



**Ecology of Seagrass Associated Fin Fishes And Conservation Perspectives Of Seagrass
Ecosystems In Palk Bay And Gulf Of Mannar, Tamil Nadu**

Thesis submitted for the award of the degree of

Doctor of Philosophy

in

WILDLIFE SCIENCE

by

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to

Saurashtra University

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DECLARATION

I, hereby, declare that the work conducted under this thesis titled “Ecology of Seagrass Associated Fin Fishes and Conservation Perspectives of Seagrass Ecosystems in Palk Bay and Gulf of Mannar, Tamil Nadu” 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. J.A. Johnson** of Wildlife Institute of India, Dehradun. 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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Ms Ghanekar Chinmaya Deepak 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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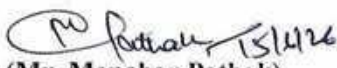
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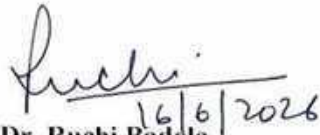
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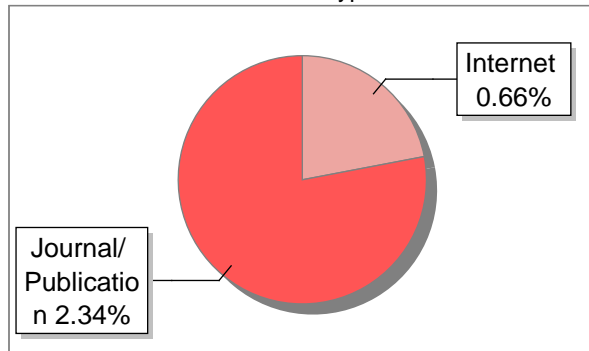
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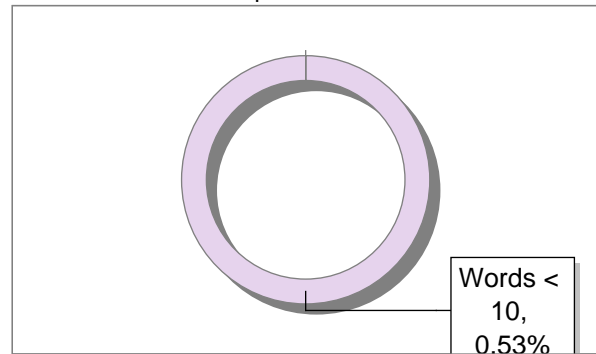
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1. **Ghanekar, C., Rajpurkar, S., Gokhale, T., Aggarwal, A., Sivakumar, K., & Johnson, J. A. (2026).** *Assessing anthropogenic pressures on seagrass ecosystems in India's first dugong conservation reserve. Journal of Wildlife Science* (Accepted for publication)
2. **Ghanekar, C., Sivakumar, K., & Johnson, J. A. (2026).** *Seagrass-dependent fisheries: Evaluating finfish productivity in Palk Bay, India* (Manuscript submitted for publication to *Journal of Coastal Conservation*).
3. **Ghanekar, C., Dudhat, S., Pande, A., Sivakumar, K., & Johnson, J. A. (2026).** *Comparative assessment of fish populations in seagrass habitats of the Andaman Islands* (Manuscript submitted for publication to *Journal of Applied Ichthyology*).

Conferences – National and International (Annexure 2)

1. **Ghanekar, C., Johnson, J. A., Sivakumar, K., Anant, P., Prem, J., Rukmini, S., & Madhu, M. (2018, October 4–6).** *Ecology of seagrass associated fin fish and provisioning services of seagrass ecosystems in Palk Bay and Gulf of Mannar, Tamil Nadu* [Poster presentation]. International Biodiversity Congress 2018, Forest Research Institute.
2. **Ghanekar, C. (2020, August 17–28).** *A study of seagrass habitat utilization by fishes in Palk Bay and Gulf of Mannar, India* [Poster presentation]. 6th International Marine Conservation Congress. Kiel, Germany.
3. **Ghanekar, C. (2023, April 9–11).** *Protecting the mermaids: Insights from the first Dugong Conservation Reserve of India* [Conference presentation]. Indian Conservation Conference 2023, Mysuru.

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1 Executive Summary

Seagrass meadows are among the most productive and ecologically significant coastal ecosystems that sustain marine biodiversity and human health as well. Seagrass meadows are particularly well-structured and provide habitat for many marine organisms. Their interaction with coral reefs, estuaries and coastal waters contributes to the functioning of whole seascapes. In addition to providing habitat, seagrass meadows are important for fisheries, protect coasts, stabilize sediment, and sustain millions of coastal people's lives. But with many of these benefits, seagrass ecosystems are in decline worldwide, which is a direct consequence of increasing anthropogenic pressures and their ability to sustain biodiversity and ecosystem services.

