0	25 ± 9.2	175 ± 0	625 ± 175	0	0	0	0
20	Imli Dera (Henry Lawrence-deeper, North)	complex 1	5	gp, bi, po, cr, fo	1.2	0.6876	187.5 ± 99.2	150 ± 0	350 ± 36.4	0	375 ± 34.5	25 ± 0	975 ± 120	0	0	0	0
21	Jua Tekdi (Henry Lawrence, East)	complex 3	5	gp, bi, po, ne, cr	1.1	0.5787	66.9 ± 46.9	425 ± 301.6	37.5 ± 21.6	143.8 ± 78.4	31.3 ± 15.7	31.3 ± 12	0	0	0	0	0
22	Inglis (South-west)	complex 1	7	gp, bi, po, ne, cr, fo, cni	1.7	0.9038	53.4 ± 29.5	84.4 ± 45.5	109.4 ± 33.9	96.9 ± 31.1	71.9 ± 14.5	153.1 ± 66.6	15.6 ± 10.5	3.1 ± 1.8	0	0	0
23	Chand Balu (Henry Lawrence, South-East)	complex 2	5	gp, bi, po, ne, cr	1.6	0.9514	20 ± 8.2	41.7 ± 22	50 ± 14.4	50 ± 14.4	25 ± 14.4	33.3 ± 8.3	0	0	0	0	0
24	Vijay Nagar (Swaraj Dweep, North-East)	complex 2	6	gp, bi, po, ne, cr, oph	1.4	0.7832	45.4 ± 26.7	203.6 ± 42.8	39.3 ± 12.6	123.8 ± 36.2	34.5 ± 10.1	45.2 ± 11.5	0	0	7.1 ± 2.6	0	0
25	Bharatpur (Shaheed Dweep-	complex 1	6	gp, bi, po, ne, cr, fo	1.6	0.8193	101.7 ± 51.8	320.8 ± 8.3	233.3 ± 36.9	250 ± 81.6	116.7 ± 32.1	41.7 ± 20.4	54.1 ± 17.9	0	0	0	0

	shallow subtidal, North)																
26	Laxmanpur (Shaheed Dweep, North-West)	complex 2	5	gp, bi, po, ne, cr	1.4	0.8053	54.2 ± 33.6	231 ± 41.4	57.4 ± 15.4	150 ± 28.8	48.3 ± 12.4	55.7 ± 15.4	0	0	0	0	0
27	Haddo (Port Blair, East)	complex 1	5	gp, bi, po, ne, cr	1.4	0.7768	80 ± 48.5	365.6 ± 134.9	81.3 ± 31.3	187.5 ± 80.3	109.4 ± 43	56.3 ± 52.8	0	0	0	0	0
28	Burmanallah (Port Blair, East)	complex 3	8	gp, bi, po, ne, cr, oligo, sip, oph	1.8	0.7344	49.5 ± 32.4	214.1 ± 40.4	78.9 ± 28.7	0	43 ± 10.1	46.8 ± 13	0	0	1.9 ± 1.2	1.9 ± 1.9	1.9 ± 1.7
29	Chester (MGMNP, South-East)	complex 1	5	gp, bi, po, ne, cr	1.5	0.8911	19.2 ± 8.8	41.7 ± 8.3	75 ± 14.4	33.3 ± 8.3	16.7 ± 16.7	25 ± 14.4	0	0	0	0	0
30	Tarmugli (MGMNP, West)	complex 1	5	gp, bi, po, ne, cr	1.6	0.9524	13.3 ± 5.2	41.7 ± 30	33.3 ± 22	16.7 ± 8.3	16.7 ± 8.3	25 ± 14.4	0	0	0	0	0
31	Tarmugli (MGMNP, East)	complex 1	5	gp, bi, po, ne, cr	1.5	0.9172	22.5 ± 9.1	37.5 ± 37.5	62.5 ± 12.5	37.5 ± 37.5	25 ± 0	12.5 ± 12.5	0	0	0	0	0
32	Tarmugli (MGMNP, South)	complex 1	5	gp, bi, po, ne, cr	1.6	0.9818	32.5 ± 25.5	50 ± 0	75 ± 9.2	75 ± 0	75 ± 11.5	50 ± 0	0	0	0	0	0
33	Boat (MGMNP, East)	complex 1	4	gp, bi, po, ne	1.1	1	6.4 ± 3.5	13.9 ± 4.4	25 ± 0	11.1 ± 4.4	13.9 ± 4.4	0	0	0	0	0	0

34	Twins (MGMNP, North)	complex 1	5	gp, bi, po, ne, cr	1.6	1	13.3 ± 5.9	33.3 ± 13.9	29.2 ± 7.7	25 ± 6.5	33.3 ± 15.4	12.5 ± 5.6	0	0	0	0	0
35	Patthar Nali (Little Andaman, East)	complex 3	4	gp, po, ne, cr	1.2	0.8174	150.8 ± 91.3	566.7 ± 230.1	125 ± 52	166.7 ± 110.2	0	650 ± 404.6	0	0	0	0	0
36	Dungi Ghat (Little Andaman, East)	complex 2	5	gp, bi, po, ne, cr	1.1	0.7394	52 ± 38.5	115 ± 66.4	65 ± 38.4	300 ± 176.2	35 ± 12.8	5 ± 5	0	0	0	0	0
37	Kalapatthar (Little Andaman, East)	complex 2	5	gp, bi, po, ne, cr	1.5	0.8592	46.7 ± 23.3	100 ± 25	200 ± 87.8	50 ± 25	41.7 ± 16.7	75 ± 75	0	0	0	0	0
38	Hutbay Breakwater Jetty (Right-Little Andaman, South-East)	complex 2	3	gp, po, cr	0.9	0.7877	25 ± 17.3	75 ± 75	12.5 ± 12.5	0	0	162.5 ± 112.5	0	0	0	0	0
39	Harminder Bay (Little Andaman, South-East)	complex 2	6	gp, bi, po, ne, cr, cni	1.4	0.7919	34.4 ± 21.5	106.3 ± 62.4	37.5 ± 16.1	137.5 ± 80	25 ± 10.2	31.3 ± 23.7	0	6.25 ± 2.5	0	0	0
40	Hutbay-Lighthouse (Little Andaman, South)	complex 3	5	gp,bi, po, ne, cr	1.2	0.665	60.5 ± 37.4	260 ± 120.6	60 ± 31.2	245 ± 71.8	25 ± 15.8	15 ± 10	0	0	0	0	0

41	Ship Wreck (Little Andaman, South)	complex 3	5	gp, bi, po, ne, cr	1.3	0.7576	68.8 ± 44.3	112.5 ± 37.5	287.5 ± 262.5	225 ± 125	12.5 ± 12.5	50 ± 50	0	0	0	0	0
42	Kardip (Kamorta, South-East)	complex 3	5	gp, bi, po, ne, cr	1.2	0.8645	28.5 ± 17.5	115 ± 46.5	35 ± 18.7	55 ± 39	70 ± 20	10 ± 6.1	0	0	0	0	0
43	Bada Inak (Kamorta, South-East)	complex 3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
44	Rani Tikri (Kamorta, South)	complex 1	4	gp, bi, po, ne	1	0.9428	10.6 ± 6.7	18.8 ± 6.5	50 ± 30.6	6.3 ± 6.3	31.2 ± 15.7	0	0	0	0	0	0
45	Pilpillow (Rai-Kin-Fimo; Kamorta, North)	complex 1	2	po, cr	0.2	0.6145	47.5 ± 44.8	450 ± 0	0	0	0	25 ± 0	0	0	0	0	0
46	Pilpillow (Kaloweek; Kamorta, North)	complex 2	5	gp, bi, po, ne, cr	1.4	0.8054	81.2 ± 40.4	375 ± 141.4	212.5 ± 88.4	62.5 ± 18.4	87.5 ± 17.7	75 ± 50	0	0	0	0	0
47	Pilpilow (Moh-Ryak; Kamorta, North)	complex 1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
48	Hypo (Katchal, East)	complex 1	2	gp, bi	0.5	0.8492	22.5 ± 17.7	0	175 ± 16.2	0	50 ± 0	0	0	0	0	0	0
49	Kapanga (Katchal, North-East)	complex 1	2	gp, bi	0.7	0.9938	23.1 ± 16.3	0	106.3 ± 34.4	0	125 ± 0	0	0	0	0	0	0

50	Lighthouse (Katchal, North-East)	complex 1	4	gp, bi, po, cr	1.3	0.8965	17.5 ± 9.1	25 ± 25	75 ± 50	0	25 ± 0	50 ± 50	0	0	0	0	0
51	Safed Balu (Trinket, North)	complex 3	5	gp, bi, po, ne, cr	1.2	0.7951	32.5 ± 21.1	58.3 ± 35.7	166.7 ± 82.3	33.3 ± 21.1	62.5 ± 14.1	4.2 ± 4.2	0	0	0	0	0
52	Trinket (West coast, South-West)	complex 3	2	gp, bi	0.6	0.9449	6.3 ±5.1	0	25 ± 0	0	37.5 ± 25	0	0	0	0	0	0
53	Al-Riyak (Nancowry, North)	complex 3	5	gp, bi, po, ne, cr	1.5	0.8625	39 ± 23.7	160 ± 70.1	100 ± 44.7	45 ± 39.1	15 ± 15	70 ± 57.8	0	0	0	0	0
54	Hitui (Nancowry, North)	complex 3	5	gp, bi, po, ne, cr	1.3	0.9473	13 ± 8.1	20 ± 20	25 ± 11.1	10 ± 10	55 ± 39.1	20 ± 14.6	0	0	0	0	0
55	Campbell Bay (Great Nicobar, East)	complex 1	5	gp, bi, po, ne, cr	1.2	0.6881	96.3 ± 63.8	475 ± 200	312.5 ± 287.5	62.5 ± 62.5	87.5 ± 12.5	25 ± 8.3	0	0	0	0	0

[GR, Group Richness; GC, Group Composition; po, polychaetes; gp, gastropods; ne, nematodes; bi, bivalves; cr, crustaceans; fo, foraminiferans; cni, cnidarians; oph, ophiuroids; oligo, oligochaetes; sip, sipunculids]

Annexure 4

Annexure 4: Seagrass-associated epifaunal diversity across 66 sampled locations in the Andaman and Nicobar archipelago, India [values expressed as mean ± Std. Error]

Sr. no.	**Site**	**GR**	**GC**	**H**	**E**	**Total mean densities (ind./m^2)**	**Group-specific densities, Count (ind./m^2)**													**Epibenthic cover (%/ m^2)**		
							gp	**bb**	**hol**	**poly**	**cni**	**oph**	**echi**	**cr**	**bi**	**chi**	**ast**	**cri**	**platy**	**por (%/ m^2)**	**cni (%/ m^2)**	**asc (%/ m^2)**
1	Landfall (South-East)	1	bb	0	1	17.3 ± 12.4	0	225 ± 0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	Landfall-East (Channel)	3	bb, hol, oph	1	0.9	11.5 ± 4.2	0	75 ± 0	25 ± 0	0	0	50 ± 0	0	0	0	0	0	0	0	0	0	0
3	Reef (East)	5	gp, bb, hol, cni, echi	1	0.7	199.7 ± 124.2	1100 ± 0	225 ± 0	25 ± 0	0	630 ± 0	0	616 ± 0	0	0	0	0	0	0	0	68	0
4	Reef (South)	4	gp,bb, oph, por	1	0.6	25 ± 15.7	25 ± 0	275 ± 0	0	0	0	25 ± 0	0	0	0	0	0	0	0	9	0	0
5	Paget (North-East)	2	bb, cni	0	0.5	19.2	0	250 ± 0	0	0	0	0	0	0	0	0	0	0	0	0	55	0

6	Point (North)	4	gp,bb, poly, cni	0	0.4	238.5 ± 37.5	2750 ± 565.7	212.5 ± 123.7	0	125 ± 76.8	12.5 ± 7.7	0	0	0	0	0	0	0	0	0	0	0
7	Radhanagar Channel (Opening)	5	gp, bb, cni, cr,ast	1	0.4	91.3 ± 57.3	137.5 ± 94.5	950 ± 237.4	0	0	12.5 ± 7.7	0	0	5	75 ± 70.7	0	12.5 ± 12.8	0	0	0	0	0
8	Excelsior (West)	4	bb, cni, cr, bi	1	0.5	93.5 ± 52.6	0	475 ± 0	0	0	690 ± 0	0	0	25	25 ± 0	0	0	0	0	0	0	0
9	Delgarno (West)	4	bb, hol, cni, bi	1	0.6	101.9 ± 66	0	275 ± 0	75 ± 0	0	950 ± 0	0	0	0	0	0	0	0	0	0	0	0
10	Temple (West)	1	bb	0	1	23.1	0	300 ± 0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
11	Smith (North-East)	6	gp, bb, poly, cni, echi, bi	1	0.4	72.9 ± 3.3	25 ± 17.7	60 ± 48.5	0	775 ± 548	50 ± 35.4	0	12.5 ± 7.7	0	0	0	0	0	0	0	18	0
12	Smith (East)	3	gp, bb, bi	1	0.9	54.8 ± 78.1	37.5 ± 0	637.8 ± 0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
13	Kohassa (Shibpur)	3	bb, bi, asc	0	0.6	46.2 ± 15	0	575 ± 0	0	0	0	0	0	0	0	0	0	0	0	0	0	6
14	Kalipur	4	gp, cr, bi, por	0	0.4	389.4 ± 44.8	4850 ± 848.5	0	0	0	0	0	0	87.5	87.5 ± 17.7	0	0	0	0	6	0	0
15	Craggy	2	bb, echi	0	0.5	150 ± 33.4	0	1925 ± 0	0	0	0	0	25 ± 0	0	0	0	0	0	0	0	0	0
16	North Reef (East)	1	bb	0	1	15.4 ± 5.5	0	200 ± 0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

17	Jhau Nala (Interview, North)	1	bb	0	1	5.8 ± 1.8	0	75 ± 0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
18	Pokkadera (Mayabunder)	7	gp, bb, oph, cr, bi, chi, ast	1	0.6	32.6 ± 9.2	155 ± 57.5	70 ± 15.2	0	0	0	150 ± 25.2	0	8.3	8.3 ± 8.3	10 ± 2.4	5 ± 1.2	0	0	0	0	0
19	Imli Dera (Henry Lawrence-Shallow, North)	5	gp, poly, cr, por, asc	1	0.7	23.1 ± 0	25 ± 25	0	0	250 ± 159.1	0	0	0	25	25 ± 7.8	0	0	0	0	64	0	45
20	Imli Dera (Henry Lawrence-deeper, North)	3	gp, hol, poly	0	1	20.2 ± 11.5	37.5 ± 0	0	12.5 ± 7.7	212.5 ± 0	0	0	0	0	0	0	0	0	0	0	0	0
21	Jua Tekdi (Henry Lawrence, East)	4	gp, bb, poly, asc	1	0.8	6.8 ± 5	8.3 ± 4.4	75 ± 25	0	5 ± 6.6	0	0	0	0	0	0	0	0	0	0	0	64
22	Inglis (South-West)	2	bb, cni	1	1	37.2 ± 12.3	0	300 ± 303.1	0	0	183.3 ± 80.6	0	0	0	0	0	0	0	0	0	0	0
23	Chand Balu (Henry Lawrence, South-East)	4	bb, hol, poly, por	1	0.9	27.9 ± 28.1	0	62.5 ± 0	137.5 ± 0	162.5 ± 0	0	0	0	0	0	0	0	0	0	9	0	0
24	John Lawrence (South)	1	poly	0	1	1.9 ± 2.1	0	0	0	25 ± 15.4	0	0	0	0	0	0	0	0	0	0	0	0

25	Nemo Reef (Swaraj Dweep, North)	3	gp, poly, cr	1	0.8	9 ± 3.7	33.3 ± 18.2	0	0	75 ± 66.1	0	0	0	8.3	8.3 ± 4.4	0	0	0	0	0	0	0
26	Dolphin (Swaraj Dweep, North-East)	2	gp, cr	0	0.7	8 ± 0	87.5 ± 17.7	0	0	0	0	0	0	12.5	12.5 ± 17.8	0	0	0	0	0	0	0
27	Vijay Nagar (Swaraj Dweep, North-East)	6	gp, bb, hol, poly, cr, asc	1	0.8	226.9 ± 77	950 ± 0	675 ± 0	975 ± 0	225 ± 0	0	0	0	125	125 ± 0	0	0	0	0	0	0	3
28	Busy Buro (Shaheed Dweep, North)	6	gp, poly, echi, cr, por, asc	1	0.7	8.3 ± 2.9	8.3 ± 4.4	0	0	58.3 ± 28.7	0	0	33.3 ± 18.2	8.3	8.3 ± 4.4	0	0	0	0	25	0	50
29	Bharatpur (Shaheed Dweep-deep subtidal, North)	1	poly	1	0.7	5.8 ± 0	0	0	0	75 ± 0	0	0	0	0	0	0	0	0	0	0	0	0
30	Bharatpur (Shaheed Dweep-shallow subtidal, North)	4	gp, bb, cni, echi	1	0.8	35.6 ± 24	50 ± 0	337.5 ± 260.9	0	0	62.5 ± 47.3	0	12.5 ± 12.5	0	0	0	0	0	0	0	0	0
31	Aquarium (Shaheed Dweep-deep subtidal, North)	2	poly, por	0	0.5	1.9 ± 2.1	0	0	0	25 ± 15.4	0	0	0	0	0	0	0	0	0	45	0	0
32	Aquarium (Shaheed Dweep-shallow subtidal, North)	1	gp	0	1	1.9 ± 0	25 ± 0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

33	Laxmanpur (Shaheed Dweep, North-West)	12	gp, bb, hol, poly, cni, oph, cr, bi, chi, platy, por, asc	1	0.4	43.1 ± 16.4	139.2 ± 103.9	11.1 ± 19.5	7.1 ± 9	317.8 ± 153.6	3.5 ± 1.5	17.9 ± 13.8	0	17.9	17.9 ± 17.8	35.7 ± 24	0	0	3.6 ± 9.5	18	3	19
34	Nursery (Shaheed Dweep, North-West)	6	gp, poly, cr, cri, por, asc	1	0.5	17.9 ± 5	8.3 ± 14.4	0	0	183.3 ± 76.4	0	0	0	16.7	16.7 ± 8.9	0	0	25 ± 14.4	0	27	0	39
35	Natural Bridge (Shaheed Dweep, South-West)	6	gp, hol, poly, cr, por, asc	1	0.7	17.8 ± 17.1	93.75 ± 38.1	0	25 ± 12.5	75 ± 73.8	0	0	0	37.5	37.5 ± 16.8	0	0	0	0	63	0	45
36	Macchi Gadda (Shaheed Dweep, South-West)	4	poly, echi, por, cni	0	0.7	29.5 ± 29.9	0	0	0	350 ± 63.5	0	0	33.3 ± 7.7	0	0	0	0	0	0	73	27	0
37	Chota Neil (Sir Hugh Ross, West)	3	poly, por, cni	0	0.4	5.8 ± 0	0	0	0	75 ± 0	0	0	0	0	0	0	0	0	0	82	9	0
38	Haddo (Port Blair, East)	4	gp, bb, poly, cr	0	0.4	46.8 ± 10	558.3 ± 246.6	25 ± 13.3	0	16.7 ± 18.9	0	0	0	8.3	8.3 ± 4.4	0	0	0	0	0	0	0
39	Burmanallah (Port Blair, East)	10	gp, bb, hol, poly, cni, oph, cr, bi, chi, por	2	0.8	82.1 ± 25	291.7 ± 242.8	33.3 ± 14.4	50 ± 43.3	233.3 ± 212.6	41.7 ± 12.2	191.7 ± 123.3	0	100	100 ± 66.1	41.7 ± 22.2	0	0	0	15	0	0
40	Chester (MGMNP, South-East)	6	gp, bb, hol, poly, por, asc	1	0.8	38.5 ± 10.7	75 ± 0	25 ± 0	125 ± 0	275 ± 0	0	0	0	0	0	0	0	0	0	9	0	82

41	Tarmugli (MGMNP, West)	7	bb, hol, poly, cr, chi, por, cni	0	0.3	155.8 ± 24.3	0	25 ± 0	50 ± 0	1900 ± 0	0	0	0	25	25 ± 0	25 ± 0	0	0	0	36	9	0
42	Tarmugli (MGMNP, East)	2	bb, por	0	0.5	3.8 ± 3.9	0	50 ± 0	0	0	0	0	0	0	0	0	0	0	0	45	0	0
43	Tarmugli (MGMNP, South)	3	bb, poly, por	0	0.7	19.2 ± 2.2	0	225 ± 0	0	25 ± 0	0	0	0	0	0	0	0	0	0	18	0	0
44	Boat (MGMNP, East)	2	bb, poly	1	0.8	9.6 ± 28	0	100 ± 0	0	25 ± 0	0	0	0	0	0	0	0	0	0	0	0	0
45	Twins (MGMNP, North)	5	bb, hol, poly, cni, asc	1	0.4	111.5 ± 120.8	0	1275 ± 520.3	50 ± 35.4	100 ± 0	25 ± 15.4	0	0	0	0	0	0	0	0	0	27	9
46	Patthar Nali (Little Andaman, East)	1	hol	0	0	1.9	0	0	25 ± 0	0	0	0	0	0	0	0	0	0	0	0	0	0
47	Dungi Ghat (Little Andaman, East)	10	gp, bb, hol, poly, cni, oph, cr, bi, chi, cni	1	0.4	52.9 ± 38.2	466.7 ± 42.9	16.7 ± 8.9	75 ± 75	50 ± 16.6	16.7 ± 8.9	37.5 ± 13.3	0	8.3	8.3 ± 10.4	8.3 ± 12	0	0	0	0	23	0
48	Kalapatthar (Little Andaman, East)	3	bb, hol, por	0	0.6	35.6 ± 24	0	12.5 ± 7.7	450 ± 388.9	0	0	0	0	0	0	0	0	0	0	3	0	0
49	Hutbay Breakwater Jetty (Right-Little Andaman, South-East)	3	bb, hol, oph	1	1	5.8 ± 1.2	0	25 ± 0	25 ± 0	0	0	25 ± 0	0	0	0	0	0	0	0	0	0	0

50	Harminder Bay (Little Andaman, South-East)	6	gp, bb, hol, oph, cr, cni	1	0.6	47.1 ± 26	12.5 ± 17.7	187.5 ± 17.7	25 ± 5.4	0	0	350 ± 153.6	0	37.5	37.5 ± 20	0	0	0	0	0	33	0
51	Hutbay-Lighthouse (Little Andaman, South)	2	hol, cr	0	0.8	25 ± 12.5	0	0	275 ± 212.1	0	0	0	0	50	50 ± 0	0	0	0	0	0	0	0
52	Ship Wreck (Little Andaman, South)	3	bb, hol, poly	1	1	6.7 ± 7.3	0	25 ± 5.4	25 ± 0	37.5 ± 13	0	0	0	0	0	0	0	0	0	0	0	0
53	Kardip (Kamorta, South-East)	2	bb, hol	0	0.6	50 ± 47.9	0	37.5 ± 13	612.5 ± 66.2	0	0	0	0	0	0	0	0	0	0	0	0	0
54	Bada Enaka (Kamorta, South-East)	1	bb	0	1	7.7 ± 7.8	0	100 ± 0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
55	Rani Tikri (Kamorta, South)	1	bb	0	1	37.5 ± 36.5	0	487.5 ± 218.7	0	0	0	0	0	0	0	0	0	0	0	0	0	0
56	Pilpilow (Rai-Kin-Fimo; Kamorta, North)	0	0	0	0	0.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
57	Pilpilow (Kaloweek; Kamorta, North)	1	cni	0	1	19.2 ± 9.3	0	0	0	0	250 ± 0	0	0	0	0	0	0	0	0	0	0	0
58	Pilpilow(Moh-Ryak; Kamorta, North)	1	cni	0	1	7.7 ± 7.7	0	0	0	0	100 ± 0	0	0	0	0	0	0	0	0	0	0	0
59	Hypo (Katchal, East)	3	gp, bb, cni	1	1	5.8 ± 6.3	25 ± 0	25 ± 0	0	0	25 ± 0	0	0	0	0	0	0	0	0	0	0	0

60	Kapanga (Katchal, North-East)	1	bb	0	1	7.7 ± 7.7	0	100 ± 0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
61	Lighthouse (Katchal, North-East)	2	bb	0	0.6	3.8 ± 1.9	0	50 ± 0	0	0	0	0	0	0	0	0	0	0	0	18	0	0
62	Safed Balu (Trinket, North)	4	bb, hol, cni, ast	0	0.3	219.2 ± 77.1	0	12.5 ± 0	2712.5 ± 0	0	87.5 ± 0	0	0	0	0	0	37.5 ± 0	0	0	0	0	0
63	Trinket (West coast, South-West)	3	bb, hol, por	1	0.9	23.1 ± 9.9	0	100 ± 17.7	200 ± 1361.2	0	0	0	0	0	0	0	0	0	0	4	0	0
64	Altaiyak (Nancowry, North)	6	gp, bb, hol, cni, echi, por	1	0.5	43.3 ± 40.6	375 ± 230.3	12.5 ± 12.6	12.5 ± 0	0	100 ± 0	0	62.5 ± 0	0	0	0	0	0	0	27	0	0
65	Hitui (Nancowry, North)	5	gp, hol, cni, cri, por	1	0.7	15.4 ± 14.6	87.5 ± 88.4	0	62.5 ± 17.7	0	25 ± 10.7	0	0	0	0	0	0	25 ± 0	0	3	0	0
66	Campbell Bay (Great Nicobar, East)	1	oph	0	1	0.4 ± 3.9	0	0	0	0	0	5 ± 0	0	0	0	0	0	0	0	0	0	0