In India, Palk Bay and the Gulf of Mannar are among the most extensive and diverse seagrass meadows and are ecologically unique areas where biodiversity conservation and fisheries sustainability are linked. These ecosystems support threatened species such as the dugong and provide important fishing sites for coastal communities. But over time, fishing pressure, habitat degradation and other human-induced disturbances have made it hard to sustain them in the long term. Although research has been done on the distribution and composition of Indian seagrass meadows, the ecological processes that underlie the functioning of fish and ecosystems are poorly understood.

The current study aimed to fill these knowledge gaps by integrating the assessment of commercially important finfish diversity, resource partitioning, ecosystem services and anthropogenic threats into a single ecological framework with following objectives:

1. Assess the commercially important fin fish species associated with seagrass ecosystems in Palk Bay.
2. Document the resource (food and space) partitioning patterns among fin fish species associated with seagrass ecosystems
3. Evaluate ecosystem services provided by seagrass ecosystem with reference to commercial fin fish fishery.

4. Assess major threat posed by different fishing practices in seagrass ecosystem and provide option for conserving seagrass ecosystems.

Rather than focusing on these aspects in isolation, I investigated how they interact and contribute to the healthy functioning and resilience of seagrass ecosystems. Fish diversity, habitat complexity, ecological connectivity and ecosystem services are linked and it is suggested that disturbances affecting one component can affect the health and sustainability of the whole system. Thus, the synthesis in this chapter synthesizes the findings of the study and considers their relevance in the management of fisheries and biodiversity conservation and the sustainable management of seagrass ecosystems in Palk Bay and the Gulf of Mannar.

1. Commercially Important Finfish Species Associated with Seagrass Meadows

The first objective of the present study was to assess the commercially important finfish species associated with seagrass ecosystems of Palk Bay and the Gulf of Mannar and to understand the ecological factors influencing their distribution and habitat use. Although seagrass ecosystems are widely recognized as important fish habitats, information on commercially important finfish species associated with Indian seagrass meadows has remained limited. This investigation was therefore undertaken to document fish diversity, evaluate regional variation in fish assemblages, and examine the relationship between habitat characteristics and fish communities.

A combination of fish market surveys and underwater visual census techniques was employed to obtain a comprehensive understanding of seagrass-associated finfish diversity. Prior to ecological assessments, a comparison between belt transects and point count methods was carried out to standardize the sampling protocol. Both methods produced similar estimates of species diversity and evenness, but point counts recorded higher guild-wise fish densities and provided better opportunities for behavioural observations and size-class assessments. Based on these observations, point counts were adopted as the standard method for subsequent underwater surveys.

Fish market surveys conducted across the major landing centres of Palk Bay confirmed that seagrass ecosystems support a large number of commercially important fish species. A total of 161 fish species belonging to 58 families were found to be consistently associated with seagrass fishing grounds. Considerable variation was observed among fish markets, with larger landing centres recording greater species and family richness. These observations indicate that seagrass

ecosystems contribute substantially to local fisheries and support a diverse range of economically valuable species.

Underwater visual surveys further demonstrated the ecological importance of seagrass meadows. A total of 85 fish species representing 51 genera and 31 families were recorded during field observations. The Gulf of Mannar supported greater species richness and diversity than Palk Bay, while Palk Bay exhibited higher species dominance. Family-wise composition also differed between the two regions, with reef-associated families being more abundant in the Gulf of Mannar and estuarine and shallow-water associated families showing greater representation in Palk Bay. These differences suggest that local habitat characteristics and connectivity with surrounding ecosystems strongly influence fish assemblages.

The analyses of community composition indicated that a relatively small number of species contributed substantially to the differences between the two regions. Species such as *Terapon puta* and *Siganus* spp. emerged as important contributors to regional dissimilarity, suggesting that changes in the abundance of key taxa may significantly influence community structure.

Environmental analyses showed that seagrass height, seagrass cover, water depth, coral cover and substrate composition were important factors determining fish distribution. Species exhibited distinct associations with particular habitat characteristics, indicating that habitat heterogeneity plays an important role in structuring seagrass-associated fish communities. The results also emphasize that seagrass meadows function as part of a larger coastal seascape where interactions with coral reefs, sandy bottoms and estuarine habitats influence the organization of fish populations.

One of the important findings of this objective was the strong evidence supporting the nursery function of seagrass ecosystems. Juvenile and sub-adult fishes occurred at higher densities within seagrass habitats than in adjacent non-seagrass areas across almost all habitat and feeding guilds. The predominance of younger life stages suggests that seagrass meadows provide shelter, feeding opportunities and favourable conditions for growth and survival during critical phases of the fish life cycle. Many commercially important species therefore appear to depend on these habitats before recruiting to adult populations.