[GR, Group Richness; GC, Group Composition; H, Shannon's index; E, Evenness H/S; gp, gastropods; bb, burrowers; hol, holothuroids; poly, polychaetes; cni, cnidarians; oph, ophiuroids; echi, echinoids; cr, crustaceans; bi, bivalves; chi, chitons; ast, asteroids; cri, crinoids; platy, platyhelminthes; por, poriferans; asc, ascidians]

Annexure 5

Annexure 5: Summary of multi-variate generalized linear regression analysis

INFAUNA Total (mean) infaunal densities	**B estimate**	**Std. Error**	**Adjusted SE**	**Z**	**Pr (>|z|)**		**EPIFAUNA Total (mean) epifaunal densities**	**B estimate**	**Std. Error**	**Adjusted SE**	**Z**	**Pr (>|z|)**
(Intercept)	2.572	0.627	0.638	4.03	5.57e-05***		**(Intercept)**	0.437	1.064	1.075	0.406	0.6844
seagrass biomass	-0.004	0.025	0.025	0.164	0.87		**seagrass biomass**	0.045	0.088	0.088	0.505	0.6134
seagrass densities	-0.251	0.187	0.190	1.321	0.186		**seagrass densities**	0.328	0.261	0.261	1.243	0.2139
water depth	-0.184	0.112	0.114	1.614	0.107		**water depth**	0.003	0.033	0.033	0.087	0.9303
epiphytic algae	0.001	0.011	0.011	0.065	0.948		**epiphytic algae**	0.120	0.111	0.112	0.977	0.3284
non-epiphytic algae	0.063	0.102	0.103	0.617	0.537		**non-epiphytic algae**	0.078	0.150	0.151	0.512	0.6086
fine sand	0.063	0.153	0.155	0.409	0.682		**fine sand**	-0.191	0.372	0.375	0.508	0.6114
silt	-0.041	0.080	0.081	0.503	0.615		**silt**	0.152	0.173	0.175	0.873	0.3829
rubble	-0.044	0.084	0.085	0.522	0.602		**rubble**	-0.066	0.146	0.148	0.444	0.657
rock	-0.019	0.062	0.063	0.304	0.761		**rock**	0.342	0.198	0.203	1.694	0.0902
dead coral algae	-0.0001	0.016	0.017	0.007	0.995		**dead coral algae**	0.002	0.033	0.033	0.065	0.9485
POLYCHAETES (Mean densities)	**B estimate**	**Std. Error**	**Adjusted SE**	**Z**	**Pr (>|z|)**		**GASTROPODS (Mean densities)**	**B estimate**	**Std. Error**	**Adjusted SE**	**Z**	**Pr (>|z|)**
(Intercept)	3.359	1.226	1.250	2.687	0.00722 **		**(Intercept)**	1.134	0.737	0.749	1.515	0.12983
seagrass biomass	-0.001	0.032	0.033	0.043	0.96535		**seagrass biomass**	0.011	0.066	0.067	0.171	0.86406
seagrass densities	-0.540	0.363	0.370	1.457	0.14506		**seagrass densities**	-0.002	0.103	0.106	0.106	0.98148
water depth	-0.45479	0.200	0.205	2.218	0.02655 *		**water depth**	-0.758	0.246	0.251	3.026	0.0024**
epiphytic algae	0.161	0.138	0.141	1.146	0.25173		**epiphytic algae**	0.004	0.050	0.051	0.086	0.9316
non-epiphytic algae	0.467	0.202	0.208	2.251	0.02437 *		**non-epiphytic algae**	-0.386	0.340	0.344	1.122	0.26174

fine sand	-0.009	0.102	0.105	0.085	0.93232		**fine sand**	-0.090	0.334	0.338	0.266	0.78986
silt	-0.089	0.167	0.169	0.525	0.59931		**silt**	0.395	0.318	0.324	1.227	0.21998
rubble	0.027	0.098	0.099	0.272	0.78553		**rubble**	-0.003	0.073	0.074	0.034	0.97292
rock	-0.005	0.069	0.071	0.075	0.94033		**rock**	0.009	0.099	0.101	0.09	0.92859
dead coral algae	-0.022	0.097	0.099	0.225	0.82205		**dead coral algae**	0.009	0.080	0.081	0.116	0.9073
GASTROPODS (Mean densities)	**B estimate**	**Std. Error**	**Adjusted SE**	**Z**	**Pr (>|z|)**		**BURROWERS (Mean densities)**	**B estimate**	**Std. Error**	**Adjusted SE**	**Z**	**Pr (>|z|)**
(Intercept)	2.118	0.268	0.274	7.738	< 2e-16 ***		**(Intercept)**	-1.392	1.350	1.374	1.014	0.3104
seagrass biomass	-0.009	0.034	0.034	0.253	0.79993		**seagrass biomass**	-0.233	0.202	0.205	1.138	0.2553
seagrass densities	-0.008	0.056	0.057	0.132	0.89536		**seagrass densities**	0.925	0.493	0.501	1.847	0.0648
water depth	0.004	0.030	0.030	0.124	0.90167		**water depth**	0.001	0.053	0.054	0.013	0.9898
epiphytic algae	0.002	0.022	0.023	0.111	0.91159		**epiphytic algae**	-0.019	0.081	0.082	0.239	0.8108
non-epiphytic algae	-0.004	0.034	0.035	0.103	0.91794		**non-epiphytic algae**	-0.007	0.069	0.070	0.102	0.9185
fine sand	-0.004	0.074	0.076	0.052	0.95841		**fine sand**	-0.005	0.143	0.146	0.035	0.9725
silt	-0.180	0.131	0.134	1.345	0.17859		**silt**	0.630	0.284	0.290	2.173	0.0298 *
rubble	-0.313	0.112	0.115	2.713	0.00666 **		**rubble**	-0.038	0.136	0.138	0.273	0.7852
rock	-0.026	0.075	0.076	0.335	0.73795		**rock**	0.017	0.116	0.118	0.142	0.8871
dead coral algae	-0.004	0.035	0.036	0.123	0.90236		**dead coral algae**	-0.120	0.215	0.217	0.553	0.58
NEMATODES (Mean densities)	**B estimate**	**Std. Error**	**Adjusted SE**	**Z**	**Pr (>|z|)**		**POLYCHAETES (Mean densities)**	**B estimate**	**Std. Error**	**Adjusted SE**	**Z**	**Pr (>|z|)**
(Intercept)	1.881	0.967	0.981	1.919	0.0549		**(Intercept)**	6.11E+00	1.02E+00	1.04E+00	5.858	< 2e-16 ***
seagrass biomass	-0.015	0.073	0.068	0.221	0.8251		**seagrass biomass**	8.10E-05	3.56E-02	3.64E-02	0.002	0.99822
seagrass densities	-0.080	0.241	0.244	0.328	0.7433		**seagrass densities**	-8.46E-03	9.16E-02	9.33E-02	0.091	0.92779
water depth	-0.426	0.276	0.280	1.522	0.128		**water depth**	-8.70E-05	4.63E-02	4.73E-02	0.002	0.99853
epiphytic algae	0.147	0.165	0.168	0.877	0.3807		**epiphytic algae**	2.24E-01	1.61E-01	1.64E-01	1.365	0.17222
non-epiphytic algae	0.0003	0.036	0.037	0.009	0.9932		**non-epiphytic algae**	-3.64E-02	1.24E-01	1.25E-01	0.291	0.7713
fine sand	-0.099	0.307	0.311	0.32	0.749		**fine sand**	-2.71E+0	5.31E-01	5.42E-01	4.998	6e-07 ***

silt	-0.057	0.155	0.157	0.36	0.7189		**silt**	-7.12E-01	2.37E-01	2.42E-01	2.942	0.00326 **
rubble	0.003	0.039	0.034	0.07	0.9441		**rubble**	2.01E-04	6.44E-02	6.57E-02	0.003	0.99756
rock	-0.0521	0.160	0.163	0.321	0.7485		**rock**	-1.01E-02	8.36E-02	8.51E-02	0.119	0.90523
dead coral algae	0.239	0.286	0.289	0.827	0.4085		**dead coral algae**	4.62E-02	1.30E-01	1.31E-01	0.352	0.72452
BIVALVES (Mean densities)	**B estimate**	**Std. Error**	**Adjusted SE**	**Z**	**Pr (>|z|)**		**HOLOTHUROIDS (Mean densities)**	**B estimate**	**Std. Error**	**Adjusted SE**	**Z**	**Pr (>|z|)**
(Intercept)	1.624	0.684	0.693	2.344	0.0191 *		**(Intercept)**	-2.49E-01	1.20E+00	1.22E+00	0.205	0.83778
seagrass biomass	-0.007	0.042	0.043	0.171	0.8641		**seagrass biomass**	4.92E-01	1.68E-01	1.71E-01	2.875	0.00405 **
seagrass densities	-0.077	0.194	0.197	0.393	0.6945		**seagrass densities**	1.39E-01	2.98E-01	3.02E-01	0.46	0.64558
water depth	0.136	0.164	0.167	0.816	0.4146		**water depth**	-1.38E-01	2.10E-01	2.12E-01	0.65	0.51588
epiphytic algae	0.167	0.124	0.127	1.322	0.1862		**epiphytic algae**	7.57E-04	2.11E-02	2.15E-02	0.035	0.97192
non-epiphytic algae	-0.002	0.040	0.041	0.056	0.9557		**non-epiphytic algae**	1.36E-02	8.40E-02	8.50E-02	0.16	0.87292
fine sand	0.003	0.082	0.084	0.038	0.97		**fine sand**	-1.94E-01	4.32E-01	4.36E-01	0.445	0.65627
silt	0.001	0.039	0.040	0.047	0.9623		**silt**	-2.89E-02	1.18E-01	1.20E-01	0.241	0.80943
rubble	-0.004	0.040	0.041	0.104	0.9172		**rubble**	1.38E-01	2.19E-01	2.21E-01	0.623	0.53355
rock	-0.113	0.183	0.185	0.613	0.5399		**rock**	-3.09E-03	7.07E-02	7.20E-02	0.043	0.96581
dead coral algae	-0.002	0.041	0.042	0.052	0.9589		**dead coral algae**	1.12E-01	1.95E-01	1.97E-01	0.567	0.57058
CRUSTACEANS (Mean densities)	**B estimate**	**Std. Error**	**Adjusted SE**	**Z**	**Pr (>|z|)**		**CNIDARIANS (Mean densities)**	**B estimate**	**Std. Error**	**Adjusted SE**	**Z**	**Pr (>|z|)**
(Intercept)	4.55	1.128	1.158	3.931	8.46e-05 ***		**(Intercept)**	-1.03E+00	1.20E+00	1.22E+00	0.844	0.399
seagrass biomass	-0.031	0.090	0.092	0.341	0.733195		**seagrass biomass**	-2.87E-03	4.10E-02	4.18E-02	0.069	0.945
seagrass densities	-0.843	0.341	0.350	2.405	0.016181 *		**seagrass densities**	-2.01E-02	1.21E-01	1.23E-01	0.163	0.871
water depth	-0.497	0.221	0.226	2.198	0.027973 *		**water depth**	7.50E-03	6.33E-02	6.44E-02	0.117	0.907
epiphytic algae	0.023	0.073	0.074	0.309	0.757671		**epiphytic algae**	-1.16E-02	6.14E-02	6.22E-02	0.186	0.852
non-epiphytic algae	0.105	0.179	0.181	0.579	0.562517		**non-epiphytic algae**	6.98E-03	7.35E-02	7.49E-02	0.093	0.926
fine sand	-0.002	0.087	0.089	0.02	0.98441		**fine sand**	9.70E-01	6.32E-01	6.42E-01	1.511	0.131
silt	-0.706	0.197	0.203	3.479	0.000502 ***		**silt**	-2.83E-03	7.11E-02	7.26E-02	0.039	0.969
rubble	-0.006	0.061	0.063	0.101	0.919941		**rubble**	5.19E-03	7.30E-02	7.44E-02	0.07	0.944
rock	0.002	0.047	0.048	0.047	0.962471		**rock**	-4.19E-03	8.40E-02	8.56E-02	0.049	0.961

dead coral algae	-0.179	0.218	0.221	0.81	0.418102		**dead coral algae**	-3.83E-01	2.42E-01	2.45E-01	1.56	0.119

Total Epifaunal Cover (%)	**B estimate**	**Std. Error**	**Adjusted SE**	**Z value**	**Pr (>|z|)**
(Intercept)	2.589	0.658	1	3.86	0.000113 ***
Dead Coral Algae	0.299	0.121	0	2.425	0.015308 *
Fine Sand	-1.177	0.351	0	3.288	0.001010 **
Non-Epiphytic Algae	-0.305	0.142	0	2.102	0.035523 *
Rubble	0.057	0.119	0	0.476	0.634281
Rock	-0.04	0.107	0	0.37	0.711348
Coarse Sand	0.008	0.045	0	0.18	0.85743
Seagrass Cover	-0.004	0.049	0	0.08	0.936087

Annexure 6

Annexure 6: Faunal densities across vegetation status and type, seagrass species richness, and habitat heterogeneity [n= sample size; values expressed as mean ± Std. Error]

INFAUNAL		**Veg**	**Unveg**	**W**	***p* value**	**EPIFAUNAL**		**Veg**	**Unveg**	**W**	***p* value**
vegetation status (ind./m^2) (n=307)	**total infaunal densities**	56.4 ± 37.2	48.8 ± 42.1	1561	0.917	**vegetation status (ind./m^2) (n=597)**	**total epifaunal densities**	4 ± 1.6	3.9 ± 3.9	1561	0.917
	polychaetes	301.1 ± 45.3	295.68 ± 55.9	358.5	0.047		**gastropods**	4.9 ± 5	7 ± 6	43313	0.405
	gastropods	91.5 ± 70.3	75.9 ± 79.1	786	0.254		**burrowers**	12.7 ± 11.4	3.7 ± 1.5	38291	0.0005
	nematodes	152.1 ± 63	53.4 ± 6.3	433	0.005		**polychaetes**	13.8 ± 1.9	12.8 ± 1.1	45104	0.027
	bivalves	34.6 ± 12	33.6 ± 17	790	0.194		**holothuroids**	2.8 ± 1.3	2.0 ± 1.5	42710	0.727
	crustaceans	117.6 ± 55	112.9 ± 70	741.5	0.513		**cnidarians**	0.9 ±1.9	2.5 ± 2.4	44268	0.009
species richness (ind./m^2) (n=200)		**Mono-species**	**Mixed-species**	**W**	***p* value**	**species richness (ind./m^2) (n=1251)**		**Mono-species**	**Mixed-species**	**W**	***p* value**
	total infaunal densities	104.9 ± 80.4	85.2 ± 78.4	3873.5	0.008		**total epifaunal densities**	27.9 ± 20.1	78.9 ± 18.9	604	0.045
	polychaetes	133.9 ± 143.9	139.8 ± 45.5	262	1		**gastropods**	31.2 ± 24.9	285 ± 78.7	506.5	0.489
	gastropods	93.1 ± 75.1	100.5 ± 79.3	253	0.849		**burrowers**	121.6 ± 47.1	201.5 ± 28.2	546.5	0.230
	nematodes	104.5 ± 39.9	81.9 ± 131.6	252	0.832		**polychaetes**	59.7 ± 29.3	103.8 ± 53.9	466.5	0.950
	bivalves	42.5 ± 35.5	65.8 ± 61.4	305.5	0.367		**holothuroids**	31.9 ± 15.8	127.2 ± 67.5	476.5	0.815
	crustaceans	50.2 ± 18.1	50.2 ± 29.9	191.5	0.133		**cnidarians**	27.2 ± 29.6	118.6 ± 39.2	466	0.952

species composition (ind./m^2) (n=200)		**Comp1**	**Comp2**	**Comp3**	***p* value**	**species composition (ind./m^2) (n=1251)**		**Comp1**	**Comp2**	**Comp3**	***p* value**
	total infaunal densities	93.5 ± 14.8	104.5 ± 27.2	298 ± 136.3	0.375		**total epifaunal densities**	85.5 ± 18.9	94.2 ± 19.2	286.3 ± 128.7	0.252
	polychaetes	112.7 ± 40.5	170.8 ± 149.9	181.3 ± 155.6	0.159		**gastropods**	217.9 ± 149.4	1340 ± 195.3	310 ± 125.6	0.063
	gastropods	97.2 ± 74.7	97.0 ± 87.1	102.6 ± 87. 8	0.832		**burrowers**	340.5 ± 43.4	70.25 ± 53.88	214.6 ± 118.9	0.413
	nematodes	75.7 ± 35.1	134.9 ± 52.7	81.3 ± 45.9	0.091		**polychaetes**	156.5 ± 44.5	335.5 ± 44.1	95.8 ± 52.3	0.782
	bivalves	75.1 ± 22.9	25 ± 26.9	43.6 ± 23.8	0.037		**holothuroids**	10.11 ± 16.6	210 ± 23.9	212.5 ± 119.0	0.001
	crustaceans	38.7 ± 12.9	104 ± 16.4	30.9 ± 10.5	0.464		**cnidarians**	119.6 ± 37.2	10 ± 2.6	20.8 ± 2.6	0.800
Habitat heterogeneity (ind./m^2) (n=200)		**Homo-geneous**	**Hetero-geneous**	**W**	***p* value**	**Habitat heterogeneity (ind./m^2) (n=1251)**		**Homo-geneous**	**Hetero-geneous**	**W**	***p* value**
	total infaunal densities	51.1 ± 47.2	46.2 ± 45.7	6314	0.606		**total epifaunal densities**	61.6 ± 48.9	61.16 ± 38.9	570	0.436
	polychaetes	133.8 ± 45.5	141.9 ± 40.5	380	0.190		**gastropods**	149.2 ± 78.7	249.5 ± 125.2	572	0.370
	gastropods	117.3 ± 79.3	80.6 ± 72.5	211	0.051		**burrowers**	232.8 ± 128.2	114.6 ± 134.7	360.5	0.041
	nematodes	58.8 ± 31.6	116.2 ± 34.9	406.5	0.067		**polychaetes**	36.9 ± 23.8	143.7 ± 59.3	662.5	0.024

	bivalves	85.6 ± 61.4	34.1 ± 23.2	136.5	0.0007		**holothuroids**	93.2 ± 67.5	95.7 ± 76.1	701	0.003
	crustaceans	59.6 ± 29.9	41.5 ± 12.9	387	0.145		**cnidarians**	154.3 ± 39.2	15.7 ± 36.3	420	0.137

EPIBENTHIC COVER (%/ m^2)			
Vegetation status	Veg	Unveg	
	17.8 ± 7.5	23.8 ± 70.7	*p* value= 0.008, W= 38898
Species richness	Monospecies	Mixed-species	
	9.7 ± 14.5	5.2 ± 13.7	*p* value= 0.476, W= 415
Species composition	Comp1 14.3 ± 5.5 Comp2 12.5 ± 9.2 Comp3 4.49 ± 2.27		*p* value= 0.428
Habitat heterogeneity	Homogeneous	Heterogeneous	
	3.4 ± 13.7	10.4 ± 14.0	*p* value= 0.007, W= 696

(Veg, Vegetated; Unveg, Unvegetated habitats; Comp1, Comp2, Comp 3- Seagrass species composition 1, 2 and 3 respectively)

LIST OF PUBLICATIONS AND CONFERENCES

Publications

1. Gole, S., Prajapati, S., Prabakaran, N., Das, H., Kuppusamy, S. and Johnson, J.A., 2023. Spatial diversity and habitat characteristics of seagrass meadows with management recommendations in the Andaman and Nicobar Islands, India. *Frontiers in Marine Science*, 10. https://doi.org/10.3389/fmars.2023.1251887
2. Gole, S., Kuppusamy, S., Das, H. and Johnson, J.A., 2023. Flowering and fruiting of Tape Seagrass *Enhalus acoroides* (Lf) Royle from the Andaman Islands: observations from inflorescence buds to dehiscent fruits. *Journal of Threatened Taxa*, *15*(1), pp.22494-22500. http://dx.doi.org/10.11609/jott.8163.15.1.22494-22500
3. Gole, S., Gaidhani, P., Bose, S., Pande, A., Johnson, J.A. and Kuppusamy, S., 2022. New distribution record of globally threatened Ocean Turf Grass *Halophila beccarii* Ascherson, 1871 from the North Andaman Islands highlights the importance of seagrass exploratory surveys. *Journal of Threatened Taxa*, *14*(1), pp.20406-20412. http://dx.doi.org/10.11609/jott.7719.14.1.20406-20412
4. Bayyana, S., Pawar, S., Gole, S., Dudhat, S., Pande, A., Mitra, D., Johnson, J.A. and Sivakumar, K., 2020. Detection and mapping of seagrass meadows at Ritchie's archipelago using Sentinel 2A satellite imagery. *Current Science*, *118*(8), pp.1275-1282.

Conferences attended

International

1. Gole, S., Dudhat, S., PremJothi P.V.R., Pande, A., Shekar, R., Pathan, S., Sivakumar, K., Johnson, J.A. **(2018)**, Study of Seagrass habitats from the Andaman and Nicobar Islands, India.

   Abstract (ISBW030): Oral Presentation, **World Seagrass Conference and International Seagrass Biology Workshop 13**, Singapore; 11th-17th June, 2018.

2. Gole, S., Dudhat, S., PremJothi P.V.R., Pande, A., Shekar, R., Pathan, S., Sivakumar, K., Johnson, J.A. **(2018)**, Meadows of the Sea: Characterisation of Seagrass habitats of the Andaman Islands.

   Abstract: Poster presentation, **International Biodiversity Congress,** Forest Research Institute, Dehradun, India; 4th-6th October, 2018

Institutional

3) Gole, S., Prajapati, S., Bose, S., Chakraborty, O., Prabakaran, N., Das, H., Kuppusamy, S., Johnson, J.A. **(2023),** Lesser-known fauna: Seagrass-associated macrobenthos in a tropical insular system.

   Abstract: Oral Presentation, **Annual Research Seminar**, Wildlife Institute of India, Dehradun, India; 12th-14th September, 2023.

ISBW13
SINGAPORE 2018
13th International Seagrass Biology Workshop
Organising Committee
c/o Department of Biological Sciences
National University of Singapore
14 Science Drive 4, Singapore 117543

isbw13@gmail.com

12 Jan 2024

Re: Confirmation of Participation at WSC2018 and ISBW13, 11-17 June 2018

To whom it may concern,

The Organising Committee of the 13th International Seagrass Biology Workshop (ISBW13), and World Seagrass Conference 2018 (WSC2018) would like to confirm the participation and attendance of Ms Swapnali Gole at the abovementioned events.

Ms Gole was also a recipient of the ISBW13-NParks Student Travel Grant.

Thank you.

Yours Sincerely,

Dr. Siti Maryam Yaakub
Co-convenor, ISBW13

2011-2020 United Nations Decade on Biodiversity

IBC

INTERNATIONAL BIODIVERSITY CONGRESS (IBC 2018)

4th to 6th October 2018

Forest Research Institute (FRI),
Dehradun, India

Book of Abstracts

Organisers

1A-PP-105

MEADOWS OF THE SEA: CHARACTERISATION OF SEAGRASS HABITATS OF THE ANDAMAN ISLANDS.

Swapnali Gole[1], Sohini Dudhat[1], Prem Jothi, P.V.R[1], Rukmini Shekar[1], Sameeha Pathan[1], Priyamvada Bagaria[1], Anant Pande[1], Johnson, J.A.[1] and Sivakumar, K.[1]

Wildlife Institute of India, Dehradun

Seagrass habitats have been relatively understudied in comparison with habitat types such as corals and mangroves ecosystems. Topographically, the Andaman and Nicobar Islands in India are endowed with varied seascapes and the continental shelf replete with seagrass habitats. Although the Islands support the second highest diversity of seagrasses (n=12 species), these habitats are consistently exposed to natural catastrophic events such as cyclones and tsunami and a continually increasing anthropogenic pressure from coastal development, fishing activities and tourism. We studied the seagrass distribution across protected and unprotected islands of the Ritchie's archipelago in the Andaman Islands. We conducted underwater SCUBA-diving surveys to assess species diversity, composition, density and extent across different depth gradients to understand the distribution of early and late successional species. Total nine species belonging to five genera were recorded from the present study with a depth distribution range of 1 to 21 meters. 25 mono as well as mixed species meadows comprising of *Halophila ovalis, Halophila decipiens, Halophila minor, Halodule uninervis, Halodule pinifolia, Cymodocea rotundata, Cymodocea serrulata, Thalassia hemprichii and Enhalus acoroides* were recorded from 12 sites. Genus *Halophila* dominated all meadows and depth gradients and our study found more diversity in unprotected islands of Havelock (n=7) and Neil (n=5) than the protected islands. Five new seagrass meadows were reported from this study, which suggests need of more exploratory surveys in the Islands.

Key words: Marine plants, Shallow habitats, Unprotected areas, Species distribution, Island ecosystem.

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12 - 14 SEPTEMBER, 2023

PROGRAMME & ABSTRACTS

Project Title:
Recovery of Dugongs and their Habitats in India: An integrated participatory approach

Principal Investigator(s):
Dr. J.A. Johnson, Dr. Nehru Prabakaran

Researcher(s):
Swapnali Gole(Project Fellow)

Funding Agency:
CAMPA, MoEFCC

Project Duration:
2025

Keywords:
NA

Twitter Handles:
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Tweet:
Plunging deep into the Andaman and Nicobar Islands waters to know more about the biodiversity of the seagrass habitats, behold!

Lesser-known fauna: Seagrass-associated macrobenthos in a tropical insular system

-Swapnali Gole

Aim: The tropical seagrasses of the Andaman and Nicobar Islands (ANI) alone support > 60 % of total seagrass-associated faunal species in India. However, fauna beyond mega species is seldom quantified, and the underlying ecological patterns remain unexplored. Our study investigated the critical environmental and biological determinants driving Macrobenthic community structure across the Andaman and Nicobar Islands.

Methods: Macrobenthos diversity and distribution were assessed using line-intercept transects (50 m) on foot for intertidal and SCUBA-aided in subtidal meadows. Across 66 meadows, we hand-scooped infauna sediments (n=9/ site; total= 390) from upper 10 cm soil (20 X 20 cm area). Epifaunal data was collected, intercepting the LIT by 0.5 X 0.5 m2 quadrat (11 points/ transect; total=1251). We used a combination of non-parametric tests (Man–Whitney U and Kruskal–Wallis tests) and Gaussian regression analysis to check for the influence of potential predictors on macrofaunal densities.

Results: Infaunal and epifaunal groups recorded were 10 and 13 respectively, across the depth gradient (0.2 to 21 m). Mean infaunal and epifaunal densities varied from 46.8 ± 49.2 ind./m2 to 94.5 ± 125.9 ind./m2, respectively. Dominant infaunal and epifaunal guilds were polychaetes (138 ± 145.5 ind./m2) and gastropods (410.2 ± 65.3 ind./m2). We observed vegetated habitats to support higher macrofaunal densities than bare regions. Water depth was the primary determinant for infaunal polychaete densities (β estimate- -0.454786; p- 0.03) and crustaceans (β estimate- -0.49672; p- 0.03). Furthermore, non-epiphytic algae positively influenced infaunal polychaetes whereas crustaceans showed negative correlation with silt. Infaunal gastropod densities significantly reduced in hard substrata such as rubble (β estimate- -0.31324; p- 0.00666). Infaunal crustaceans were the only group that negatively correlated with seagrass shoot densities.

Conclusion: The species richness of seagrass in the meadows played a regulatory role on epifauna but not infauna, while seagrass species identity did not influence Macrobenthic densities. We imply that seagrass presence, habitat variability, sediment profile, and water depth are the key variables influencing macrofaunal abundances from the studied meadows. This first baseline on seagrass macrofauna contributes to the research and management of seagrasses in ANI.

Detection and mapping of seagrass meadows at Ritchie's archipelago using Sentinel 2A satellite imagery

Sharad Bayyana[1,*], Satish Pawar[1], Swapnali Gole[2], Sohini Dudhat[2], Anant Pande[2], Debashis Mitra[3], Jeyaraj Antony Johnson[4] and Kuppusamy Sivakumar[2]

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This study presents an attempt to utilize seagrass data acquired from field surveys to compare classification models for mapping seagrasses using Sentinel-2A satellite data. Out of three models tested, viz. Random Forest, Support Vector Machine and K-Nearest Neighbor; Random Forest classification model proved most effective in the given scenario with 0.99 model accuracy. Seagrasses present as deep as 21 m were detected post water column correction, presenting the capability of Sentinel-2A satellite in detecting submerged benthic habitat.

Keywords: Depth Invariant Index, Ritchie's archipelago, seagrass, Sentinel-2A.

SEAGRASS meadows, one of the most productive ecosystems on the planet, are estimated to lose 7% of their global area annually[1]. Spatial data analysis for seagrass studies towards their sustainable management and conservation has been an emerging field. Globally, satellite remote sensing tools have proven to be cost effective in comparison to conventional field surveys[2–8] and traditional geospatial methods such as aerial photography[9]. Since, satellite sensors are repeatable in their path and are geometrically accurate, change detection in seagrass distribution over temporal scale is possible[10–12]. Landsat imagery has been efficiently used in seagrass and benthic substrate mapping, despite its spectral and spatial limitations[12–15]. Multispectral imagery from compact airborne spectrographic imager (CASI) with satellite imagery of Landsat and Spot, has been shown to exhibit more accurate results from airborne high-resolution sensor compared to aerial photography in classification of submerged benthic features including seagrasses[2].

Sensing of submerged benthic vegetation in the coastal waters is achieved with multispectral observations (400–650 nm) of reflected radiance in the visible range which is enhanced with finer spatial resolution[16]. Certain regression models developed for mapping benthic features have opened up the doors to overcome the limitations of attenuation of radiance within the water column[17–19]. Assuming that variance in reflectance from same benthic substrate is primarily due to its presence at various depths and the diffused attenuation coefficient (K_d) is same for all the bands[17,18], regression from logarithmic values of individual bands provides proxy attenuation coefficients which are independent of depth[20]. Assessment of submerged sea grasses is reliable with remote sensing when appropriate correction (such as water depth correction) is applied to satellite images[21]. Medium resolution multispectral satellite images from Landsat OLI were effective in mapping of submerged benthic features with application of depth invariant index (DII), which is independent of depth effect[22]. High resolution multispectral imagery such as Sentinel-2A with 10 m spatial resolution has also proved effective to detect and estimate the cover of seagrass beds along the coast of Lombok in Indonesia[23]. The quality of results post DII when utilized for VHR Worldview-2 imageries was significantly high (up to 83% at Kotok Island in Indonesia)[24].

In India, seagrass are distributed along the coastline of nine states and two union territories with major patches found along Tamil Nadu (Palk Bay and Gulf of Mannar), Odisha, Gujarat, Lakshadweep Islands and Andaman and Nicobar Islands[25]. Remote sensing for the seagrass detection was first initiated at Lakshadweep islands to study the coral reefs and seagrass beds using black and white aerial photographs[26]. Later, loss of seagrass habitats in Gulf of Mannar group of islands due to anthropogenic activities was detected using LISS III satellite imagery[27]. Seagrass area was estimated to be around 85.5 sq. km around the islands of Gulf of Mannar based on IRS-1D LISS III satellite data from 1998 (ref. 28).

Earlier, a few studies have utilized conventional field survey methods to map seagrass ecosystems in the Andaman and Nicobar group of islands[29–31]. One study used satellite geospatial data (LISS III and LISS IV) for the mapping across the entire Andaman islands[32]. Seagrass meadows in Andaman and Nicobar Islands serve as foraging grounds for globally threatened species such as dugongs, green sea turtles[33], and act as nurseries for several species of fish and invertebrates and thus support fisheries in the islands. In the light of proposed infrastructure developments in the islands[34], understanding the extent of seagrass distribution in the islands will be useful in identifying critical areas to aid their conservation and management.

In this study, we mapped the seagrass meadows at Ritchie's archipelago (henceforth RA; 11°46′N–12°19′N and 92°54′E–93°08′E) within the Andaman and Nicobar group of islands using multi-spectral imager (MSI) Sentinel-2A satellite imagery (Supplementary Table 1). Ritchie's archipelago is a group of 13 islands, east of the main group of Andaman islands, consisting of two

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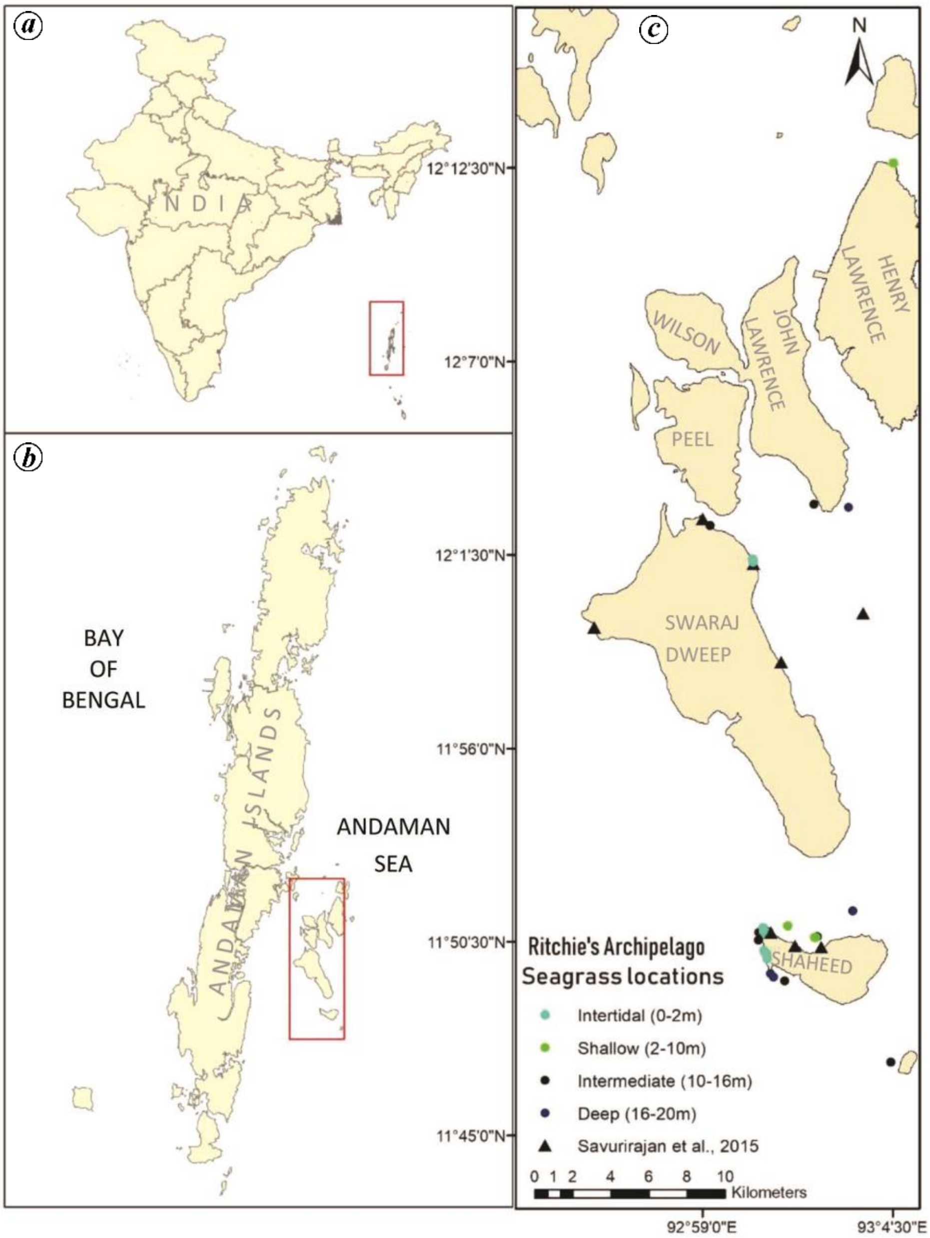

Figure 1. Study area map of Ritchie' Archipelago, Andaman and Nicobar Islands with seagrass locations.

inhabited (Havelock, now *Swaraj Dweep* and; Neil, now *Shaheed Dweep*) and 11 uninhabited islands (North button, middle button, south button, Outram, Inglis, Henry Lawrence, John Lawrence, Wilson, Nicholson, Peel and Sir Hugh Ross) spread across an area of 225 sq. km (ref. 35) (Figure 1). Seven of these islands, viz. North button, middle button, south button, Outram, Inglis, Henry Lawrence and John Lawrence, form part of the Rani Jhansi Marine National Park protected area whereas Sir Hugh Ross is a Wildlife Sanctuary. With a tidal amplitude of 3 m during spring and neap tide, semidiurnal tide is seen in the region.

We carried out seagrass surveys using line intercept transects (LITs; Figure 2) at intertidal and sub tidal areas at various depths at RA in the month of March and April 2018 (Supplementary Table 2). Subtidal areas were characterized using SCUBA diving whereas the intertidal areas were surveyed on-foot. Line intercept transects (50 m long; LIT) were deployed perpendicular to the shore to assess meadow characteristics (McKenzie and Yoshida 2012). At each transect, seagrass cover, species composition, algal cover and substrate type were recorded using a 50 × 50 cm quadrate (Supplementary Figure 1) along with GPS location (Garmin etrex 30) and depth (Aqualung i300 dive computer) for generating training sets for supervised classification and for training data accuracy assessment of the prediction models. In addition

Table 1. Depth-wise segregation of seagrass locations at Ritchie's Archipelago, Andaman and Nicobar Islands

Island	Transect points	Seagrass class	Depth range
Shaheed Dweep	NB1, NB2, NB3, NB4 LX1, LX2	Intertidal	0–2 m
Swaraj Dweep	DL1, DL2		
Shaheed Dweep	AQ, BH2, BH3	Shallow	2–10 m
Henry Lawrence	HL		
Shaheed Dweep	NU1, NU2, NU3, MG3, BH1	Intermediate	10–16 m
Swaraj Dweep	NR		
Hugh Ross	CHN		
John Lawrence	JL2		
Shaheed Dweep	MG1, MG2, BB,	Deep	16–20 m
John Lawrence	JL1		

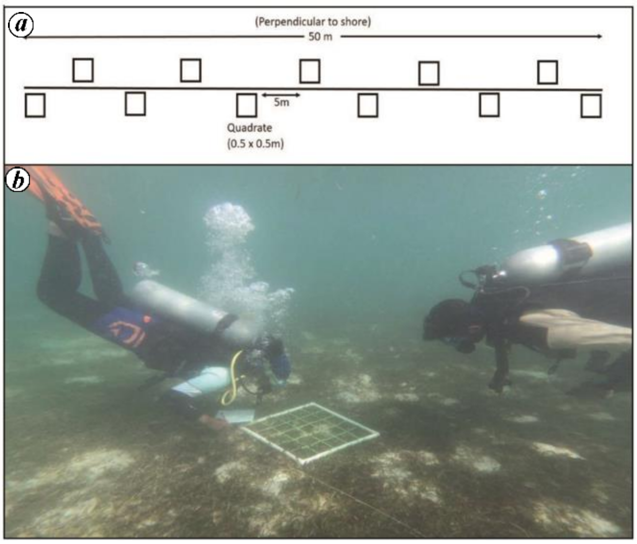

Figure 2. ***a***, Illustration of Line Intercept Transect survey method. ***b***, Image showing quadrant survey along the transect line.

to this, we used seagrass locations provided for RA from Savurirajan *et al.*[31], to cross-validate the efficiency of the prediction models.

We accessed the Sentinel-2A level 1C (top of atmosphere radiance) imagery acquired on 22 March 2018 (10 : 30 local time overpass) over the South Andaman region by European Space Agency (ESA) (http://scihub.copernicus.eu). The tidal range on the date of acquisition was 0.28–2.06 m. Atmospheric correction was done to 'top of surface, water leaving reflectance' product using 'sen2cor' additional plug-in[36] on SNAP 6.0 platform by ESA (https://step.esa.int/main/download/snap-download/) for Sentinel series image processing. Visible bands (band 2-blue, 3-green and 4-red) of 10 m spatial resolution were utilized considering their capability to penetrate water up to considerable depth[16]. We used the Lyzenga method[18] to obtain coefficient values to generate a normalized index value independent of the depth factor. Reflectance values from each band were extracted using 'point sampling tool' plug-in in QGIS. Simple linear regression was carried out using the logarithmic values of reflectance between two bands. The coefficient of the slopes of

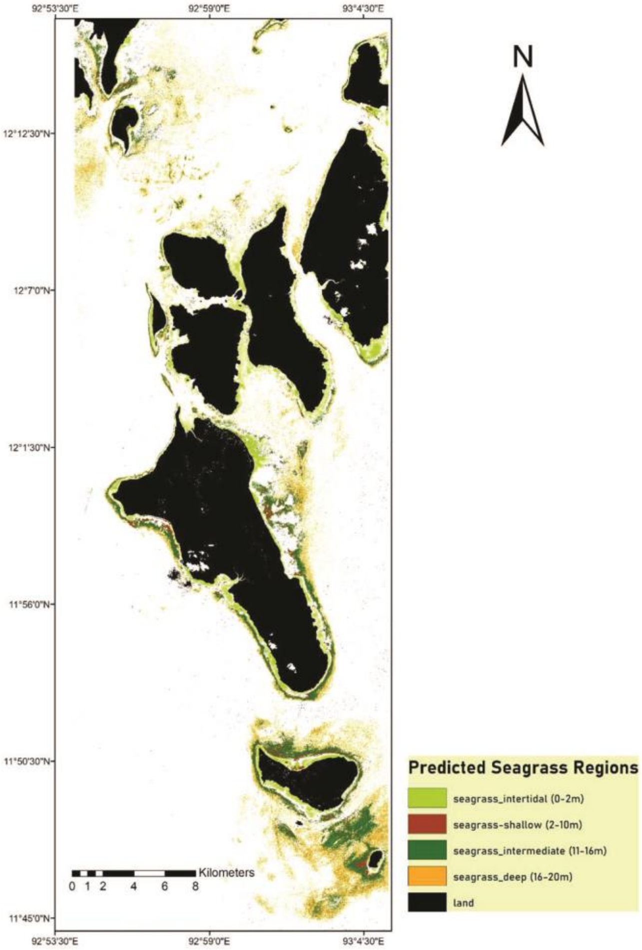

Figure 3. Random Forest Classification Map of Ritchie's archipelago from Sentinel 2A image. Image was acquired on 22 March 2018 at approximately 10 : 30 local time (satellite over-pass time). Tidal range on the particular day was 0.28–2.06 m.

regression were utilized as attenuation coefficient. Three bands generated from original band combination (i.e. band blue–green, green–red and red–blue) were stacked to produce an RGB layer of depth invariant index.

We carried out supervised classification to derive four depth-based classes for seagrass locations obtained from

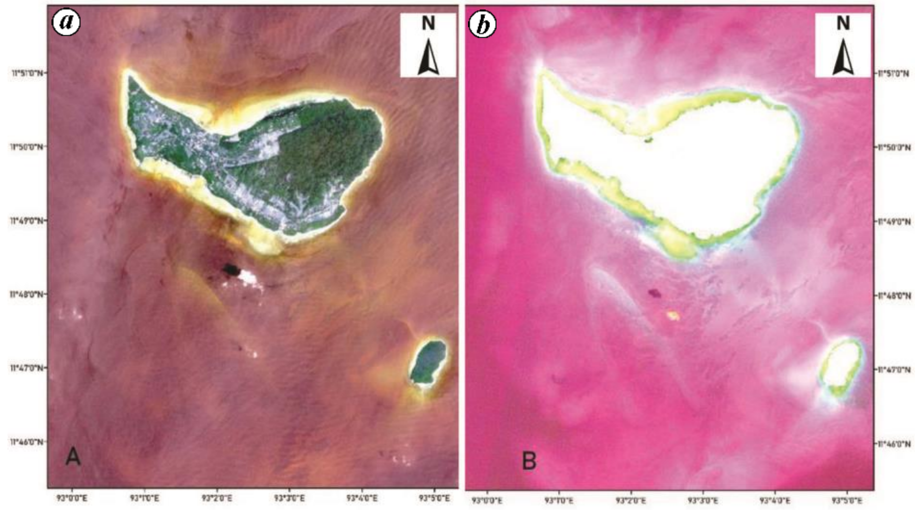

Figure 4. ***a***, True colour composite of subset of *Shaheed Dweep* Island from Sentinel-2A image. ***b***, RGB stack of depth invariant Index of bands of same image.

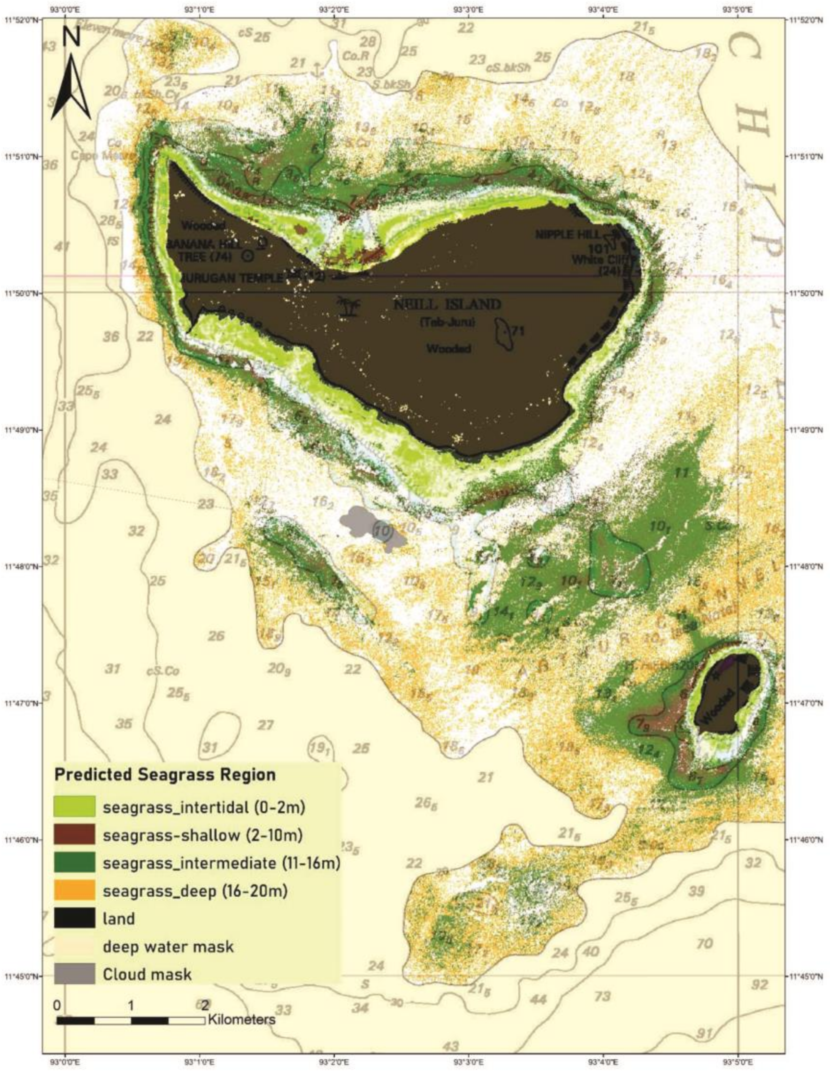

Figure 5. Classified map of *Shaheed Dweep* Island from Sentinel-2A image using Random Forest model.

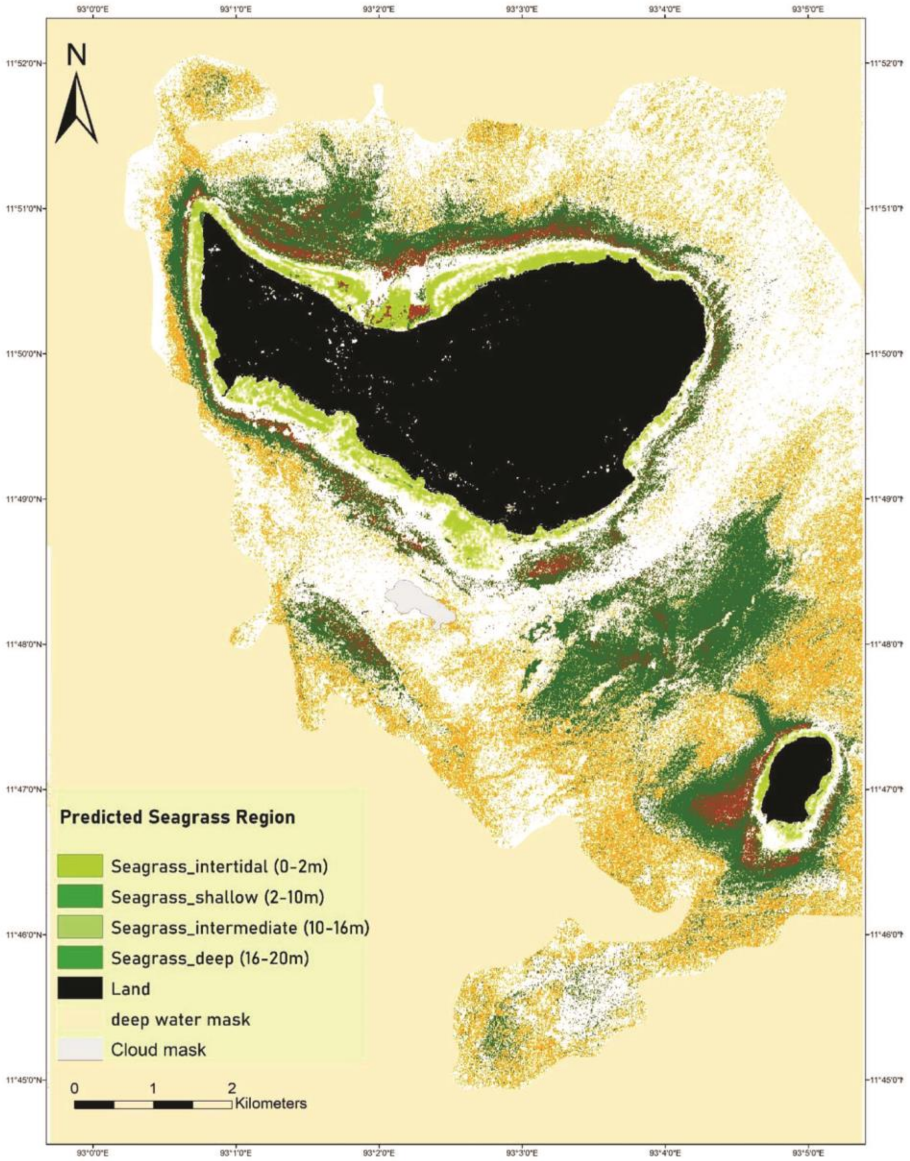

Figure 6. Classified map of *Shaheed Dweep* Island from Sentinel-2A image using K-Nearest Neighbor model.

Table 2. Training data accuracy of respective models used for supervised classification of Sentinel 2A images

Classification models	Overall accuracy	Kappa accuracy
Random forest	0.99	0.97
Support vector machine	0.96	0.93
K-nearest neighbor	0.96	0.93

field surveys (intertidal: 0–2 m; shallow: 2–10 m, intermediate: 10–16 m and; deep: 16–20 m) and validated with NHO bathymetry chart (Chart 4016, NHO; see Table 1). We used 70% of the seagrass locations obtained from field surveys to generate Region of Interests (RoIs) to train three different models (Random Forest (RF), Support Vector Machine (SVM) and K-Nearest Neighbor (KNN)) on Program-R (https://www.R-project.org/) using remaining 30% field data for model validation. For the cross validation of the classification models, transect NB3 LX2 for Intertidal, AQ for Shallow, CHN NU2 for Intermediate class and MG1 for Deep class were utilized. Classification models were run on R-studio IDE platform using ‘caret’, ‘rgdal’, ‘raster’, ‘e1071’ and ‘tidyverse’ packages. Further validation was done using previously published seagrass locations[31] for *Swaraj Dweep* and *Shaheed Dweep* islands. Later, classified outputs were presented for *Shaheed Dweep* to clearly illustrate segregation of depth classes obtained from each model.

During field surveys, we recorded seagrasses at 24 locations within the RA, namely at Henry Lawrence

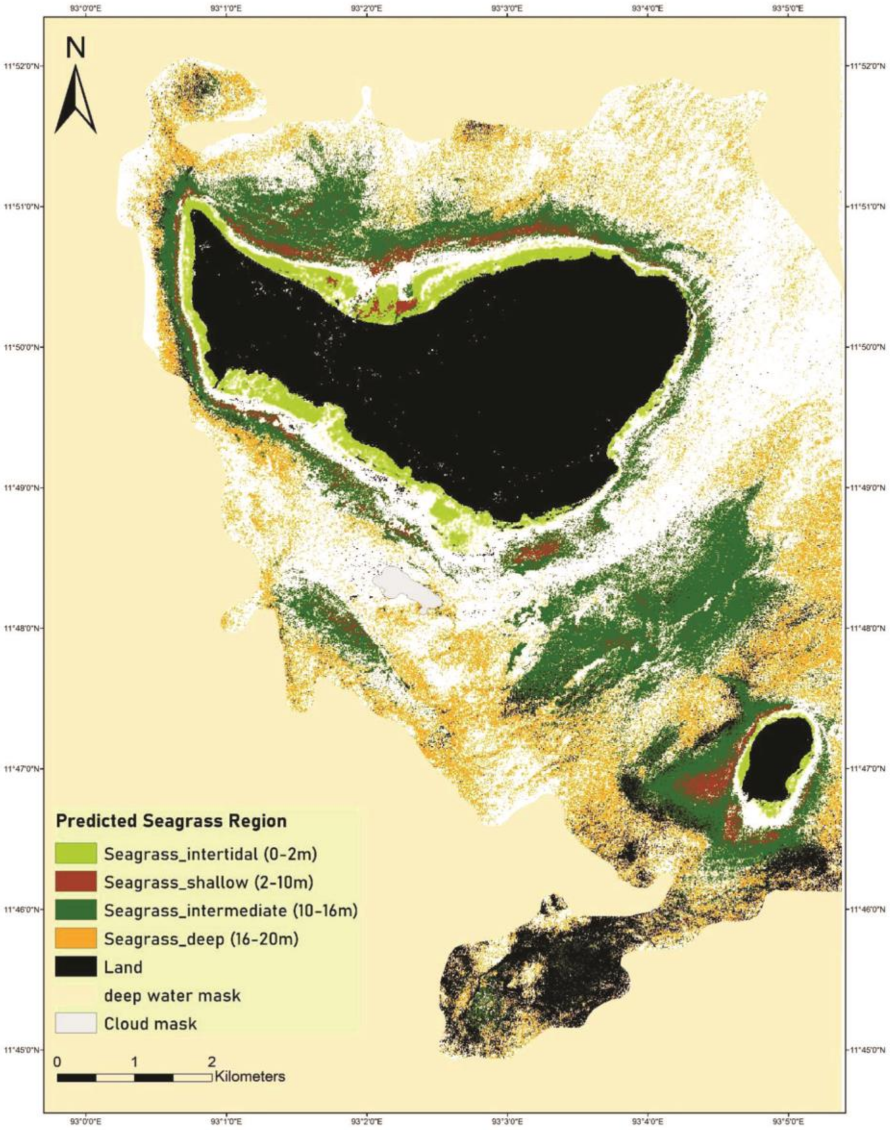

Figure 7. Classified map of *Shaheed Dweep* Island from Sentinel-2A image using Support Vector Machine model.

(*n* = 1), John Lawrence (*n* = 2), *Swaraj Dweep* (*n* = 3), *Shaheed Dweep* (*n* = 17) and Sir Hugh Ross (*n* = 1) islands.

RF model (Figure 3) produced highest training data accuracy (0.99) for detecting seagrass in the study area followed by SVM and KNN (0.96) (Table 2). We obtained better signatures for the benthic features (Figure 4) using the water column correction method resulting in better classification. Seagrasses were detected at the depth of 20 m around *Shaheed Dweep* Island, complementing the field observations (Figure 5). Random Forest model (Figure 5) and K-Nearest Neighbor model (Figure 6) were able to detect all depth classes whereas SVM model was unable to detect the 'Deep – 16 to 20 m' class in addition to misclassification of land over the sea (Figure 7). All the models used in the study detected seagrasses in deep water (>25 m) which were ignored considering the limitations of Lyzenga Method[18] to detect seagrass beyond 25 m. The results show 50% accuracy using the data points obtained from Savurirajan *et al*.[31].

The sea around Andaman and Nicobar Islands are oligotrophic waters due to less nutrient availability[37]. This results in low turbidity and hence deeper penetration of sunlight which allows seagrasses to grow at deeper regions. In our study, there is a high possibility of mixed signals, as seagrass distribution in the Andaman Islands is known to be sparse and interspersed with sandy patches[32,33]. Moreover, the accuracy of the models might be affected due to seasonal shifting of seagrass with respect to the sand dunes and thus their locations might change from previously reported studies[38,31]. In comparison to previously used LISS III and IV data[4,28,32], Sentinel-2A was efficient in seagrass detection at higher depths. Previous studies were restricted to a depth of 5 m only[22,32].

Our results establish the efficacy of Sentinel 2A satellite imagery for seagrass mapping at higher spatial scale as well as for deeper coastal waters. Supervised classification using RF model method proved to be better model for seagrass classification in the given scenario with limited field data (Supplementary Figure 2). Depth variant index improved the classification of underwater features for Sentinel-2A imagery. Seagrass detection was successful at the ground points used for the cross validation of the classification even for the deepest locations mapped in the study area (~21 m).

Despite mounting anthropogenic pressure on seagrass ecosystems and its associated species across the world[39,40], there is limited data on seagrass ecosystems in India[41,25]. With acceleration in human activities in the islands[34], threats such as coastal pollution including oil and plastic waste, mechanical damage from vessel anchors, higher turbidity from vessel movement and port construction activities, etc. are likely to intensify in the near future. Spatial mapping of seagrass beds in the islands using high resolution satellite imagery will be helpful in delineating critical areas for long-term change monitoring at a larger spatial scale.

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Development of wind speed retrieval model using RISAT-1 SAR cross-polarized observations

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In this study, a method for retrieving ocean surface wind speed using C-band cross-polarization SAR observations has been outlined. A linear least square technique has been used to develop a Geophysical Model Function (GMF), C2P. The GMF was derived using NRCS observations from RISAT-1 and wind-speed observations from ASCAT. The correlation between observed and simulated NRCS values obtained from C2P was 0.66, with a negative bias of 0.01 dB and the corresponding root mean square difference of 1.13 dB. Subsequently, the developed GMF was tested with 774 RISAT-1 MRS datasets to retrieve wind speed along the Indian coast and also of the tropical cyclone 'Megh'. The measured intensity and radius of maximum wind speed were 30 m s^{-1} and 16.65 km respectively. Subsequently, the retrieved wind speed was validated with ASCAT wind-speed observations. The statistical comparison of RISAT-1 and ASCAT observed wind speed showed negative biases of 0.90 and 0.34 m s^{-1} with the corresponding RMSD of 2.11 and 1.77 m s^{-1} respectively, for CMOD5.N and C2P. The developed GMF C2P showed 16% more accuracy than that of CMOD5.N.

Keywords: Cross-polarization, geophysical model function, ocean surface, wind speed retrieval.

OCEAN surface winds are highly important for numerical weather and ocean state forecasting, study of oceanic transportation and processes occurring at the air–sea interface. For the last four decades, ocean surface vector winds at synoptic scales are operationally being retrieved from spaceborne scatterometers. Such observations of ocean surface winds are assimilated in numerical models for improving operational forecasts at moderate resolution. Scatterometer-based observations are available with coarser spatial resolution in the range 12–50 km with wider data gaps in the coastal regions. However, wind intensity of cyclones computed using Ku-band scatterometer data tends to underestimate the actual scenario. Therefore, in extreme conditions like cyclones, backscattered power received by microwave scatterometers mainly

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Caption: ***Cyrtodactylus myintkyawthurai*, endemic to Myanmar. Medium: Water colours on watercolor sheet. © Aakanksha Komanduri**

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COMMUNICATION

New distribution record of globally threatened Ocean Turf Grass *Halophila beccarii* Ascherson, 1871 from the North Andaman Islands highlights the importance of seagrass exploratory surveys

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Abstract: *Halophila beccarii*, listed as 'Vulnerable' on the IUCN Red List, aids in seagrass and mangrove succession, acts as a substrate stabilizer and provides feeding grounds for mega-herbivores like dugongs. This species was first recorded from the Andaman & Nicobar Islands in 2015, and its distribution status within the archipelago remains under-investigated. We report a new distribution record of *H. beccarii* from the North Andamans and shed light on its inter-island distribution. *H. beccarii* was recorded from a mixed meadow comprising of *Cymodocea rotundata* (20.5 ± 28.8%, mean seagrass cover), *Thalassia hemprichii* (16.3 ± 23.3%, mean seagrass cover), and *Halodule pinifolia* (6.3 ± 12.1%, mean seagrass cover) at Pokkadera, North and Middle Andaman district. *H. beccarii* had the highest mean seagrass cover (30 ± 34.7%) and shoot density (103.5 ± 68.3 shoots/ m^2) among sympatric seagrass species. We also recorded eight seagrass-associated macrofaunal groups (gastropods, bivalves, polychaetes, foraminiferans, nematodes, brachyurans, decapods and asteroids) from the infaunal and epibenthic micro-habitats within the meadow. Infaunal macrobenthos had a much higher density (73.5 ± 129.7 individuals/m^2) than the epibenthic macrofauna (0.4 ± 1.5 individuals/m^2), possibly influenced by the seagrass canopy structure and biomass. Overall, gastropods were the most dominant macrobenthic faunal group (overall mean 95.0 ± 106.1 individuals/m^2). The present findings emphasize the need for more exploratory surveys to understand *H. beccarii* distribution in the Andaman & Nicobar archipelago to identify priority conservation areas.

Keywords: Andaman & Nicobar Islands, Dugongs, epifauna, habitat conservation, macrobenthos, seagrass associated.

Abbreviations: ANI—Andaman & Nicobar Islands | LIT—Line Intercept Transect.

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INTRODUCTION

Seagrasses are ecosystem engineers (Hoegh-Guldberg & Bruno 2010) that stabilize sediments (Ondiviela et al. 2014), modify habitats they colonize (Koch 2001) and contribute to coastal protection (Ondiviela et al. 2014). Seagrass meadows contribute to local carbon sinks (Suchanek et al. 1985), trophic transfer within habitats (Costanza et al. 1997), and primary production (Waycott et al. 2009), and they support a diversity of associated invertebrate fauna (Orth et al. 1984; Lee et al. 2001; Leopardas et al. 2014; Su et al. 2020).

In India, seagrasses are distributed along the coastlines of Gujarat, Maharashtra, Karnataka, Kerala, Tamil Nadu, and Odisha states, and the Lakshadweep and Andaman & Nicobar archipelagos (Thangaradjou et al. 2018). These ecologically valuable and fragile coastal habitats are threatened in Indian waters by high anthropogenic dependency, destructive practices like boat anchorage, extractive fishing, and nutrient enrichment through agricultural run-offs or domestic sewage disposal (Thangaradjou et al. 2008; Sridhar et al. 2010; Nobi & Thangaradjou 2012). Despite being protected under the ‘Coastal Regulation Zone Act’ (Dhiman et al. 2019), seagrasses have received less attention than other marine ecosystems (Jagtap et al. 2003).

Seagrass research in the Andaman & Nicobar Islands (ANI) has been sporadic. Pioneering work by Jagtap (1991, 1992) and Das (1996) collectively reported nine species. *Halodule uninervis, Thalassia hemprichii*, and *Halophila ovata* were the first seagrass records from ANI (Jagtap 1991), followed by new regional records of *Halophila ovalis, Cymodocea rotundata, Enhalus acoroides*, and *Syringodium isoetifolium* (Jagtap 1992). Pan-Island seagrass exploratory surveys by Das (1996) reported *Cymodocea serrulata* and *Halodule pinifolia*, followed by a two decadal gap in investigating species distribution status in ANI. Later, *Halophila minor* and *Halophila decipiens* were reported from the island waters (D’Souza et al. 2015).

The most recent addition to the species checklist from Andaman waters is *Halophila beccarii* reported from the Haddo Bay of South Andaman (Savurirajan et al. 2015). Globally, *H. beccarii* has a fragmented distribution range in the Indo-Pacific region which extends from the eastern coast of Africa up to southeastern Asia (Green & Short 2003). Although the species was first reported from Indian waters in 1991 (Jagtap 1991), its distribution was not known from the Andaman Islands till 2015. Furthermore, little is known about its inter-island distribution, as records post the first report (Savurirajan et al. 2015) are restricted to South Andaman (Ragavan et al. 2016).

In this study, we report a new distribution site for *Halophila beccarii* in the Andaman Islands and update its current distribution status for the Andaman group. Our study provides detailed meadow characteristics and associated macrofaunal assemblages, and highlights the habitat importance of seagrass meadows.

STUDY AREA

The Andaman and Nicobar archipelago is situated in the Bay of Bengal (6.750–13.683 ^{0}N and 92.2–93.95 ^{0}E) and encompasses 836 islands, islets, and rocky outcrops with a total geographical area of 8,249 km^2 (http://andaman.gov.in) and a 1,962 km long coastline (Census Directorate 2011). The shallow waters of the archipelago support 830 hectares of seagrass cover (Ragavan et al. 2016).

The present study was carried out in May 2019 as a part of a pan-island seagrass mapping survey at Pokkadera (12.902^{0}N & 92.910^{0}E). Pokkadera is situated on the East coast of Mayabunder (North & Middle Andaman district) in the Andaman archipelago. It’s a large intertidal unprotected area, with a vertical zonation expanse (distance between high to low tide when exposed) in low tide, up to ~ 400 m. The benthic substrate profile is characterized by mixed muddy-sandy sediment in the upper and lower intertidal zones and exposed sand bars in the mid-intertidal area (Figure 1). Pokkadera is an ecologically diverse site, which supports critical coastal ecosystems like seagrass meadows, mangroves, sandy, and rocky intertidal habitats, along with tropical littoral vegetation.

METHODS

Field sampling

We carried out on-foot exploration during low tide in the upper intertidal zone of Pokkadera. After locating a seagrass meadow we walked the perimeter and GPS marked the points at the edges (transition of seagrass habitat and adjacent unvegetated sediments). Later, we plotted the coordinates on Google Earth Pro version 7.3 to calculate the total area of the sampled study site. We used systematic line intercept transects (LIT) to assess seagrass meadow characteristics such as species composition, seagrass cover, shoot density, shoot length,

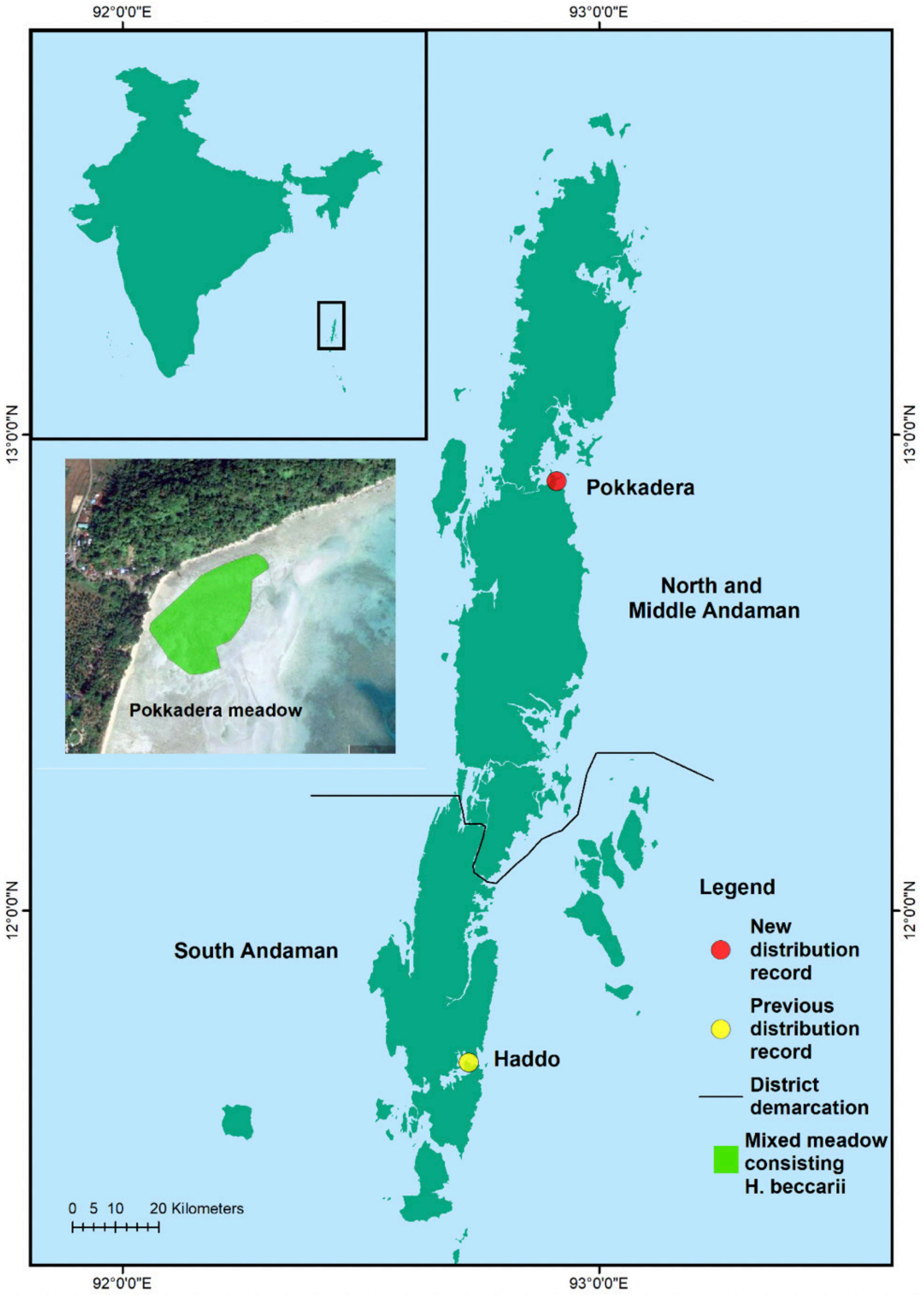

Figure 1. *Halophila beccarii* distribution records from Pokkadera seagrass meadow, Mayabunder, North and Middle Andaman district and Haddo seagrass meadow, South Andaman district at Andaman & Nicobar Islands.

total biomass (above and below ground; dry weight), and non-epiphytic algal cover (English et al. 1997). We deployed four 50 m long LITs inside the meadow, spaced apart at a distance of 150–200m. A 50 x 50 cm quadrat was placed after every 5 m interval on the LIT to record meadow characteristics (percentage seagrass cover, species composition, non-epiphytic algal cover). Algal shoots, independent of seagrass blades with distinct substratum penetration, were quantified to estimate non-epiphytic algal cover within the quadrat. We recorded seagrass-associated epibenthic macrofaunal groups within the quadrat to estimate group densities (ind. /m^2).

We collected seagrass samples from a 20 X 20 cm quadrat within the larger (50 x 50 cm) quadrat in each transect (n= 3/ transect) to estimate seagrass shoot density, shoot length, and total biomass (above and below ground; dry weight) in the laboratory. To assess the seagrass-associated infaunal (within the sediments) macrobenthic communities, we hand-scooped (up to 10 cm) sediment samples in triplicates from 20 X 20 cm area, randomly from each transect (n= 3/ transect). Seagrass and macrobenthic sediment samples were stored in ziplock bags on the field and transported to the laboratory for further analysis.

We also recorded environmental parameters on the field, like pH and sea surface temperature using a handheld multi-parameter tester (Eutech Oaklon- PCS Testr 35) and salinity with a handheld refractometer (LABART).

Laboratory analysis

In the laboratory, we rinsed seagrass samples with fresh water to remove sediment particles from the shoots and roots. We discarded any algal shoots within the samples and thoroughly rinsed them again. Later, we counted seagrass shoots (species-specific) present in the samples to estimate shoot density (shoots/ m^2). Further, using a measuring scale (cm), we recorded the length of randomly picked ten shoots to give species-specific shoot length. For *Halophila beccarii*, we noted additional measurements (shoot width, n=9, and internodal length, n=6), species characteristics, and natural history observations. Lastly, we sun-dried the seagrass samples (whole plant, shoots, and roots) and calculated total biomass above and below ground by dry weight (g/m^2) on a micro-scale weighing balance (WENSAR PGB-220/ 0.001 to 200 g).

Infaunal macrobenthic analysis

We immediately preserved the macrobenthic sediments in 4% (buffered) formalin-Rose Bengal solution and later sieved them on a 500 micron mesh to retain macrobenthic fauna (0.5mm and above; Ingole et al. 2009). We identified the seagrass associated macrofauna up to group level under a stereoscope (Zeiss discovery V.8) and, groups were validated using standard identification manuals (Fauchald 1977; Keppner & Tarjan 1989; Sturm et al. 2006; Sasaki 2008). Lastly, we counted individuals of each group to estimate their abundances.

RESULTS

We recorded four seagrass species and eight macrobenthic groups associated with seagrass habitats from the present study. We report a new distribution record of globally threatened seagrass species, *Halophila beccarii*, from the North Andaman region. Pokkadera seagrass meadow spreads across ~8.2 hectares (Figure 1), comprising early-successional species like *H. beccarii, Halodule pinifolia,* and *Cymodocea rotundata;* and late-successional species like *Thalassia hemprichii* (Vonk et al. 2015; Nowicki et al. 2017).

The mean seagrass cover in the meadow was 18.3 ± 24.7 %, with a non-epiphytic algal cover of 18.3 ± 35 %. *H. beccarii* (30 ± 34.7 %) and *H. pinifolia* (6.3 ± 12.1 %) contributed to the highest and lowest seagrass cover. *H. beccarii* had the highest shoot density (103.5 ± 68.3 shoots/ m^2), whereas *C. rotundata* added to maximum total biomass (44.0 ± 56.1 g/ m^2; Table 1).

Halophila beccarii

Halophila beccarii belongs to the family Hydrocharitaceae in the order Alismatales. The specimen recorded at the Pokkadera meadow had 4–8 lanceolate leaves with no cross venation (Image 1B & C). The mean shoot length was 1.3 ± 0.4 cm (n= 10), mean shoot width was 1.3 ± 0.5 mm (n= 9) with a mean internodal length of 1.7 ± 0.3 cm (n= 6). Rhizomes were smooth as observed for the species (Image 1B).

Habitat

Halophila beccarii was distributed in the upper intertidal zone, either as monospecific strands on sand flats or was found associated with *T. hemprichii*, *C. rotundata*, and *H. pinifolia* in a mixed species meadow (Image 1A). The species was present in intertidal puddles or exposed on sand bars in line with previous observations (Waycott et al. 2004) and here was dominantly distributed at the fringes of the intertidal zone, adjacent to littoral vegetation.

Associated macrobenthic fauna

We recorded a total of eight macrofaunal groups, both epibenthic (n= 5 groups; number of quadrats= 44) and infaunal (n= 5 groups; number of sediment samples = 12) belonging to six phyla, associated with the seagrass beds at Pokkadera viz; gastropods, bivalves, polychaetes, nematodes, brachyuran, decapods, asteroids, and foraminiferans. Gastropods and bivalves were common groups found in both the micro-habitats.

In order of abundance, gastropods (51.4%) dominated the infaunal assemblages, followed by bivalves (35.2%) and polychaetes (7.4%), while the least dominant groups were nematodes (3%) and foraminifera (3%). Gastropods were dominant in epibenthic assemblages (50%), followed by brachyurans (31.3%; Table 2). The total mean density of epibenthic groups (0.4 ± 1.5 ind. / m^2) was much lower than infaunal assemblages (73.5 ± 129.7 ind. /m^2; Table 2).

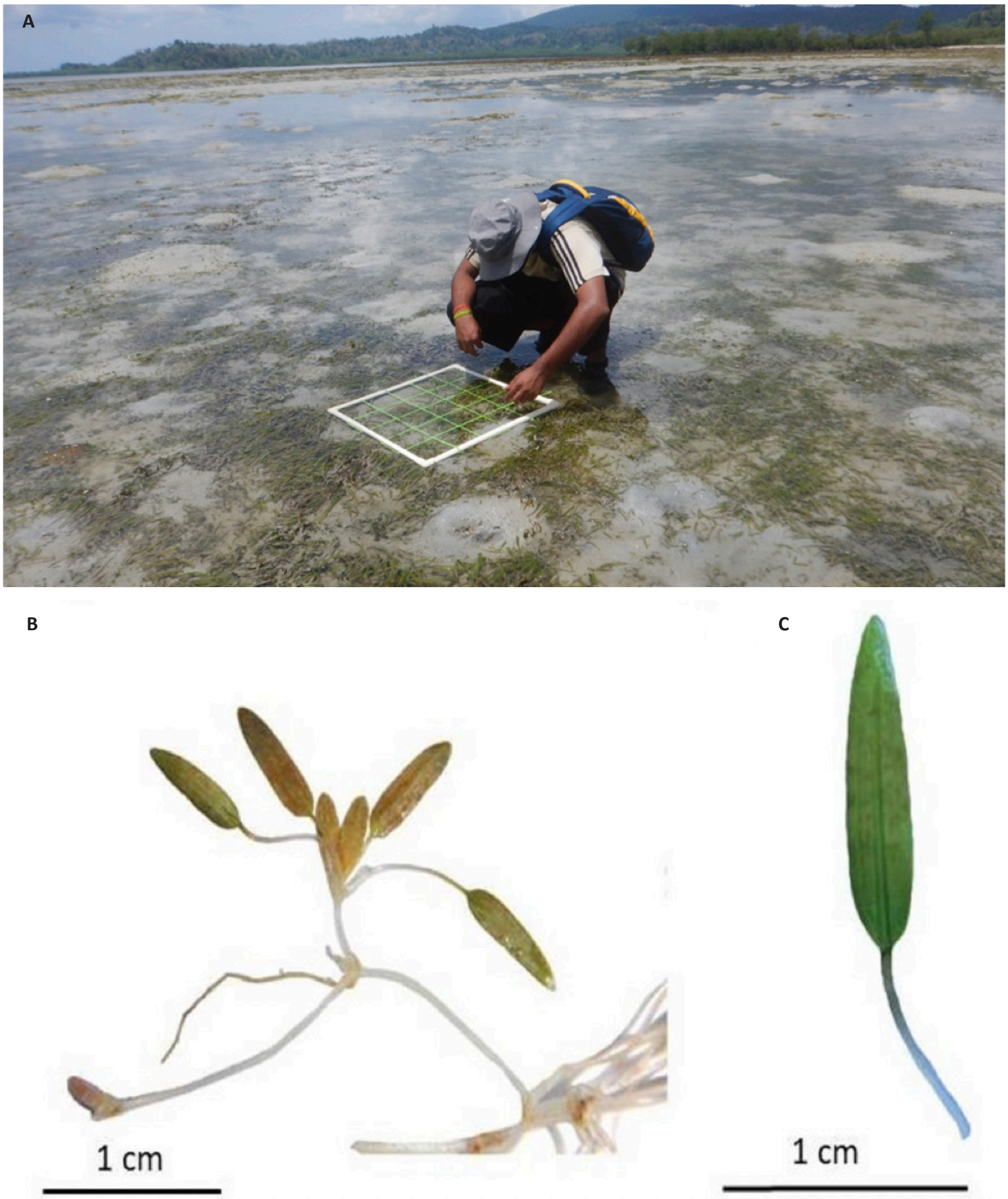

Image 1. A—Habitat characterization of seagrass meadow at Pokkadera, Mayabunder coast, North and Middle Andaman | B—*Halophila beccarii* species specimen | C—*H. beccarii* leaf structure. © Swapnali Gole.

Table 1. Seagrass meadow characteristics of Pokkadera seagrass meadow, Mayabunder, North and Middle Andaman district of Andaman & Nicobar Islands.

Meadow characteristics	Seagrass species			
	Halophila beccarii	*Cymodocea rotundata*	*Thalassia hemprichii*	*Halodule pinifolia*
Mean seagrass cover (%)	30 ± 34.7	20.5 ± 28.8	16.3 ± 23.3	6.3 ± 12.1
Shoot density (shoots/ m^2)	103.5 ± 68.3	45.5 ± 24.4	40.6 ± 30	42.5 ± 12
Shoot length (cm; n= 10)	3.2 ± 2.8	6.9 ± 1.7	5.1 ± 3.5	4.3 ± 1.4
Total Biomass (above and below; dry weight) (g/ m^2)	1.3 ± 2.2	44.0 ± 56.1	14.1 ± 25.1	0.6 ± 1.8
Sea surface temperature- (°C) 37.3 ± 0.7		Salinity- (ppt) 29.0 ± 1.0	pH- 8.8 ± 0.1	

(Values expressed as mean ± standard deviation).

Table 2. Mean densities of major seagrass-associated macrobenthic taxonomic groups recorded at Pokkadera seagrass meadow.

Faunal groups	Infaunal (ind. / m²)	Epifaunal (ind. / m²)
Gastropods	188.9 ± 151.8	1 ± 1.7
Bivalves	129.2 ± 391	0.1 ± 0.7
Polychaetes	27.1 ± 52.2	not recorded
Nematodes	11.1 ± 26	not recorded
Foraminiferans	11.1 ± 27.4	not recorded
Asteroids	not recorded	0.1 ± 0.7
Brachyurans	not recorded	0.6 ± 3.5
Decapods	not recorded	0.1 ± 0.7

DISCUSSION

Halophila beccarii is a euryhaline species found associated with mangrove vegetation (Jagtap 1991) that provides numerous ecosystem services. Studies have highlighted the role of *H. beccarii* meadows as sediment stabilizers, refugia to macrobenthic and fish diversity (Mathews et al. 2010), and pioneers for seagrass succession (Aye et al. 2014). The species is presently listed as 'Vulnerable' in the IUCN Red List (Short et al. 2010) and some of the major threats are coastal infrastructure development, marine pollution, and exploitative fishing practices, leading to modifications of its natural habitat (Short et al. 2010).

In addition to reporting a new distribution record, our study emphasizes the importance of mixed seagrass beds for associated species thus, highlights the value of these coastal ecosystems. Studies have highlighted habitat importance of *H. beccarii* meadows in supporting macrobenthic diversity (Su et al. 2020). Our findings suggest high numerical dominance of infaunal assemblages which needs further investigation, as epifaunal and infaunal abundance in seagrass meadows is influenced by meadow characteristics like structural complexity, canopy height, leaf morphology, shoot density, and above and below ground biomass (Orth et al. 1984; Lee et al. 2001; Leopardas et al. 2014).

The intertidal region at Pokkadera is an unprotected area, and the seagrass habitats are open ground for shoreline fishing activities and cattle trampling during ebb tide, posing a threat to the existing seagrass beds, and in turn associated fauna. Based on few anecdotal reports by local fishers, Pokkadera is a dugong feeding habitat, which signifies the importance of the site and adds to the necessity for habitat and species conservation.

Scientists have emphasized the need for integrating research with policy-making to conserve *H. beccarii* habitats (Ramesh et al. 2018). Our work highlights *H. beccarii* distribution for prioritizing its conservation in the Andaman and Nicobar Islands, in line with recommendations to aid ecological assessments globally (Short et al. 2010). Lastly, we strongly recommend the need for more seagrass exploratory surveys and long-term monitoring of critical meadows to form a robust baseline for seagrass management in the Andaman Islands.

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Flowering and fruiting of Tape Seagrass *Enhalus acoroides* (L.f.) Royle from the Andaman Islands: observations from inflorescence buds to dehiscent fruits

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Abstract: Seagrass phenophases are crucial in understanding their reproductive biology but are seldom documented. We studied flowering and fruiting phenophases of *Enhalus acoroides* from a mixed-species intertidal seagrass meadow in Ritchie's archipelago, Andaman Islands, India. The estimated mean densities of pistillate and staminate flowers were 16.0 ± 12.0/ m^2 and 12.7 ± 7.3/ m^2, respectively. We observed the bloom of free-floating male flowers (961.7 ± 360.4/ m^2) during the spring low tides (at mean sea surface temperature ~30°C). Seagrass cover, shoot density, and canopy height of *E. acoroides,* along with flowering densities, showed a zonal variation within the sampled meadow. We report the first-time observations of several phenophases of *E. acoroides,* such as female inflorescence buds, male inflorescence, a bloom of released male flowers, pollination, and fertilized flowers from the Indian waters. We also report the prevailing threats to seagrass meadows, such as meadow scarring done by boat anchorage in the Andaman Islands.

Keywords: Mass bloom, meadow scarring, mixed-seagrass meadow, Swaraj Dweep.

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Author contributions: SG—Study design, field data curation, data processing and analysis, conceptualization, and drafting of the manuscript; SK—Funding acquisition, Study design, supervision, review, and editing of the manuscript; HD—Methodology design, supervision of work, validation of phenophases, review, and editing of the manuscript; JAJ—Funding acquisition, Supervision, review, and editing of the manuscript.

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INTRODUCTION

Characterizing the demography of local seagrass populations is essential to understanding the phenology and ecological processes of seagrass species (Inglis 1999). Such information is critical to improving the knowledge and management of high ecological value species like *Enhalus acoroides* (L.f.) Royle that regulates the food web, primary production, & sediment dynamics and supports a diversity of benthic organisms & fish communities (Estacion & Fortes 1988; Komatsu et al. 2004; Yu et al. 2018). *E. acoroides* has a wide distribution range in the Indo-Pacific region, extending from the eastern coast of Africa to northern Australia (Waycott et al. 2004; Short & Waycott 2010). The species is dioecious and reproduces asexually (through clonal growth) and sexually (pollination). Pollination in *E. acoroides* is epi-hydrophilous, and fruiting and flowering occur throughout the year (Hartog 1970; Brouns & Heijs 1986; Ackerman 2006; Rattanachot 2008). The positively buoyant seeds (Hartog 1970) and released fruits have a higher potential for long-distance dispersal, thus facilitating the wider species distribution and ensuring succession (Lacap et al. 2002; Kendrick et al. 2012).

In the Indian waters, *E. acoroides* is known to occur on the southeastern coast, Andaman & Nicobar Islands (ANI), and Lakshadweep Islands (Jagtap 1991, 1992; Das 1996). In ANI, *E. acoroides* distribution is reported from the North Andaman (Paschim Sagar and North Reef), South Andaman (Tarmugli, Chidiyatapu, Wandoor, Dugong Creek, and Vivekandapur), Ritchie's archipelago (Kalapatthar, Vijay Nagar, Inglis, and Henry Lawrence), and Nicobar archipelago (Pilomilow, Camorta, Trinket, Nancowry, Katchal, and Great Nicobar) (Jagtap 1992; Das 1996; Thangaradjou et al. 2010; D'Souza et al. 2015; Ragavan et al. 2016; Savurirajan et al. 2018; Figure 1). Although the seagrass distribution, status, and associated fauna of *E. acoroides* are well documented, the reproductive phenology of this species was rarely observed from the Indian coastal waters including from ANI (Patankar et al. 2019).

Seagrasses in the ANI are vulnerable to human-induced (coastal modification and pollution) and natural stressors (tsunami and recurrent cyclones). These threats may vary in intensity and subsequently have caused habitat alteration or in worst-case scenario, a complete wipe-out of the local populations. For example, the 2004 tsunami in the Indian Ocean critically impacted several seagrass meadows and changed the species composition, with the local extinction of a few species (Thangaradjou et al. 2010). For recovering from such major disturbances through recolonization, sexual reproduction (seeds) has proven to be more effective than clonal expansion (ramets) in the seagrass restoration initiatives (Darnell & Dunton 2016). Thus, for directing local efforts for seagrass conservation and effective management of large-scale loss, documenting the sexual phases of seagrass species is a prerequisite (Short & Wyllie-Echeverria 1996).

Despite sexual reproductive strategies of species like *E. acoroides* contribute to the resilience of seagrass populations and genetic diversity (Duarte et al. 1997; Yu et al. 2018), these observations are scarcely reported from the Indian waters (Patankar et al. 2019). In this context, the present study aims to fill the existing research gaps in seagrass phenology of *E. acoroides* from the Indian waters and reports rare phenological phases from a mixed-species intertidal seagrass meadow of the Andaman Islands. Our study presents a detailed natural history observation on 10 different flowering and fruiting phenophases of *E. acoroides*, which provide a baseline for future research. Although opportunistic in nature, we believe our findings establishes improved knowledge of seasonality in phenology of the species, especially in the wake of *E. acoroides* gaining attention as a target species in global seagrass restoration initiatives (Lawrence et al. 2007).

MATERIALS AND METHODS

As a part of pan-archipelago seagrass exploratory surveys, we sampled a mixed species intertidal seagrass meadow in Vijay Nagar, Swaraj Dweep Island of Ritchie's Archipelago (South Andaman; Figure 1), in January 2021 at the afternoon spring low tides. We mapped the seagrass meadow by walking around its fringes with a GPS and calculated the sampled area on Google Earth Pro version 7.3. Quadrats (0.5 X 0.5 m size; n = 18) were placed randomly in the selected seagrass meadow to document the species composition and seagrass cover (Duarte & Kirkman 2001). The shoot density (shoots/ m^2) of *E. acoroides* was calculated by counting all the shoots within the quadrat. Further, we randomly selected 20 shoots of *E. acoroides* from each sampling point and recorded canopy height using a measuring scale (cm). In addition, environmental variables such as sea surface temperature (SST), pH, and salinity were recorded at each sampling point using handheld multi-parameter testers (Eutech Oaklon- PCS Testr 35; refractometer- LABART).

We conducted field surveys for 12 consecutive days and studied different phenophases of flowering and fruiting of *E. acoroides*. We estimated the densities

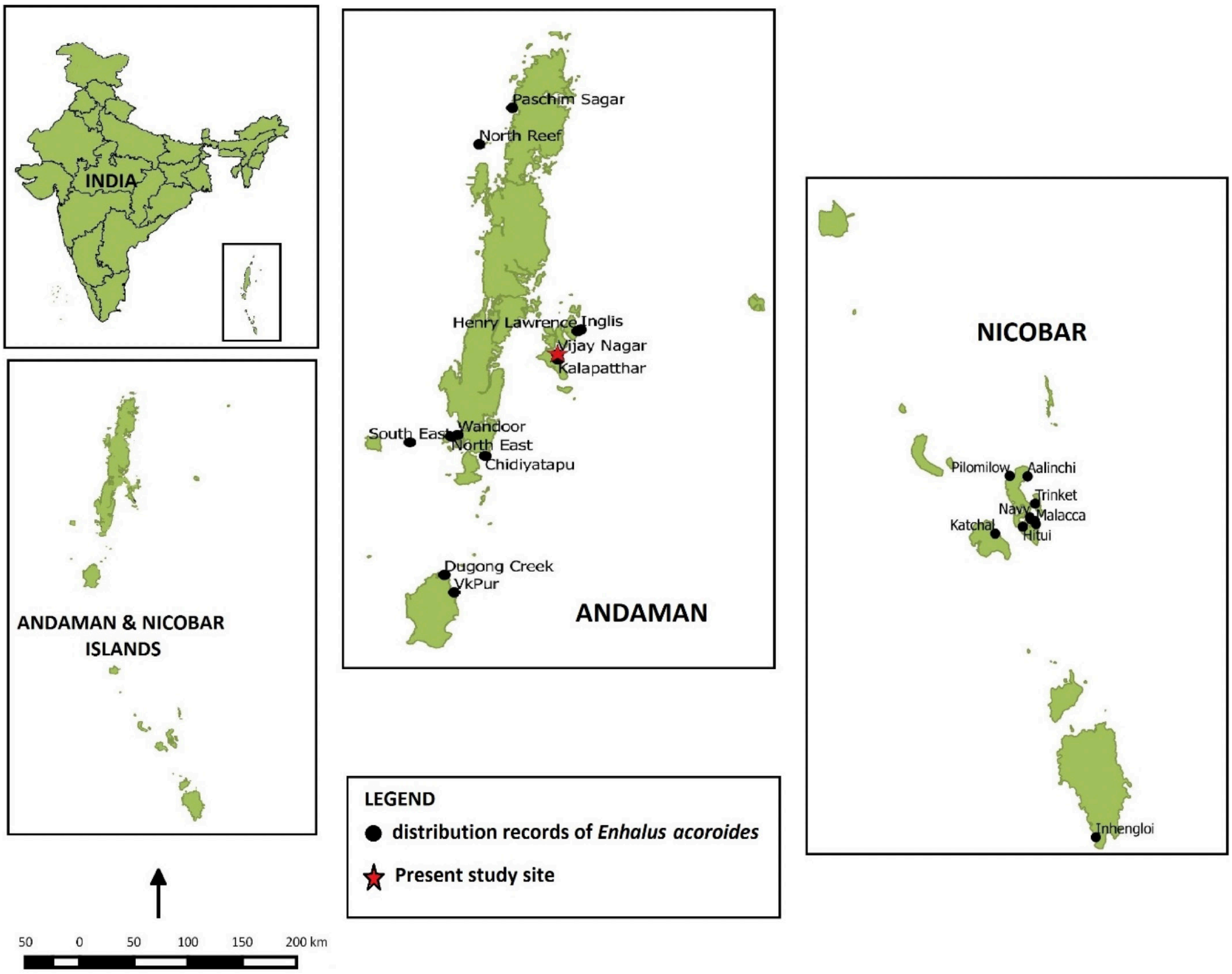

Figure 1. Study area map of *Enhalus acoroides* distribution and present sampling site at Vijay Nagar, Swaraj Dweep (Ritchie's archipelago), Andaman & Nicobar Islands, India.

of flowers and fruits within the quadrats across the sampling points. We measured peduncle length, sepal, and spathal leaf lengths of flowers using a measuring scale (cm). To study various stages of fruiting and seed development, we collected fruits of all phenophases (n = 5/ phase) except dehiscent fruits. Fruits were contained in seawater and immediately transported to the laboratory for further analysis. We dissected each fruit with a surgical blade and measured their diameter and length using a measuring scale (cm). Lastly, we recorded each fruit's seed development (immature/ mature seeds), the number of seeds, and morphometric measurements (seed length, seed base length).

We validated different flowering and fruiting stages by referring to published literature on the species (Bujang et al. 2006; Patankar et al. 2019) and through personal correspondences with seagrass experts.

RESULTS

Seagrass meadow characteristics

We observed six seagrass species from a continuous meadow spread across ~16.8 hectares in Vijay Nagar (Swaraj Dweep), viz: *Enhalus acoroides, Thalassia hemprichii* (Ehrenberg) Ascherson, 1871, *Halophila ovalis* (R. Brown) Hooker f., 1858, *Cymodocea rotundata* Asch. & Schweinf., *Halodule uninervis* (Forssk.) Asch, and *Syringodium isoetifolium* (Asch.) Dandy.

Enhalus acoroides was the dominant of all species with the highest mean cover, followed by *T. hemprichii* and *C. rotundata* (Table 1). Seagrass species exhibited spatial variation in distribution within the meadow. In the high tide zone, *S. isoetifolium* and *H. uninervis* occurred in a mixed substratum of very fine sand and silt (Table 1). The distribution of *C. rotundata* was patchy across the mid-tide edges, and the species preferred fine sand.

Table 1. Meadow characteristics, species' substratum preference, and spatial distribution of seagrasses at Vijay Nagar, Swaraj Dweep.

Seagrass species	Mean seagrass cover (%)	Shoot density (shoots/ m^2)	Shoot length (cm; n=20)	Substratum	Species distribution within the meadow
Enhalus acoroides	36 ± 39.3	289.9 ± 103.9	35.3 ± 12.1	Fine sand mixed with silt and clay	high and mid-tide zones
Thalassia hemprichii	10.9 ± 4.8	70.3 ± 43.6	10.7 ± 4.8	Coarse sand and rubble	mid and low-tide zones
Cymodocea rotundata	6.5 ± 23.1	30.3 ± 18.5	6.0 ± 3.6	Fine sand	mid-tide zone
Halophila ovalis	5.9 ± 17.1	29.3 ± 17.9	0.4 ± 0.6	Sand and rubble	mid and low-tide zones
Halodule uninervis	1.9 ± 5.7	46.9 ± 41.6	8.5 ± 2.6	Very fine sand mixed with silt	high-tide zone
Syringodium isoetifolium	1.3 ± 4.6	53.3 ± 46.0	8.2 ± 3.0	Very fine sand mixed with silt	high-tide zone
SST (°C)- 30.1 pH- 7.7 Salinity (ppt)- 30.9					

Halophila ovalis and *T. hemprichii* occupied coarse sand and rubble in the meadow's mid and low-tide edges (Table 1). Distribution of *E. acoroides* was spread across high and mid-tide zones, where the species was found either as monospecific strands in fine sand mixed with silt and clay or co-occurred with *C. rotundata*, *H. uninervis*, *S. isoetifolium,* and *T. hemprichii*.

Seagrass cover, shoot density, and canopy height for *E. acoroides* varied considerably within the high and mid-tide zones of the sampled meadow. The total mean cover of *E. acoroides* was estimated as 36 ± 39.3 % (Table 1), but we observed a reduced species coverage from high (64.8 ± 33.5 %) to mid tide zone (19.3 ± 33 %). Similarly, overall shoot density for *E. acoroides* was 289.9 ± 103.9 shoots/ m^2 (Table 1); however, mean densities in the high and mid tide zones varied as 144.9 ± 130.8 shoots/ m^2 and 30.3 ± 55.2 shoots/ m^2, respectively. We observed longer shoots of *E. acoroides* in the high tide patches (33. 9 ± 10.1 cm). Shoots in the mid-tide zone were comparatively shorter (19. 4 ± 7.2 cm), with signs of herbivory.

Flowering phases and natural history

In the present study, we recorded different stages of both pistillate and staminate flowers of *E. acoroides*—female inflorescence bud, pistillate flower at anthesis, male inflorescence, the bloom of free-floating male flowers, empty male spathe (post-release of male florets), pollination (released male florets attached to female inflorescence), and fertilized flowers (Table 2). Like species characteristics, a significant zonal variation was observed in flowering densities of *E. acoroides* within the sampled meadow. Densities of pistillate flowers in high and mid tide zones were 22.8 ± 13.4/ m^2 and 4 ± 1.4/ m^2, respectively. Similarly, densities of staminate flowers were much higher (17.7 ± 10.4/ m^2) towards the high tide shore than in the mid-tide region (4 ± 1.1/ m^2).

We observed solitary female inflorescence buds on the terminal shoots. Peduncles of female buds were shorter than pistillate flowers at anthesis (Table 2; Image 1A). Female inflorescence appeared as solitary flowers on the terminal shoots, with visible sepals, petals, and pistils/ styles (Image 1B). Petals (3) were pink and had 2–3 longitudinal ridges with folded margins, enclosing 5–6 styles. Long peduncles aided the pistillate flowers to sway in the tidal waters, with petals wide open, floating at the surface. The male inflorescence had multiple white male flowers on the spadix enclosed at the base of widely open spathal leaves (Table 2; Image 1C). All male inflorescences we observed were submerged in the water column with shorter peduncles (5.2 ± 1.1 cm above the substratum) than the female inflorescence at anthesis (26.1 ± 8.0 cm; Table 2).

A noteworthy observation in the present study was the mass bloom of released male florets free-floating in the high tide zone. Male florets (white) were 0.2 ± 0.1 cm long, with 2–3 stamens and 5–6 tepals. We observed released male florets in masses (961.7 ± 360.4/ m^2; n=3 quadrats) along the sandy coastline (~1.5 km), floating on the water surface and trapped in seagrass blades (Image 1D). After the release of male flowers, a male spathe with two valves and a barren spadix (light orange) was visible. Shorter peduncles supported empty spathes filled with sand in the seagrass meadow (Image 1E). Further, we observed released male florets attached to the pistil of a wide-open female inflorescence on the water surface (2–8 male flowers/ female inflorescence; Image 1F). Lastly, a fertilized inflorescence observed had shed its petals, and the ovary was swollen, indicating the beginning of fruit formation (Image 1G).

Fruiting phases, seed development, and natural history

Based on the stages of seed development, we categorized the fruits observed as immature, mature, and dehiscent fruits. Immature fruits were fleshy,

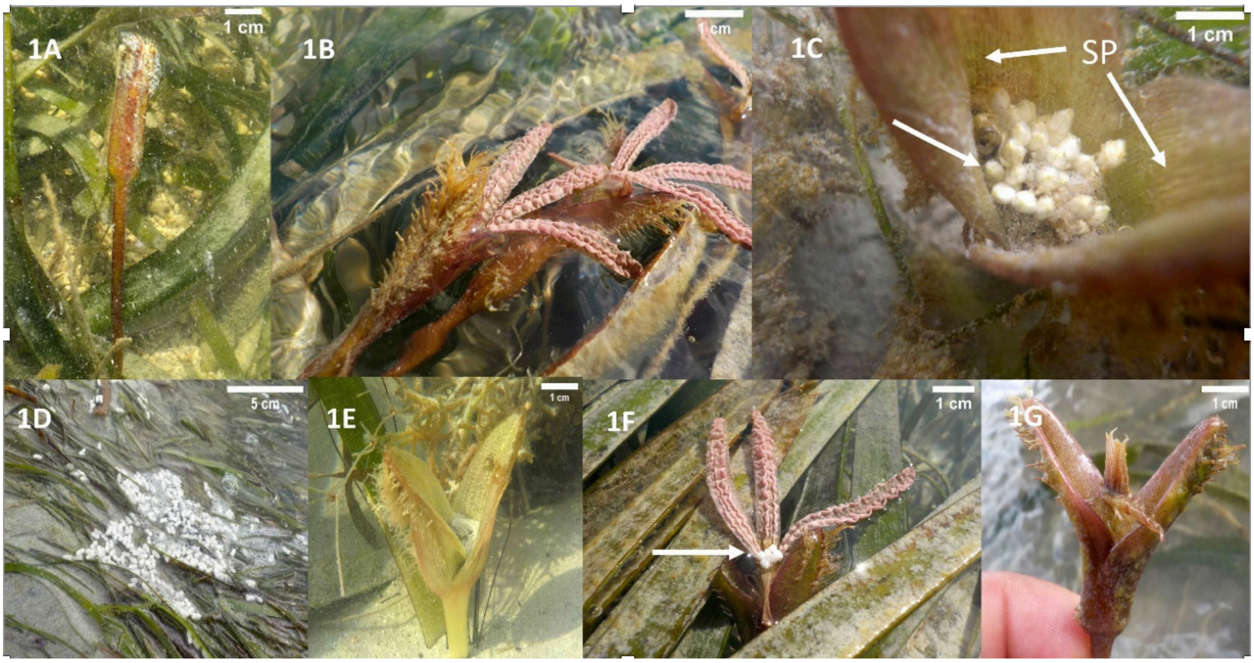

Image 1. Stages of flowering of *Enhalus acoroides*: 1A—Female Inflorescence bud (only sepals visible) | 1B—Pistillate flowers at an anthesis at the water surface (visible sepals, petals, pistils/ styles) | 1C—Male inflorescence with spathal leaves (SP) enclosing multiple white flowers (indicated by white arrow) | 1D—Released male flowers trapped in seagrass blades | 1E—Empty spathe filled with sand, post-release of male flowers | 1F—Pollination; male flowers attached to the pistil of female inflorescence at anthesis (indicated by white arrow) | 1G—Fertilized inflorescence. © Swapnali Gole and Ajay Kumar.

Table 2. Different phenophases of flowering and fruiting of *Enhalus acoroides* reported from the sampled seagrass meadow in Andaman Islands, India.

Stages of flowering	Density/ m^2	Peduncle length (cm)		Sepal/ Spathal leaf length (cm)			
Female inflorescence bud	3.2 ± 1.8	23.2 ± 7.8		3.9 ± 0.7			
Pistillate flower at anthesis	16.0 ± 12.0	26.1 ± 8.0		3.9 ± 0.8			
Male inflorescence	12.7 ± 7.3	5.2 ± 1.1		4.2 ± 0.3			
Male spathe (Post-release of male flowers)	3.3 ± 1.5	6.4 ± 1.6		4.1 ± 0.1			
Pollination (Male flowers attached to female inflorescence)	10 ± 1.3	26.4 ± 8.0		3.9 ± 0.7			
Fertilized flower	2.2 ± 1.0	20.3 ± 4.9		4.0 ± 0.6			
Stages of fruiting	**Density/ m^2**	**Diameter (cm; n = 20)**	**Fruit length (cm; n = 20)**	**No. of seeds/ Fruit (cm)**	**Seed length (cm)**	**Seed base (cm)**	
Immature fruits (Seeds still developing)	7.3 ± 2.0	4.6 ± 2.2	5.2 ± 0.8	11.3 ± 1.5	0.7 ± 0.1	0.8 ± 0.1	
Mature fruits (Developed seeds)	8.0 ± 3.9	9.2 ± 2.8	6.7 ± 1.0	11.8 ± 3.3	0.9 ± 0.2	1.1 ± 0.1	
Dehiscent fruits	2.2 ± 0.9	12.6 ± 0.7	-	-	-	-	

Values expressed as mean ± standard deviation; (- not recorded).

greenish-brown in color, with an uncoiled peduncle. Solitary fruits were erect on terminal shoots of the peduncle and concealed 10–13 spherical white seeds still developing (Images 2A & 2B). Mature fruits were large, ovoid-shaped, and fleshy, with a pointed tip. The fruit cover was greenish, with longitudinal rows of brown spikes, and the coiled peduncle positioned above the substratum supported the fruits (Image 2C). We found 8–14 fully developed, germinating seeds per mature fruit (Image 2D). A membranous white seed coat concealed

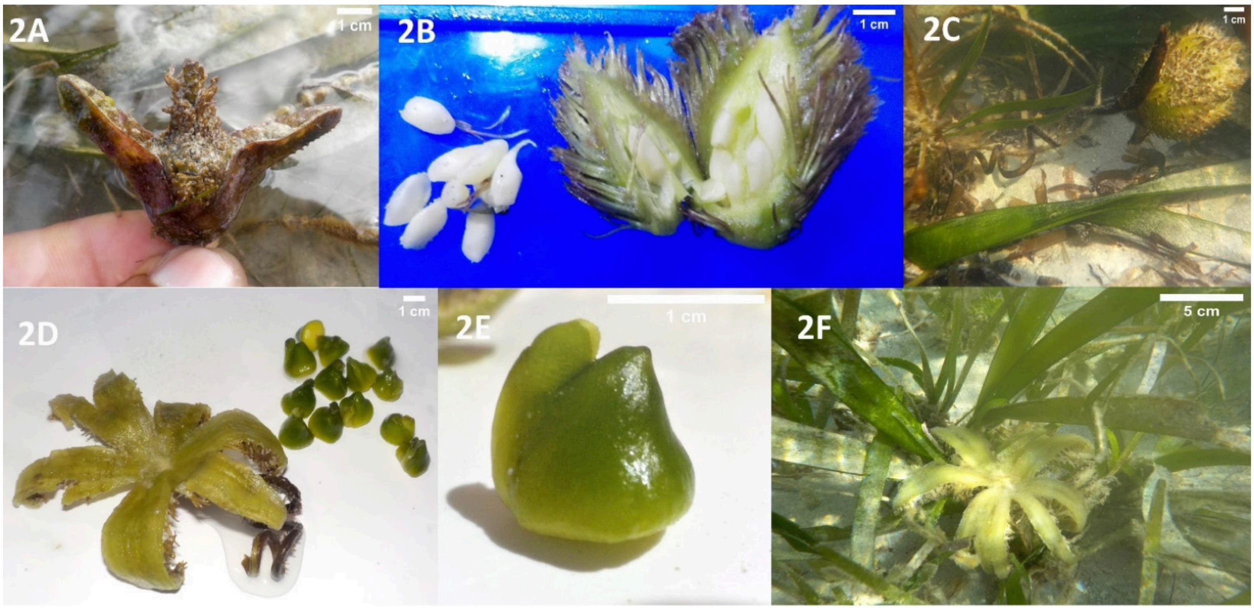

Image 2. Stages of fruiting of *Enhalus acoroides*: 2A—Young, immature fruit | 2B—Dissected immature fruit with developing seeds | 2C—Mature fruit with a coiled peduncle | 2D—Dissected mature fruits with developed seeds | 2E—Germinated seed with shoot bud visible | 2F—Dehiscent fruit. © Swapnali Gole and Ajay Kumar.

the seeds. Seeds were conical, yellow at the base and dark green at the apex. We observed visible shoot buds with a length of 1.2 ± 0.3 cm in each germinating seed (3 shoot buds/ seed; Image 2E). Dehiscent fruits were observed at the base of plant shoots, right above the ground (Image 2F). Fleshy fruit cover (mean diameter 12.6 ± 0.7 cm; Table 2) was broken into 6–7 halves post-release of seeds.

DISCUSSION

The lack of information on the phenology of *E. acoroides* from the Andaman Islands and Indian waters limits our understanding of the species' reproductive phases and seasonality. Densities of shoots, fruits, and flowers, in the present study (post-monsoon) were higher than previous reports in pre-monsoon (Patankar et al. 2019), possibly due to different sampling seasons. Additionally, no male flowers (inflorescence or released), pollination event, or fertilized flowers were recorded by Patankar et al. (2019). Since both the studies were opportunistic in nature, our findings supplement and strengthen the previous observations Patankar et al. (2019) made on *E. acoroides* phenology in the Andaman Islands.

In the present study, no correlation can be established between zonal variation in meadow characteristics and flowering densities of *E. acoroides*, given limited data. However, this aspect credits detailed investigation as studies have highlighted the role of meadow characteristics (seagrass cover, shoot density, and canopy height) and herbivory on the reproductive success of *E. acoroides* (Vermaat et al. 2004; Rattanachot 2008). Novel observations on the mass bloom of released male flowers (at SST ~30°C; mean) align with similar notes reported for the species (Hartog 1970; Rollon 1998).

In conclusion, based on higher densities of multiple phenophases observed in the present study (from buds to dehiscent fruits) as compared to previous reports (Patankar et al. 2019), we presume that January could be a critical period for *E. acoroides* phenology at a local scale, but this needs further validation through seasonal studies. Furthermore, the fruit ripening period for *E. acoroides* is long (2–3 months; Rollon 1998), after which the seeds are released. Thus, we assume that pollination is somewhere in October–November for the fruits observed in the present study. Thus, we recommend long-term seasonal monitoring studies to understand the peak flowering and fruiting season of *E. acoroides* and assess local drivers influencing the species' phenology in the Andaman Islands.

Lastly, our observations also report meadow scarring of the seagrass bed, as the study site is a fishing transit lane used for boat anchorage by local fishers (personal observations). Also, the entire inhabited coastline of Swaraj Dweep is known for gleaning activities and recreational and commercial fishing using 'khevla/ feka jaal' (cast net) and 'taana jaal' (shore seine). Moreover, anecdotal reports (from local fishers) and our field observations (direct encounters) suggest that these seagrass beds are important to support threatened species like green sea turtles and dugongs. Hence, detailed baseline information on the seagrass meadow, including its biodiversity, needs to be established to emphasize its management and conservation and to understand the species' natural history. Therefore, although our observations have provided detailed documentation of the meadow and natural history notes on different phenophases for *E. acoroides*, this baseline needs to be supplemented with future research and long-term studies.

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Spatial diversity and habitat characteristics of seagrass meadows with management recommendations in the Andaman and Nicobar Islands, India

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The Andaman and Nicobar Islands, India, a geographically remote region, harbor a diverse island ecosystem. Limited exploration has hindered our understanding of marine floral biodiversity in this area. To address this gap, we investigated seagrass meadows in the Andaman and Nicobar Islands to understand their spatial distribution, species composition, and habitat characteristics. We assessed 66 seagrass meadows, including 32 newly discovered ones, filling data gaps in the region's seagrass coldspots. Seagrasses were found across a wide range of depths, with the majority occurring in shallow subtidal waters (< 8 m). Large-sized species such as *Thalassia hemprichii*, *Enhalus acoroides*, *Cymodocea rotundata*, *Cymodocea serrulata*, and *Syringodium isoetifolium* dominated the littoral and shallow subtidal zones, while smaller species such as *Halophila* spp. and *Halodule* spp. exhibited broader depth distributions. *H. beccarii* and *H. decipiens* were strictly intertidal and subtidal species, respectively. Water depth significantly influenced seagrass occurrence ($p < 0.0001$), cover ($\beta = -0.2759$; SE = 0.02471; $p < 0.0001$), shoot densities ($\beta = -0.3556$; SE = 0.1231; $p = 0.005$), and biomass ($\beta = -0.3526$; SE = 0.1159; $p = 0.003$). Sand availability emerged as the second significant predictor of seagrass distribution, cover, and biomass (p values < 2e-16, < 2e-16, and 0.01, respectively). Habitat heterogeneity decreased with increasing water depth, and seagrass species exhibited strong preferences for specific substrata, resulting in spatial niche partitioning. Our study provides novel insights into the seagrass spatial diversity, habitat characteristics, and seagrass-environment relationship in the Andaman and Nicobar Islands. Further, it highlights the importance of water depth, habitat characteristics, and substratum heterogeneity in seagrass distribution and growth. Lastly, our findings imply that any change to the benthic profile of the meadows will influence the seagrass species distribution and growth. Understanding these factors is crucial for seagrass conservation and management in the region, aiding the development of targeted strategies to protect these valuable marine habitats and associated biodiversity.

KEYWORDS

intertidal, water depth, substrate availability, niche partitioning, seagrass distribution, dugongs, deepwater habitats

1 Introduction

Seagrass meadows are critical marine ecosystems that provide numerous ecological and economic benefits. The diversity and distribution of seagrasses are influenced by various regulatory factors, including benthic light availability, sediment profile, wave exposure, water temperature, and nutrient dynamics (Dennison and Alberte, 1987; Duarte, 1991; Malmer and Grip, 1994; Greve and Binzer, 2004). These factors play a crucial role in the growth and persistence of seagrass populations, as seagrasses rely on optimal light for photosynthesis, suitable sediments for proliferation, and nutrients for growth (Duarte, 2002). Resultant declines in seagrass populations are reported due to light reduction (Short and Wyllie-Echeverria, 1996), altered nutrient dynamics (Lee and Dunton, 2000), and wave action (Japar Sidik et al., 2018). Impacts of wave exposure are more prominently seen in intertidal zones, which are at the transition of land and sea. Only species able to cope with the heavy tidal fluctuations and associated parameters can thrive in these littoral zones, thus restricting the upslope distribution of seagrasses (Hemminga and Duarte, 2000). Variations in water temperature, whether seasonal or due to climate change (marine heat waves), are also known to influence seagrass photosynthesis and productivity (Barber and Behrens, 1985; Seddon and Cheshire, 2001; Díaz-Almela et al., 2009; Garrabou et al., 2022). Nevertheless, seagrasses exhibit wide-ranging acclimation strategies as a response to changes in their natural environment (Vermaat et al., 1998; Lee et al., 2007). An experimental study in the Philippines demonstrated that seagrass species have a varied tolerance to enhanced siltation and altered light irradiance in the water column (Bach et al., 1998; Terrados et al., 1998). Besides, the shift in turbidity levels resulted in local variation in seagrass diversity, growth, and depth limits. Accordingly, global research provides substantial evidence that natural variability in the environment influences seagrass ecosystems at local and regional scales.

Additionally, unprecedented human-induced stressors catalyze the natural factors impacting seagrasses (Orth et al., 2006). The rise in anthropogenic footprints in the seagrass meadows is majorly attributed to dredging, marina construction, destructive fishing practices, land reclamation, nutrient and sediment loading, turbidity, and habitat alteration (Short et al., 2007). As a result, subsequent seagrass declines are reported worldwide (Waycott et al., 2009; Gunderson et al., 2016). Unfortunately, the degradation and loss of seagrass habitats have significant implications for the environment and society. With global recognition as a valuable marine ecosystem, seagrass shares a multifaceted relationship with its environment. Seagrass meadows provide essential services by maintaining the health of adjacent habitats such as coral reefs and mangroves (Green and Short, 2003; Short et al., 2007). They also serve as nursery grounds for commercially important fish and invertebrates, supporting fisheries and contributing to local economies (Hemminga and Duarte, 2000; Unsworth et al., 2019; Berkström et al., 2020; United Nations Environment Programme [UNEP], 2020). Furthermore, seagrasses are crucial for the survival of megaherbivores like dugongs, as they constitute their primary food source (Short et al., 2007). Under the socioeconomic context, seagrasses provide economical services higher than terrestrial habitats (Costanza et al., 2014) and support local communities' livelihood and well-being (Mtwana Nordlund et al., 2016; Unsworth et al., 2019). Thus, seagrass losses or deterioration significantly impact these valuable services offered (Duarte, 2002; Orth et al., 2006). For instance, Unsworth (2007) reported a reduction in fish and invertebrate stocks in the Wakatobi Marine National Park, Indonesia, in response to seagrass degradation.

Similar seagrass trajectories are predicted to accelerate, particularly in developing countries, since these regions critically lack legislative measures to protect seagrasses (Duarte, 2002). Sadly, seagrass management has received little attention in the tropics than the adjacent coral reefs (Mumby et al., 2006). Although positive human interventions have reported an optimistic reversing of seagrass losses (Elliott et al., 2007; de los Santos et al., 2019; Tan et al., 2020), such initiatives, along with *in situ* seagrass management are yet substantially lacking in the tropics, including Indian waters. The widely accepted global seagrass distribution model classifies India into a diverse Indo-Pacific bioregion (Short et al., 2007). Of which the ecologically rich Andaman and Nicobar Islands (ANI) form the country's second most varied seagrass habitats (Thangaradjou and Bhatt, 2018). Seagrass meadows in ANI are crucial to supporting the dugong's remnant insular population (D'Souza et al., 2015). A recent study highlighted the importance of resource-rich seagrass beds for aggregating dugongs, possibly for calf protection (Gole et al., 2023). Despite such crucial ecological significance of seagrass meadows, there is a lack of information on their spatiotemporal changes, threats, and ecological and economic impacts in ANI. A report by Paulose et al. (2013) outlines the large-scale seagrass denudation in ANI (~1619 ha) caused by the Sumatra-Andaman earthquake and the

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Abbreviations: ANI, Andaman and Nicobar Islands.

2004 Indian Ocean Tsunami. The severe deposition of marine debris from this disturbance has further altered the species distribution trends (Thangaradjou et al., 2010a). In addition, ANI is also a geologically vulnerable region, with reports of ~ 486 earthquakes (Richter scale >4; United States Geological Survey, 2023[1]) and 25 cyclonic storms/depressions (Indian Meteorological Department, 2023[2]) that have hit the islands' coastline in the recent times (2018 to 2022). Unfortunately, the extent of seagrass loss to these threats remains uncertain due to sparse and discontinuous spatial seagrass assessments in the Islands.

For effective seagrass management, the accuracy of spatial studies and robust ecological knowledge is of utmost importance. Detailed information on species' checklists, distribution ranges, depth limits, and, most importantly, regulatory factors governing distribution and growth is essential for translating seagrass science to management and conservation (Unsworth, 2007; International Seagrass Biology Workshop 13, 2013[3]; McKenzie et al., 2020). A few significant challenges to studying seagrasses in ANI are the inaccessibility of sites to researchers, funds, and logistics required to perform marine surveys. Despite this, prior studies have given valuable baselines on species distribution, natural history, descriptive habitat preferences, and spatial extent of seagrasses in ANI (Jagtap, 1991; Jagtap, 1992; Das, 1996; Thangaradjou et al., 2010a; Thangaradjou et al., 2010b; Paulose et al., 2013; D'Souza et al., 2015; Ragavan et al., 2016; Savurirajan et al., 2018). However, a data gap is still reflected in many of the management crucial aspects of the region. Published literature largely lacks precise spatial information (locality) of meadows, hindering spatiotemporal comparisons like other global initiatives (Sudo et al., 2021). Despite three decades of seagrass exploration and research, only limited studies have a quantified seagrass-environment relationship (Savurirajan et al., 2018). Likewise, recent reports of new species' local distribution and range (Savurirajan et al., 2015; Gole et al., 2022) indicate more seagrass exploration to upgrade species checklist and distribution trends. As most of the seagrass meadows in ANI are recovering from the impact of the 2004 tsunami, it is essential to update existing information on the species composition, distribution, and factors that determine the existing trends. To address these knowledge gaps, this study aimed to investigate the spatial diversity and distribution patterns of seagrass meadows along the accessible coastline of ANI. Contrary to prior spatial assessments, our work instead focused on studying the complex interactions of seagrass species with their natural environment. Thus, we also aimed to understand the environmental regulatory factors that influence seagrass occurrence and distribution locally. By conducting a comprehensive assessment of seagrass ecology, this study will complement the existing knowledge on seagrasses and collectively contribute to developing effective management and conservation strategies for seagrass habitats in ANI.

2 Materials and methods

2.1 Study area and site selection

India's Andaman and Nicobar Islands support a tropical insular ecosystem as part of two global biodiversity hotspots (Myers et al., 2000). The ANI has a long and sheltered coastline spanning 1962 km (Andaman and Nicobar Administration, 2023[4]), providing favorable conditions for the growth and diversification of shallow coastal habitats such as coral reefs, mangroves, and seagrasses (Tigga and Rao, 2004). We explored the coastal waters of ANI, ranging from a depth of 0.2 m (intertidal) to 37 m (deep waters), for seagrass presence between 2018 to 2022 (January to April). We identified seagrass meadows using three approaches: a) tapping local knowledge of fishers through community interactions, b) published literature and correspondences with prior seagrass researchers, and c) exploratory free dives or swims in potential sandy habitats. Based on the geographical proximity of the investigated regions, assuming these sites will have a shared environment for seagrasses, we broadly divided ANI into five island groups: 1) North and Middle Andaman (NMA), 2) South Andaman (SA), 3) Ritchie's archipelago (RA), 4) Little Andaman (LA), and 5) Nicobar Islands (NIC) (Figure 1).

2.2 Field surveys

We conducted intertidal surveys (0.2 to 0.5 m) during the spring tides when the region was maximally exposed, extending to the reef ward edges. We performed subtidal exploration using SCUBA diving-assisted surveys in both shallow and deep waters. However, due to saltwater crocodile hotspots in more than 80% of the sampled regions, deepwater investigations were limited to approximately 10 m, except for RA, which has a flourishing tourism industry and diving-friendly sites, allowing efforts up to 37 m. Coasts with strong wave action that hindered SCUBA exploration were excluded from the study. The line intercept transects (LIT; English et al., 1997) method was employed for systematically sampling seagrass meadows after locating them intertidally and sub-tidally. We surveyed 18 sites from NMA (25 LITs), 19 sites from RA (44 LITs), 8 from SA (11 LITs), 7 from LA (14 LITs), and 14 from NIC (20 LITs). At each site, the 50 m long LITs were placed perpendicular to the shore, and spatial replicates (3 to 4 LITs) were spaced 150-200 m apart. Within each transect, a 50 x 50 cm quadrat was used at every 5 meters to record seagrass meadow characteristics, including species composition, total and species-specific seagrass cover, shoot density, shoot length, total biomass (above and below ground, dry weight), and algal cover (epiphytic and non-epiphytic).

In addition, we recorded the following predictor variables at each sampling point: water depth (using a Dive Computer for subtidal meadows), pH and water temperature (measured using a handheld multi-parameter tester - Eutech Oaklon- PCS Testr 35), and salinity (measured using a handheld refractometer - LABART). We recorded

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[1] https://earthquakes.usgs.gov/(accessed on March 2023).

[2] https://mausam.imd.gov.in/(accessed on March 2023).

[3] https://wsa.seagrassonline.org/(accessed on January 2023).

[4] www.andaman.gov.in (accessed on February 2023).

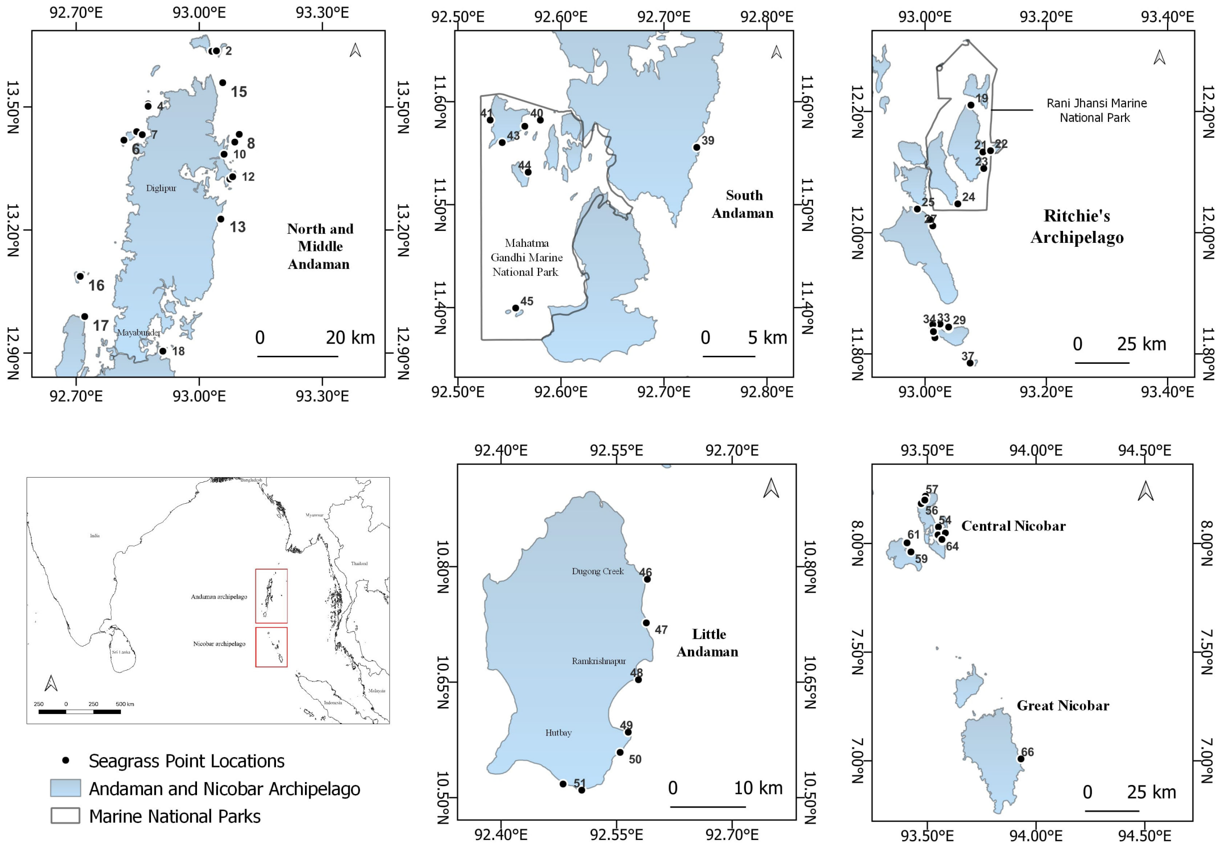

FIGURE 1
Seagrass distribution sites in the Andaman and Nicobar Islands (Sites codes and names in Supplementary Material Annexure 1).

major substrate types from the same quadrat for fine-scale habitat characterization, such as sand, dead coral with macroalgae, rock, rubble, and live coral. The habitat profile was calculated as the mean cover (%) from each sampling point, and it was further classified as either homogenous (100% sand) or heterogenous (approximately 50% sand along with other substrate types). The seagrass meadows were characterized based on the three criteria: a) observed depth gradient, b) seagrass cover, and c) species composition. We classified meadows' depth profile as intertidal (0.2 to 0.5 m), shallow-subtidal (< 8 m), and deep waters (> 8 m; McKenzie et al., 2020). Based on the total seagrass cover, meadows were further profiled as a) sparse (0-25% cover), b) moderate (25-50% cover), c) dense (50-75% cover) and d) very dense (75-100% cover; Sabilah and Amran, 2020), and grouped as either mono-specific (single species) or mixed-species (2 or more co-occurring species).

2.3 Laboratory assessments

To estimate shoot density and biomass (above and below ground), we collected samples from a 20 X 20 cm smaller quadrat within each transect (n= 3/transect). The collected seagrass samples were stored in zip-lock bags and transported to the field base for further analysis. We rinsed the seagrass samples to remove sediment particles and algae and counted seagrass shoots (species-specific) to estimate shoot densities (shoots/m^2). Lastly, we air-dried the seagrass samples and calculated total biomass (above and below ground - g/m^2) on a micro-scale weighing balance (WENSAR PGB-220/0.001 to 200 g). Sediments were hand-scooped in triplicates from 0.4 m^2 within the sampled seagrass beds and air-dried for texture analysis to assess the habitat suitability of the seagrass species.

2.4 Data analysis

2.4.1 Step 1-Data normalization and collinearity

We used a generalized linear model (GLM) framework to elucidate the influence of 11 potential explanatory variables on four response variables, namely seagrass occurrence, cover, biomass, and density. Since the normal distribution was not observed for three quantitative response variables (seagrass cover, density, and biomass), the data were transformed using Z-score normalization. Before GLM, collinearity among the 11 quantified explanatory variables (water depth, pH, water temperature, salinity, epiphytic macroalgae, non-epiphytic macroalgae, sand, rubble, dead-coral with macroalgae, live coral, and rock) was assessed using Variance Inflation Factor (VIF) values. The VIF value for sand, which is the primary substrate for seagrass occurrence and growth, was found to be considerably higher than the other independent variables. Therefore, we conducted a bivariate regression analysis to determine the strength and relationship of other independent variables with sand (Table 1). We observed that the least important variables for seagrass growth such as live coral and rock substantially correlated with sand (Table 1), so these two variables were removed from further analysis. The VIF values were rechecked, and it was found that all nine remaining explanatory variables exhibited low collinearity (VIF < 3), which is recommended for regression analysis (Bolker, 2008).

2.4.2 Step 2-Regression analysis

We assumed the response variable of seagrass occurrence to follow a binomial distribution, and analysis was performed on the seagrass presence-absence matrix. An "Intercept-only" model was created with the response variable, and nine independent models were built for each predictor variable versus seagrass occurrence (Johnson and Omland, 2004). We excluded models with Akaike Information Criterion (AIC) values higher than the "Intercept-only" model from further analysis (Johnson and Omland, 2004; Arnold, 2010). We generated different combinations of informative models, and the model with the lowest AIC value and highest corresponding AIC weight was selected as the best-fit model. For quantitative variables, we assumed that the normalized data (Z-score) for seagrass cover (mean percentage), shoot densities (shoots/0.04 m^2), and seagrass biomass (total dry weight/0.04 m^2) followed a Gaussian distribution. Thus, GLM analyses were performed on their respective matrices. However, the AIC values of informative models did not differ significantly, making it challenging to select one best-fit model and potentially discarding relevant explanatory variables. To overcome this, we employed an information-theoretic model averaging approach. We created multiple combinations of models using the function "dredge" in the Mumin package in R (version 4.2.1). A total of 512 models were created for seagrass cover, density, and biomass. The models with the lowest AIC and AIC delta < 2 (indicating a small difference in AIC values) were averaged (Burnham and Anderson, 2002), providing a more robust understanding of the influence of potential explanatory variables on seagrass cover, density, and biomass.

2.4.3 Step 3-Species habitat and substratum preference

Canonical Correspondence Analysis allows for the exploration of relationships between species abundances and environmental variables. We performed Canonical Correspondence Analysis (CCA plots) on the species-densities matrix to assess the impact of habitat and sediment profile on seagrass species densities. All data analysis was conducted in R (version 4.2.1) using packages such as CAR, AICcmodavg, and ggplot2. Functions like glm, AIC, Loglik, and aictab were utilized to perform GLM analysis, calculate AIC values and likelihoods, and create plots (R core development team, 2019[5]).

3 Results

3.1 Spatial distribution of seagrasses

The Andaman and Nicobar Islands (ANI) coastal waters host 12 species of seagrasses. Our study encompassed 66 meadows from 34 islands across five clusters, allowing us to identify 11 out of the 12 reported seagrass species in the region (Table 2). These seagrasses exhibited varying distribution patterns, ranging from dense and continuous beds to moderate to sparse stands. They were found in both homogeneous and heterogeneous habitats across different depth gradients. Among the identified species, *Halophila ovalis* and *Halodule pinifolia* demonstrated the widest distribution range, spanning from Landfall (Site 1), the northernmost limit, to Great Nicobar Islands (Site 66), the southernmost limit (Figure 1). These two species collectively occurred in over 50% of the investigated meadows. Following them, *Halodule uninervis* (34.8%), *Thalassia hemprichii* (31.8%), and *Cymodocea rotundata* (19.7%) were the next most frequently encountered species (Supplementary Material Annexure 1). However, the spatial spread of the remaining six species was relatively limited. An interesting finding was the rare occurrence of *H. beccarii*, observed only once at Pokkadera (Site 18) (Supplementary Material Annexure 1; Figure 1), indicating its scarcity in the study areas. *Syringodium isoetifolium* exhibited a restricted distribution, being confined to just five sites: Jua Tekdi (Site 21) and Vijay Nagar (Site 27) in the RA, and the shallow waters of Kardip (Site 53), Trinket (Site 63), and Al-Reak (Site 64) in the Nicobar Islands (Supplementary Material Annexure 1; Figure 1). Notably, *C. serrulata* was absent in the NMA sites, while *H. minor* and *Enhalus acoroides* were exclusively found in the RA and NIC regions (Supplementary Material Annexure 1). We observed highest seagrass coverage, and total plant biomass in shallow subtidal meadows of Safed Balu and Kardip respectively, in the Nicobar archipelago (Supplementary Material Annexure 1). Shoot densities however were the highest in the mixed intertidal meadow of Vijay Nagar (6392.5 ± 672.5 shoots/m^2).

3.2 Species distribution across depth gradients

Seagrass meadows in the study area exhibited a range of depth distributions, occurring from the littoral zone (n=17) to subtidal regimes, shallow-subtidal (n=39), and deep waters (n=10; Supplementary Material Annexure 1). Most meadows in NMA, SA, and NIC were found in shallow-subtidal areas (Table 2). Deepwater seagrass beds were primarily restricted to RA, with the exception of Delgarno in the NMA (Table 2; Figure 1). In LA, seagrasses were exclusively intertidal and distributed along the island's North-Eastern to Southern coast (Figure 1). No subtidal seagrasses were detected along Little Andaman's West and North coasts. Intertidal and shallow-water seagrass meadows exhibited similar species richness, with ten species each and nine species overlapping between the two zones. The exceptions were *H. beccarii*, which was restricted to intertidal regions (0.4 m), and *H. decipiens*, which occurred exclusively in subtidal zones (3 to 21 m). *T. hemprichii* and

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[5] https://www.R-project.org/(accessed on December 2022).

TABLE 1 Bivariate regression analysis carried out on 11 explanatory variables considered for the regression analysis.

	water depth	pH	temperature	salinity	sand	rubble	dead coral algae	Live coral	rock	Non-Epiphytic Algae	Epiphytic Algae
water depth	**1**	0.053	0.035	-0.121	0.203	-0.102	-0.123	0.023	-0.147	-0.146	0.014
pH	0.053	**1**	0.327	-0.240	-0.124	-0.042	0.206	0.013	0.013	0.030	-0.181
temperature	0.035	0.327	**1**	-0.340	-0.079	0.079	0.014	0.000	0.056	0.057	-0.141
salinity	-0.121	-0.240	-0.340	**1**	0.118	0.021	-0.115	-0.003	-0.100	0.020	0.112
sand	0.203	-0.124	-0.079	0.118	**1**	-0.472*	-0.636*	-0.332	-0.484*	-0.053	0.086
rubble	-0.102	-0.042	0.079	0.021	-0.472	**1**	-0.045	0.015	-0.037	0.042	-0.023
dead coral algae	-0.123	0.206	0.014	-0.115	-0.636*	-0.045	**1**	0.075	-0.032	0.043	-0.024
Live coral	0.023	0.013	0.000	-0.003	-0.332	0.015	0.075	**1**	0.024	-0.012	-0.010
rock	-0.147	0.013	0.056	-0.100	-0.484*	-0.037	-0.032	0.024	**1**	0.012	-0.108
Non-Epiphytic Algae	-0.146	0.030	0.057	0.020	-0.053	0.042	0.043	-0.012	0.012	**1**	-0.068
Epiphytic Algae	0.014	-0.181	-0.141	0.112	0.086	-0.023	-0.024	-0.010	-0.108	-0.068	**1**

*Indicates significant correlation.
Values expressed as spearman's correlation co-efficient (r).

C. rotundata were dominant species in the intertidal meadows (0 to 0.5 m), occurring with 88% and 59% frequency rates, respectively. However, *T. hemprichii* was observed colonizing down to a depth of 2.5 m. *E. acoroides*, *Cymodocea* spp., and *S. isoetifolium* had a down slope limit of 5 m, beyond which these species were not found. The *Halophila* spp. + *Halodule* spp. Complex, excluding *H. beccarii*, dominated the depth regimes beyond 5 m, accounting for approximately 96% of the observed occurrences, particularly within the range of 8-15 m (Supplementary Material Annexure 1; Figure 2). *H. ovalis* was the most frequent species (66% occurrence rate), followed by *Halodule pinifolia* (50%) and *Halodule uninervis* (39%) in the shallow-subtidal seagrass beds. *H. ovalis* also dominated the deepwater meadows, occurring in ~ 80% of the sites.

3.3 Meadow species composition and distribution trends

Based on depth profile and species composition, we classified the observed seagrass meadows into six categories; (1) Intertidal, mono-species meadows (n=4), (2) Intertidal, mixed-species meadows (n=13), (3) Shallow, mono-species meadows (n=15), (4) Shallow, mixed-species meadows (n=24), (5) Deep, mono-species meadows (n=3), (6) Deep, mixed-species meadows (n=7). Of the 66 meadows, 44 were mixed-species, while 22 were mono-specific (Supplementary Material Annexure 1). A clear trend of decreasing seagrass species richness and coverage with increasing water depth was observed. Mixed-species beds exhibited dense coverage and were limited to intertidal and shallow waters (Supplementary Material Annexure 1). In contrast, single species dominated all depth regimes but rarely formed dense meadows. In category 1, *T. hemprichii* was the dominant species in the sparse to moderate seagrass beds found in the heterogeneous habitats of RA and SA (Supplementary Material Annexure 1). In category 3, *H. ovalis* accounted for 40% of the sparse to moderate, mono-species meadows along with *C. rotundata, H. decipiens, H. minor, H. ovalis, Halodule pinifolia*, and *Halodule uninervis*. Similarly, *H. ovalis*, *H. minor*, and *Halodule pinifolia* formed deep water, mono-species stands in category 5 (Supplementary Material Annexure 1).

The species richness in mixed-seagrass meadows ranged from a minimum of two to eight species. Interestingly, we found that the probability of two co-occurring species was more frequently observed (>50% of meadows) than a greater number of species in a single mixed-species meadow. Six species exhibited the highest co-occurring tendencies; '*Halophila* spp. with *Halodule* spp.' (in all-depth regimes), '*T. hemprichii* with *C. rotundata*' (in intertidal habitats), and '*S. isoetifolium* with *E. acoroides*' (in intertidal habitats). Three to eight co-occurring species characterized intertidal, mixed meadows (category 2) and showed a wide range of seagrass coverage ranging from sparse to very dense (Supplementary Material Annexure 1). Particularly within this category, we observed highly diverse (4 to 8 co-occurring species), dense, and contiguous seagrass meadows in sheltered bays such as Jua Tekdi (Site 21), Vijay Nagar (Site 27), Haddo (Site 38), Burmanallah (Site 39), and Light House-South Bay (Site 51) (Figure 1, Supplementary Material Annexure 1). Except for Haddo, all other intertidal seagrass-rich sites exhibited habitat heterogeneity (Supplementary Material Annexure 1). The mixed-species meadows of categories 4 and 6 were predominantly dominated by *Halophila* spp. and *Halodule* spp. Complex.

TABLE 2 Island wise summary of seagrass meadow characteristics in the Andaman and Nicobar Islands, India.

Island group	Sites sampled	New Seagrass beds	Sampling Range	Species Richness	Species Composition	Water Depth Range (m)	Total Seagrass Cover (%)	Total biomass (dry wt.; g/ $0.04m^2$; mean ± SE)	Shoot density (shoots/ m^2; mean ± SE)
North and Middle Andaman	18	10	13° 38’7.91”N,93° 1’50.66”E to 12° 54’15.44”N, 92°54’40.50”E	8	*Halophila beccarii, Halophila decipiens, Halophila ovalis, Halodule uninervis, Halodule pinifolia, Cymodocea rotundata, Thalassia hemprichii, Enhalus acoroides*	0.4 to 8.5	32.9	87.2 ± 51.4	1448.8 ± 212.4
Ritchie’s archipelago	19	12	12° 12’37.84”N, 93° 4’31.94”E to 11° 47’4.81”N, 93° 4’26.94”E	10	*Halophila ovalis, Halophila decipiens, Halophila minor, Halodule uninervis, Halodule pinifolia, Cymodocea rotundata, Cymodocea serrulata, Thalassia hemprichii, Enhalus acoroides, Syringodium isoetifolium*	0.2 to 21.5	28	131.8 ± 82.5	1147.9 ± 313.9
South Andaman	8	2	11° 40’55.56”N, 92°43’32.12”E to 11° 23’58.12”N, 92°33’21.65”E	6	*Halophila ovalis, Halodule uninervis, Halodule pinifolia, Cymodocea rotundata, Cymodocea serrulata, Thalassia hemprichii*	0.2 to 6.6	32.8	55.5 ± 28.5	2124.7 ± 427.3
Little Andaman	7	2	10°47’1.00”N, 92°35’23.89”E to 10° 30’49.21”N, 92°29’39.82”E	6	*Halophila ovalis, Halodule uninervis, Halodule pinifolia, Cymodocea rotundata, Cymodocea serrulata, Thalassia hemprichii*	0.1 to 0.5	35.8	158.2 ± 35.9	2556.4 ± 488.7
Nicobar	14	6	8° 2’21.88”N, 93°32’55.61”E to 7° 0’31.25”N, 93° 55’49.58”E	10	*Halophila ovalis, Halophila decipiens, Halophila minor, Halodule uninervis, Halodule pinifolia, Cymodocea rotundata, Cymodocea serrulata, Thalassia hemprichii, Enhalus acoroides, Syringodium isoetifolium*	0.2 to 5	44.5	870.1 ± 306	1764.2 ± 288.9

3.4 Habitat-sediment characterization and species’ affinities

Seagrasses were found predominantly in five habitat types; sand, rubble, dead coral with macroalgae, rock, and live coral (Supplementary Material Annexure 1; Figure 3). The sediment texture consisted of fine and coarse sand, clay, and silt. Homogeneous seagrass beds exhibited high siltation and turbidity. Sites in NMA and NIC were predominantly homogeneous, while LA and SA indicated habitat heterogeneity. RA displayed a more diverse habitat profile with a mix of homogeneous and heterogeneous benthic profiles (Supplementary Material Annexure 1). Seagrass patches in sites with fine sand were often found around dunes formed by crustacean burrows, such as Pokkadera, Dolphin, Temple, Nemo Reef, and Imli Dera (Figure 1). The presence of habitat heterogeneity supported highly diverse and extensive mixed-species meadows. The dominant non-epiphytic macroalgae were the *Padina* spp., followed by *Halimeda* spp. and *Caulerpa* spp. Epiphytic algal cover varied from thin or dense matt algal film over seagrass shoots. We observed the epiphyte *Melobsia* spp. on *T. hemprichii* shoots in Laxmanpur, Natural Bridge, and Burmanallah (Figure 1). 14 seagrass sites, mainly from NMA and RA, exhibited a high cover of mat-forming algae on shoots and the seabed (Supplementary Material Annexure 1).

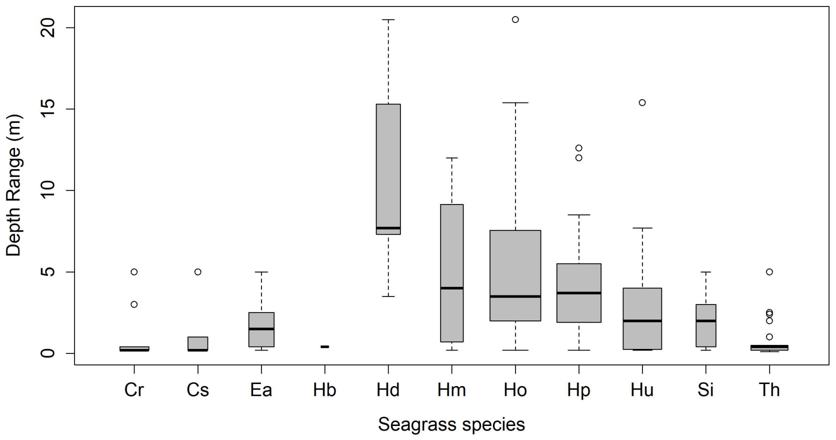

FIGURE 2
Depth wise distribution trends of seagrass species (Cr, *Cymodocea rotundata*; Cs, *Cymodocea serrulata*; Ea, *Enhalus acoroides*; Hb, *Halophila beccarii*; Hd, *Halophila decipiens*; Hm, *Halophila minor*; Ho, *Halophila ovalis*; Hp, *Halodule pinifolia*; Hu, *Halodule uninervis*; Si, *Syringodium isoetifolium*; Th, *Thalassia hemprichii*).

Seagrass species' densities clustered according to their habitat and substratum preferences, with Axes 1 and 2 of the CCA plots explaining a cumulative variance of 76. 32% (54.96% and 21.36%, respectively). While most species were dominant along a sediment gradient of sand, silt, and fine sand, distinct preferences for *H. ovalis*, *T. hemprichii*, and *C. rotundata* densities were observed. *H. ovalis* showed higher shoot densities in sandy substrata mixed with clay. It also occurred sparsely around the fringes of coral reefs in subtidal meadows (Figure 3). *H. decipiens* and *H. minor* displayed a strong preference for sandy habitats. *H. beccarii* was observed as a one-time occurrence in a muddy substratum, occupying fine sand mixed with mud near the high tide edges of Pokkadera (Site 18; Figure 1). *E. acoroides* and *S. isoetifolium* were positively associated with fine sand, while *Halodule* spp. was predominantly observed in silt. *T. hemprichii*, *C. rotundata*, and *C. serrulata* favored heterogeneous habitats consisting of sand, rock, dead coral with macroalgae, and rubble across all sites (Figure 3). However, there were differences in microhabitat preferences among these species. *T. hemprichii* densities correlated with coarse sand mixed with rubble, while *C. rotundata* was found in coarse sand as random sparse stands interspersed within the rubble, dead coral with macroalgae, and rocks. Additionally, *C. rotundata*, along with *C. serrulata*, also preferred fine sand in shallow waters or the upper edges of intertidal zones (Figure 3).

3.5 Factors influencing seagrass distribution and meadow characteristics

We used multiple regression models to examine factors influencing seagrass distribution and meadow characteristics

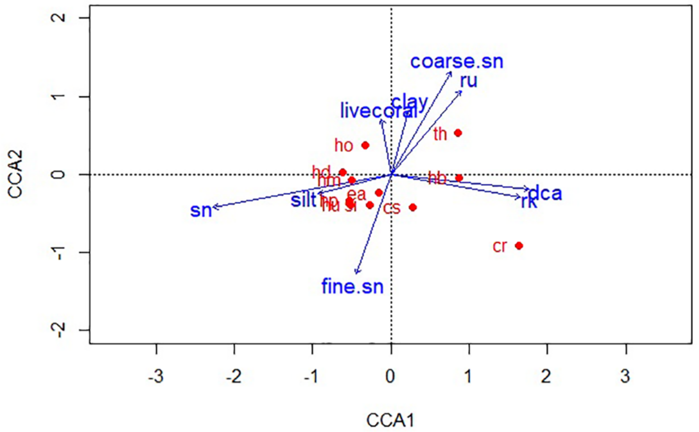

FIGURE 3
Canonical Correspondence Analysis ordination showing the influence of habitat profile and sediment texture on seagrass species' shoot densities (sn, sand; fine.sn, fine sand; rk, rock; DCA, dead coral with macroalgae; coarse. sn, coarse sand; ru, rubble; cr, *Cymodocea rotundata*; cs, *Cymodocea serrulata*; ea, *Enhalus acoroides*; hb, *Halophila beccarii*; hd, *Halophila decipiens*; hm, *Halophila minor*; ho, *Halophila ovalis*; hp, *Halodule pinifolia*; hu, *Halodule uninervis*; si, *Syringodium isoetifolium*; th, *Thalassia hemprichii*).

(seagrass occurrence, cover, biomass, and shoot densities). Water depth and sand (except shoot densities) were the key environmental variables significantly predicting all response variables. Seagrass occurrence was found to decline with water depth (*p*=3.72e-15), as well as the presence of dead coral with macroalgae (*p*=<2e-16) and rubble (*p*=3.88e-10) (Figures 4A–C; Table 3). However, the presence of sand showed a positive association with seagrass occurrence (*p*- < 2e-16; Figure 4D, Table 3). Water depth exhibited a similar correlation with seagrass cover (β = -0.2759; SE= 0.02471; *p*= <2e-16), shoot densities (β = -0.3556; SE= 0.1231; *p*- 0.005) and biomass (β= -0.3526; SE= 0.1159; *p*=0.003). These variables decreased from littoral zones to deep waters (Figures 5A–C; Table 4). On the other hand, seagrass cover (β = 0.2924; SE= 0.03124; *p*- <2e-16) and biomass (β = 0.295; SE= 0.1171; *p*- 0.01) showed a positive relationship with the availability of sand (Figures 6A, B; Table 4). Furthermore, seagrass cover and biomass exhibited a positive correlation with the presence of epiphytic algae (β= 0.136, SE= 0.0244, p =<2e-16) and water temperature respectively (β= 0.4235, SE= 0.1103, p =0.0002) (Figures 6C, D; Table 4). Lastly, we observed a peak in seagrass biomass at approximately 2.5 m depth, with the highest coverage and shoot densities recorded up to 5 m depth (Figures 7A–C).

4 Discussion

The spatial diversity, distribution, and growth of seagrasses in the explored meadows are primarily determined by water depth, habitat heterogeneity, and substrate availability. Our findings reveal significant variations in species richness between intertidal/shallow and deepwater meadows, with the former habitats supporting higher species (10) than the latter (4). All 11 observed species were found up to a depth of 5 m, either in mono-species or mixed meadows. Beyond this depth, the species composition shifted toward exclusive dominance of *Halophila* spp. and *Halodule* spp. Complex, with *Halophila ovalis* and *H. decipiens* marking the deepest recorded seagrasses from our study area (ANI), reaching depths of 21 m. While the general depth limits for Indo-tropical seagrasses are commonly less than 10 m (Short et al., 2007), our findings, along with regional studies from Hervey Bay and Cape York (Queensland), the Red Sea, and the Mediterranean Sea, indicate region-specific deepwater trends (Den Hartog, 1971; Lee Long, 1996; Short et al., 2007). *Halophila* spp. has been recorded from depths of 50 m in the tropical Atlantic region, 70 m in the Red Sea (Short et al., 2007), and 90 m in the Coral Sea (Den Hartog, 1971) highlighting the species' adaptability to deeper regimes.

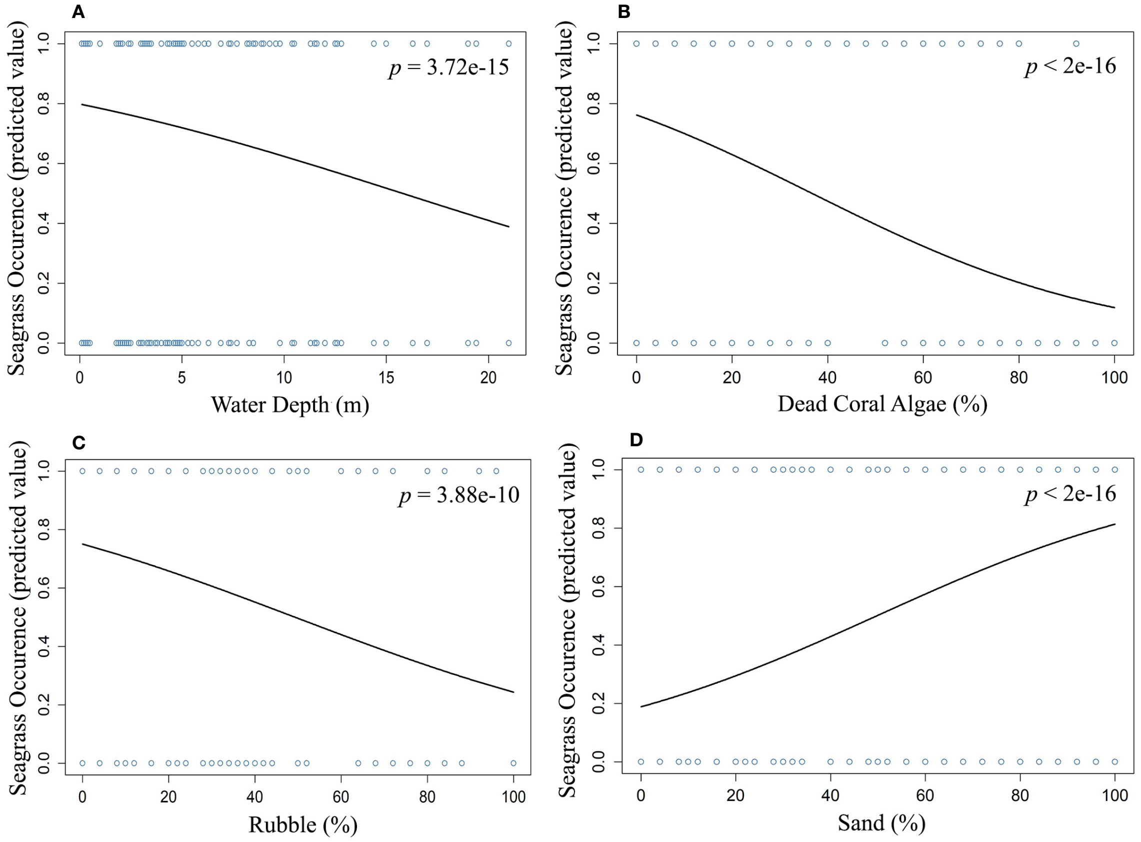

FIGURE 4
Influence and nature of the relationship between seagrass occurrence and **(A)** water depth, **(B)** dead coral with algae, **(C)** rubble, and **(D)** sand.

TABLE 3 Summary of logistic linear models used to identify key explanatory variables influencing seagrass occurrence in the Andaman and Nicobar Islands, India.

Sr. No.	Model combination	AIC	Loglik	p values		
1	seagrass occurrence vs sand	1566.404	-781.1982 (df=2)	< 2e-16 ***		
2	seagrass occurrence vs dead coral algae	1682.356	-839.1738 (df=2)	<2e-16 ***		
3	seagrass occurrence vs water depth	1723.925	-859.9586 (df=2)	3.72e-15 ***		
4	seagrass occurrence vs rubble	1745.774	-870.8831 (df=2)	3.88e-10 ***		
5	seagrass occurrence vs salinity	1765.806	-880.8991 (df=2)	6.12e-06 ***		
6	seagrass occurrence vs pH	1767.476	-881.7339 (df=2)	1.89e-05 ***		
7	seagrass occurrence vs temperature	1781.31	-888.6509 (df=2)	0.025623 *		
8	seagrass occurrence vs epiphytic algae	1782.1	-889.0459 (df=2)	0.0454 *		
9	Intercept model	1784.224	-891.1107 (df=1)			
10	seagrass occurrence vs non-epiphytic algae	1786.223	-891.1073 (df=2)	0.935		
Sr. No.	**Additive Models**	**AIC**	**AIC delta**	**AIC weights**	**Loglik**	**McFadden's R**
1	**seagrass occurrence vs. water depth+ dead coral algae+rubble+sand**	**1421.8**	**0**	**0.65**	**-705.4889 (df=6)**	**0.21**
2	seagrass occurrence vs. water depth+ dead coral algae+rubble+sand+epiphytic algae	1423.0	1.5	0.30	-705.4889 (df=6)	0.21
3	seagrass occurrence vs. water depth+ ph+temperature+salinity+dead coral algae +rubble+sand+epiphytic algae	1426.4	5.2	0.05	-704.2162 (df=9)	0.21

*Indicate significant p values.
Model in bold denotes selected best-fit model.

Additionally, *H. decipiens* has been reported from 58 m in the Great Barrier Reef (Lee Long, 1996), while *H. ovalis* is commonly observed beyond 35 m (Coles et al., 2000). The deepest recorded seagrass sample to date is a one-time dredged sample of *H. stipulacea* from 145 m (Lipkin et al., 2003; Short et al., 2007). Our findings are thus, consistent with global evidence, supporting the notion that *Halophila* spp. and *Halodule* spp. are adaptive to depths.

Although our observed depth-scaled distribution trends are consistent with previous local and regional assessments from ANI and mainland India (Das, 1996; Jagtap, 1996; Jagtap, 1998; D'Souza et al., 2015),we report some stark contrast for few species' regional colonization depths. For instance, Jagtap et al. (2003) reported *Thalassia hemprichii* and *Cymodocea serrulata* from a depth range of 0-10 m in Southeast India, as opposed to restricted littoral distribution in our study (with one-time observations from 2.5 m and 5 m, respectively). Similarly, the compensation depth of *Halodule uninervis*, one of the deepest species from our sites (15 m), was 3 m from Tamil Nadu (Jagtap et al., 2003). We speculate these differences to be driven by local variation in the physical environment of the two regions. Palk Bay and the Gulf of Mannar in Tamil Nadu have a shallow continental shelf, a vast seagrass expanse (often 5 to 10 km from the shore), and a tidal amplitude of around 0.3 to 0.5 m (Geevarghese et al., 2018). In contrast, in ANI habitat discontinuity, narrow shelf and sharp depth slopes (a few meters from the shore), results in irregularity in seagrass distribution (Das, 1996; Geevarghese et al., 2018). Considering the limited physical variation in Tamil Nadu, water depth likely plays a lesser role as a regulatory variable in shaping seagrass species distribution. Nevertheless, in ANI, we propose that water depth favors certain adaptive species over others, thus influencing the colonization depths of seagrasses (Lee et al., 2007; Short et al., 2011).

In our study, furthermore, we suggest that water depth not only regulates the species distribution ranges, but also the plant growth. Overall, seagrass coverage, shoot densities, and community biomass declined in deep waters (critical limit between ~ 2 to 5 m) consistent with reports from other geographic regions such as the Southeast coast, insular Lakshadweep (Jagtap, 1996; Jagtap, 1998), north-western Cuba (Buesa, 1975), and from the Mediterranean Sea

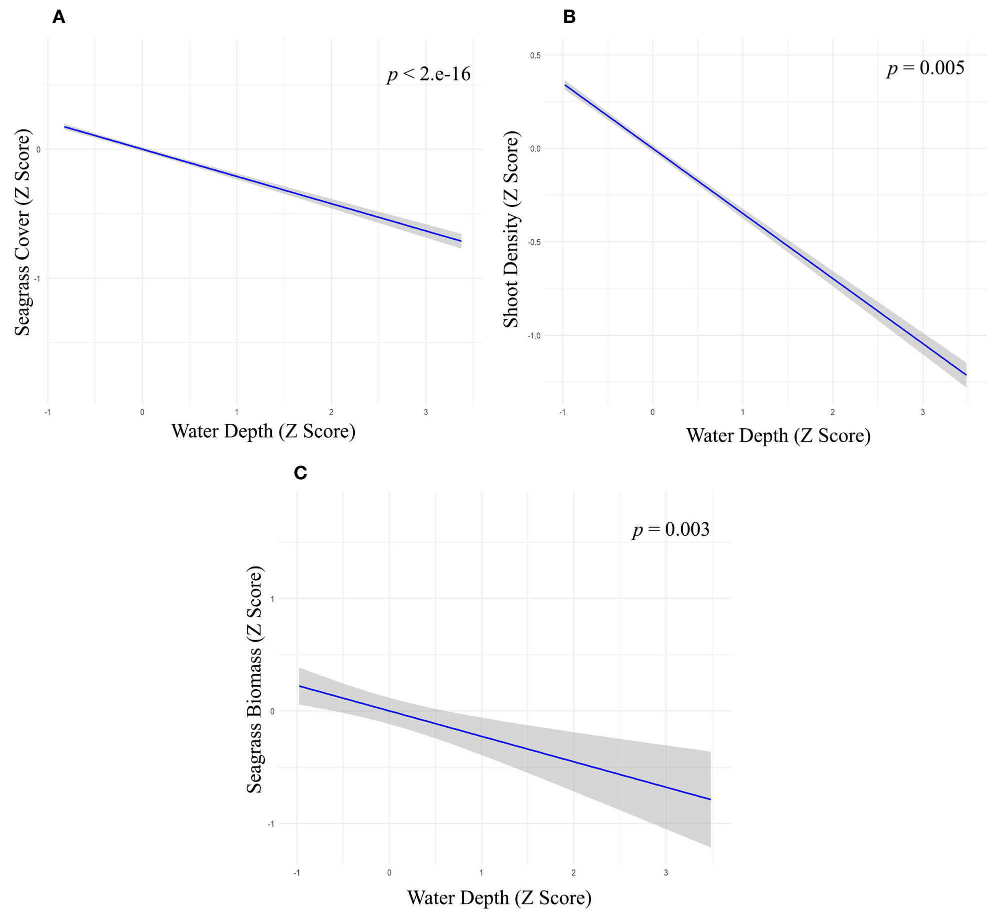

FIGURE 5
Relationship between water depth with **(A)** seagrass cover (Z-score values), **(B)** shoot density (Z-score values) and **(C)** seagrass biomass (Z-score values).

(Drew, 1978). As light attenuates strongly in deeper waters, the observed variations are a possible outcome of differential traits of seagrasses to adapt to depths (Lee et al., 2007; Short et al., 2011; Minguito-Frutos et al., 2023). Seagrass depth penetration and growth are directly influenced by light availability (Zieman and Wetzel, 1980; Duarte, 1991), owing to which conducive growth environment declines in the subtidal regions (Dennison and Alberte, 1987). Within similar environmental conditions, species-specific variation in colonization depths is a response to range of factors such as plant architecture, growth strategies, physiological responses, and acclimation potential (Dennison et al., 1993; Alcoverro et al., 2001; Greve and Binzer, 2004; Bité et al., 2007; Silva et al., 2013; Kilminster et al., 2015; Schubert et al., 2018; Tuya et al., 2019). A synthesis of the seagrass-water depth relationship indicates that seagrasses restrict their rhizome development in deeper regimes, with subsequent growth reduction (Duarte, 1991). This ability further is highly pronounced in pioneer, small-sized species with fast recolonization rates allowing them to cope up in deeper regimes. For instance, *Halophila* spp. and *Halodule* spp. can more efficiently regulate their respiratory demands in depths than large-sized seagrass species (Fourqurean et al., 1995). Therefore, deep water colonization of *Halophila* and *Halodule* species complex in our study could be accounted for higher acclimation potentials at greater depths (Minguito-Frutos et al., 2023). Since light attenuation is not the only predictor of depth distributions (Koch, 2001), in way forward, it would be critical to understand the fine-scale mechanisms which allow dominance of one species over the other across depth regimes.

Additionally, seagrass distribution is a product of habitat heterogeneity and substratum suitability from the sampled meadows. Heterogeneous habitats in the islands support a higher species richness (Das, 1996; Savurirajan et al., 2018). Our study reveals that variabilities in substratum types and habitat heterogeneity allow different species to dominate various spatial niches. Meadows with less substratum variability, such as those found in Little Andaman, Burmanallah, Laxmanpur, and Natural Bridge, had a vast extent but supported lower species richness. Our investigation of sediment texture affinities of seagrass species partially agrees with a previous study in the region by Savurirajan et al. (2018), which also reported high densities of *H. ovalis* in sand and clayey substrates. However, we observed *T. hemprichii*, *E. acoroides*, and *Halodule pinifolia* occupying coarse sand, fine sand, and silt, respectively, contrary to their preference for clayey sand in the previous study. It is important to note that the study by Savurirajan et al. (2018) focused on intertidal waters (< 2 m), while our study spanned depths up to 21 m. Therefore, the differences in

TABLE 4 Summary of gaussian model-averaged coefficients (full average) explaining influence of each explanatory variable on seagrass cover, biomass and shoot densities.

Quantitative response variable	Predictor variables	Estimate	Std. Error	Adjusted SE	z value	Pr(>|z|)
Seagrass cover	(Intercept)	2.13E-10	2.37E-02	2.38E-02	0	1
	Water depth	-2.76E-01	2.47E-02	2.47E-02	11.156	<2e-16 *
	Sand	2.92E-01	3.12E-02	3.13E-02	9.354	<2e-16 *
	Epiphytic Algae	1.36E-01	2.44E-02	2.44E-02	5.57	<2e-16 *
	Temperature	3.17E-02	3.05E-02	3.05E-02	1.036	0.3
	pH	3.33E-02	3.00E-02	3.00E-02	1.109	0.267
	Non-Epiphytic Algae	1.26E-02	2.16E-02	2.16E-02	0.58	0.562
	Dead Coral Algae	-1.06E-02	2.38E-02	2.39E-02	0.443	0.658
	Rubble	8.26E-03	1.98E-02	1.98E-02	0.418	0.676
	Salinity	-1.66E-02	2.48E-02	2.49E-02	0.667	0.505
Seagrass biomass		**Estimate**	**Std. Error**	**Adjusted SE**	**z value**	**Pr(>|z|)**
	(Intercept)	3.50E-11	1.08E-01	1.10E-01	0	1
	Sand	2.95E-01	1.17E-01	1.19E-01	2.47	0.013521 *
	Temperature	4.24E-01	1.10E-01	1.13E-01	3.764	0.000167 *
	Water depth	-3.53E-01	1.16E-01	1.18E-01	2.984	0.002849 *
	Epiphytic algae	2.08E-02	6.82E-02	6.92E-02	0.301	0.763477
Seagrass shoot densities		**Estimate**	**Std. Error**	**Adjusted SE**	**z value**	**Pr(>|z|)**
	(Intercept)	5.78E-11	1.16E-01	1.18E-01	0	1
	Water depth	-3.56E-01	1.23E-01	1.25E-01	2.837	0.00456 *
	Salinity	4.84E-02	9.77E-02	9.86E-02	0.491	0.62343
	Sand	3.94E-02	9.14E-02	9.24E-02	0.426	0.66981
	Dead Coral Algae	-1.13E-02	5.18E-02	5.24E-02	0.215	0.82941
	Epiphytic algae	9.00E-03	4.68E-02	4.74E-02	0.19	0.84951

*Indicate significant p values.
(Model-averaging pre-criterion= AIC delta < 2).

spatial scale and sample sizes may contribute to the variations in results between the two studies. Additionally, we suggest that habitat and substratum profiles change from intertidal to deeper waters, limiting direct comparisons. In addition, the absence of *H. decipiens* from the intertidal regions is in line with the same report from South Andaman (Savurirajan et al., 2018). Yet, contrary to this study, we report *C. serrulata* and *Syringodium isoetifolium* from the littoral zones (0.2 to 0.4 m) of Ritchie's archipelago and Little Andaman, updating the species' distribution ranges.

Lastly, despite the vast spatial scale of our study, we did not observe *H. ovata* from the ANI's seagrass checklist (12 species). Genus *Halophila*, with high taxonomic diversity, overlapping morphology, and phenotypic plasticity at local scales (Japar Sidik et al., 2010), has often led to species misidentification and systematic ambiguity (Fortes et al., 2018). The species was last reported in 2010 from ANI (Thangaradjou et al., 2010a; Thangaradjou et al., 2010b). A recent study (Ragavan et al., 2016) argued that *H. ovata* is a misidentified *H. minor* from all previous assessments in ANI. A similar report from Southeast Asia pointed to taxonomic discrepancies within *Halophila* spp., where the morphological resemblance between *H. ovata* and *H. minor* was "compounding" and has led to species misidentification (Fortes et al., 2018). Since all seagrass assessments in ANI have relied only on morphological traits for species identification, including our study, the possibility of misidentification cannot be ruled out. Thus, we suggest a more robust approach for species identification using molecular traits to resolve present inconsistencies.

4.1 Management recommendations

Based on our study findings, we propose the following recommendations for the effective management and conservation of seagrass ecosystems in the Andaman and Nicobar Islands (ANI):

4.1.1 Enhance legislative measures

The limited legislative measures safeguarding seagrass ecosystems in India include 1) recognition as ecologically

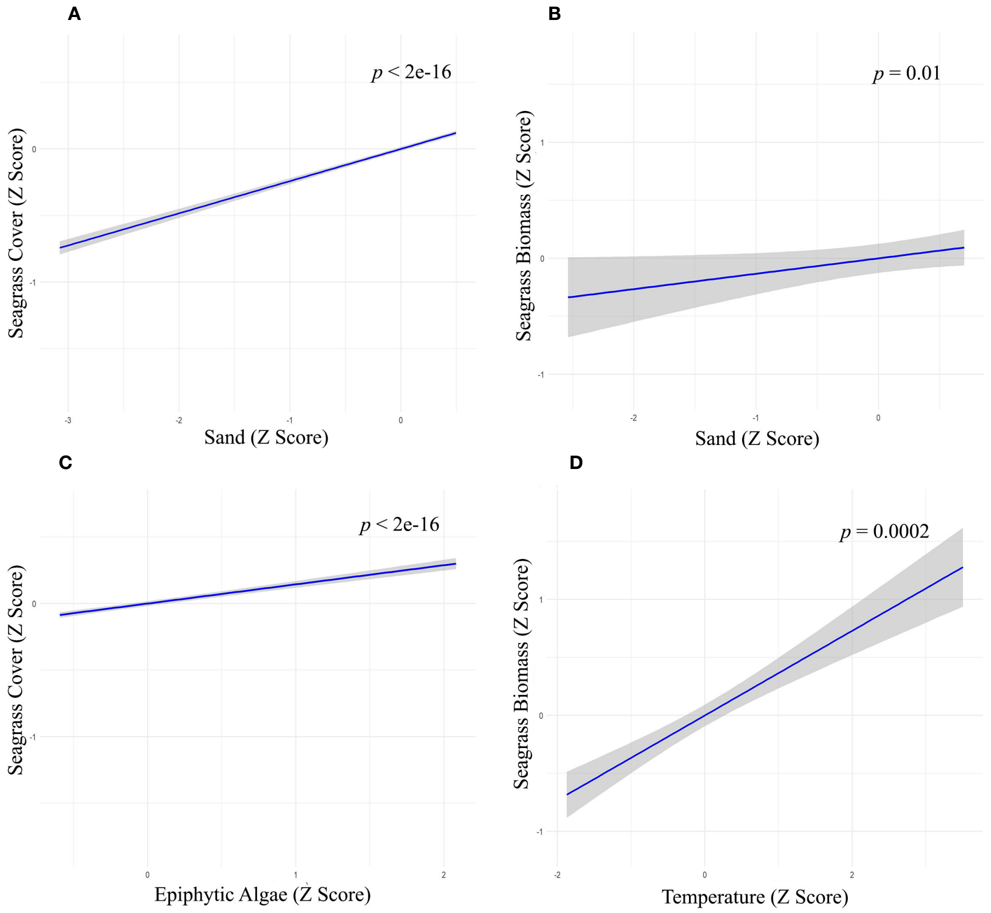

FIGURE 6
Relationship between Sand with **(A)** seagrass cover (Z-score values), **(B)** seagrass Biomass (Z-score values), **(C)** Epiphytic Algae on seagrass cover (Z-score values); **(D)** Water temperature on seagrass biomass (Z-score values).

sensitive habitats (Coastal Regulation Zone Category I; ICRZ Notification, 2021[6]) and 2) protection under the Indian Wildlife (Protection) Act (WLPA), 1972 (Ramesh et al., 2018). Seagrass ecosystems in the ANI are protected as one of the environmentally critical habitats under the Category IA of the Island Coastal Regulation Zone (ICRZ, 2019[7]). However, concerning are the revisions in the ICRZ 2019 of the Island Protection Zone Notification (2011) permitting eco-tourism and allied development in the ICRZ- IA (200 meters changed to 20-50 meters from the High tide line, ICRZ, 2019[8]), where majority of seagrasses fall. We thus recommend a top-down revised approach to strengthen the existing legislative framework to provide stronger protection for seagrass ecosystems.

4.1.2 Expand the Marine Protected Area (MPA) Network

Less than 20% of the seagrass meadows we studied are protected as MPAs in ANI. On the contrary, a recent review of the Southeast Asian seagrasses (Sudo et al., 2021) suggests that the subtropical Ryukyuan archipelago in Japan, with a coastline of 650 km (one-third of ANI) and half the geographical expanse (~ 4600 km^2) still protects more than 99% of their seagrass beds within its MPAs. The denoted figures shed light on the under-representation of seagrasses as valuable ecosystems that need protection in ANI. Within the remaining 80% of unprotected seagrasses in our study, which also includes the critical dugong habitats, the geographical remoteness of the islands (from human settlements) offers some level of natural protection.

However, these beds still fall on the geological fault lines of ANI, exposed to natural threats such as frequent cyclonic storms, earthquakes, and tsunamis, all known to impact seagrasses (Adulyanukosol and Poovachiranon, 2006; Sachithanandam et al., 2014). The rise in coastal development prospects in ANI is another matter of concern. It is likely to change seagrass ecosystems in the future, possibly with an aligning fate as reported from China (Jiang et al., 2020), Vietnam (Luong et al., 2012), Malaysia (Japar Sidik et al., 2018), and Europe (de los Santos et al., 2019), to name a few.

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[6] https://parivesh.nic.in/Notifications.aspx?id=CRZ/ (accessed on March 2023).

[7] http://www.indiaenvironmentportal.org.in/content/461888/icrz-notification2019/.

[8] https://environmentclearance.nic.in/writereaddata/SCZMAD ocument/ICRZ_Notification2019.pdf.

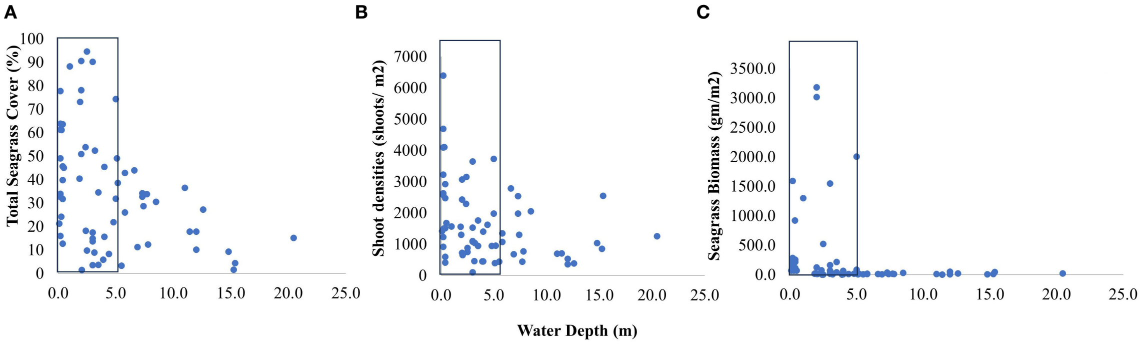

FIGURE 7
Response of seagrass growth; **(A)** seagrass cover, **(B)** shoot densities, and **(C)** biomass in relation to water depth; box indicates threshold depth limits with maximum values of response variables.

Thus, there is a need to extend the network of MPAs to encompass a larger portion of seagrass beds, ensuring the conservation of these critical ecosystems. We suggest increasing the coverage of Marine Protected Areas (MPAs) and enforcement, following a potential NEOLI approach (Edgar et al., 2014) to include a more significant proportion of seagrass meadows, especially those identified as critical dugong habitats.

4.1.3 Assess socio-ecological-economic services

Need to conduct comprehensive research to evaluate the socio-ecological-economic services provided by seagrasses (Rahman and Yaakub, 2020). Under the ecological context, this assessment should focus on lesser-known fauna, such as marine invertebrates, which are currently understudied in the region since seagrass research is largely dugong-centrical. We further suggest investigating local communities' perceptions and socioeconomic dependency on seagrass ecosystems. This should entail assessing the direct and indirect benefits of seagrasses, including their role in supporting fisheries, gleaning, shoreline protection, and tourism. Understanding the socioeconomic dynamics will inform policy and decision making (de la Torre-Castro et al., 2014; Campagne et al., 2015; Kilminster et al., 2015), along with developing sustainable management strategies that align with the needs and aspirations of local communities.

4.1.4 Quantify seagrass-centric threats

Though with a limited sample size, we observed increased sedimentation and subsequent mass die-off of coral reefs and enhanced turbidity in the seagrass beds from Shaheed Dweep and meadow-scarring in Swaraj Dweep, as a response to benthic dredging (for jetty construction) and boat anchorage respectively (personal observations). Nevertheless, these observations are mainly descriptive, lacking quantitative details of the damage or loss incurred. We, thus, suggest detailed studies to quantify the threats faced by seagrass meadows in ANI to inform policy-makers (Rahman, 2017). Assessment of the impacts of anthropogenic activities, such as dredging and boat anchorage, on seagrass health will help identify and develop targeted management strategies to minimize or mitigate these threats.

By implementing these recommendations, we can create a robust framework for the 'habitat-level' management and conservation of seagrass ecosystems in the Andaman and Nicobar Islands. Drawing from regional case studies (Fortes et al., 2018) and considering the unique context of ANI, these measures could be comprehensively put into a local-scale management perspective to create a roadmap for seagrass conservation for ANI.

5 Conclusion

Our study has provided updated information on the spatial distribution, habitat suitability, and depth ranges of seagrass meadows in the Andaman and Nicobar Islands (ANI). By conducting a comprehensive assessment across a broad spatial scale and depth gradients, we have filled significant data gaps in previously data-deficient regions of ANI. Our findings highlight key regulatory factors, such as water depth, influence seagrass growth, and species distribution. The observed differences in seagrass distribution along depth gradients can be attributed to various factors, including variations in covariates associated with water depth, species' adaptability to different depth regimes, and habitat heterogeneity and substratum availability, which also change with depth. Any alterations in the benthic habitat profile of these meadows are likely to impact species distribution patterns and overall performance. Our study suggests that *Halodule* spp. and *Halophila* spp. are generalist species, capable of occupying suitable habitats across different depth regimes, while larger-sized species like *Enhalus acoroides*, *Thalassia hemprichii*, and *Cymodocea* spp. exhibit specialist characteristics. The presence of seagrasses in deepwater regions of Ritchie's archipelago further confirms the availability of conducive growth environments in deeper regimes. Replicating similar investigations in other island groups would provide valuable insights to complement our findings. In summary, the outcomes of this study will have significant implications for the management and conservation of seagrass habitats in the region. The findings will provide valuable baseline information for policymakers, conservationists, and stakeholders and contribute to the broader scientific understanding of seagrass ecosystems and their responses to environmental changes.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

SG: conceptualization, data curation, sample processing, formal analysis, drafted the manuscript, SP: data curation, sample processing, NP: formal analysis, critical inputs in manuscript review, HD: methodology designing, supervision, manuscript review, SK and JJ: funding acquisition, methodology designing, resources, supervision, manuscript review. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fmars.2023.1251887/full#supplementary-material

ANNEXURE 1

Seagrass meadow characteristics of the 66 beds investigated from the Andaman and Nicobar Islands, India. Sites in bold indicate new meadow record. *Indicates new species distribution record for the region

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