The assessment of feeding and habitat guilds further demonstrated that seagrass ecosystems support a broad range of ecological functions. Carnivorous, herbivorous, omnivorous, benthivorous and planktivorous fishes were all represented within the meadows, reflecting the

diversity of food resources available in these habitats. Similarly, the occurrence of estuarine, reef-associated, sandy habitat and strictly seagrass-associated fishes indicates that these ecosystems support species with varied habitat requirements and ecological strategies.

The study also highlighted the ecological connectivity between seagrass meadows and adjacent coastal ecosystems. Reef-associated juvenile fishes constituted a major component of the observed assemblage, while many species were associated with multiple habitat types across different depth zones. These findings indicate that seagrass meadows act as ecological corridors linking coral reefs, estuaries and coastal waters and contribute to the maintenance of biodiversity across the wider seascape.

Overall, the first objective demonstrates that seagrass ecosystems of Palk Bay and the Gulf of Mannar support a rich assemblage of commercially important finfish species and play a crucial role in maintaining coastal fisheries. Habitat complexity, environmental gradients and connectivity with adjacent ecosystems strongly influence fish diversity and community composition, while the high abundance of juvenile fishes emphasizes the nursery value of these habitats. The findings establish that conservation of seagrass ecosystems is important not only for preserving biodiversity but also for sustaining fisheries productivity and the livelihoods dependent upon these resources.

The documentation of fish diversity and habitat associations provides the ecological basis for the subsequent objective of the study, which examines how numerous species coexist within seagrass meadows through the partitioning of food and spatial resources. Understanding these ecological interactions is essential for explaining the mechanisms that maintain fish diversity and ecosystem stability in tropical seagrass habitats.

2. Resource (Food and Space) Partitioning among Seagrass-associated Commercial Finfishes

The second objective of the present study aimed to understand how commercially important finfish species coexist within the seagrass ecosystems of Palk Bay and the Gulf of Mannar by examining patterns of habitat use and food resource utilization. Since numerous fish species occupy the same seagrass meadows, understanding the mechanisms that reduce competition is essential for explaining the maintenance of biodiversity and the ecological functioning of these habitats.

The assessment of habitat use demonstrated that seagrass ecosystems are highly heterogeneous environments, offering a range of microhabitats that differ in seagrass density, canopy height, substrate type and depth. Fish species did not utilize these habitats uniformly but exhibited distinct habitat preferences. Some species were closely associated with dense seagrass meadows, while others preferred sparse habitats, sandy bottoms or reef-associated areas. This indicates that habitat heterogeneity plays a significant role in structuring seagrass-associated fish communities. Behavioural observations revealed that seagrass meadows perform multiple ecological functions, serving as feeding grounds, refuge areas and movement corridors. Differences in behavioural activities between Palk Bay and the Gulf of Mannar suggest that habitat complexity and local environmental conditions influence how fishes utilize available resources. The analysis of vertical habitat use further showed that species occupied different levels within the seagrass canopy and adjacent substrates, reducing direct spatial competition. The evaluation of habitat niche breadth and habitat overlap demonstrated the coexistence of both habitat specialists and habitat generalists. Species with broad niche breadths exploited a variety of habitats and exhibited greater ecological flexibility, whereas species with narrow niche breadths depended on specific habitat conditions. Similarly, habitat overlap analyses indicated that although some species shared common habitats, others exhibited clear spatial segregation, suggesting that multiple strategies contribute to coexistence within seagrass ecosystems.

Gut content analysis provided additional evidence for resource partitioning. The commercially important species examined displayed contrasting feeding strategies, with some exhibiting broad and opportunistic diets while others specialized on particular prey groups such as crustaceans. These differences in food utilization reduce trophic competition and allow species occupying similar habitats to exploit different components of the available food resources.

The combined assessment of habitat use and feeding ecology indicates that food and space partitioning operate simultaneously within seagrass ecosystems. Species sharing similar habitats often consume different prey, whereas species utilizing similar food resources frequently occupy different microhabitats. Such multidimensional partitioning allows a large number of commercially important finfish species to coexist within relatively small areas and contributes to the high biodiversity observed in tropical seagrass meadows.

The findings also highlight the importance of habitat complexity and seascape connectivity in maintaining ecological stability. The presence of both habitat specialists and generalists

suggests that structurally diverse seagrass meadows enhance ecosystem resilience by supporting species with different ecological requirements. At the same time, the close association of many fishes with adjacent coral reefs and sandy habitats indicates that seagrass ecosystems function as integral components of larger coastal landscapes. From a conservation perspective, the maintenance of habitat heterogeneity is essential for sustaining fish diversity and fisheries productivity. Simplification of habitat structure through seagrass degradation, destructive fishing practices or coastal disturbances may disproportionately affect specialized species and alter community composition. The protection of diverse seagrass habitats and their ecological connectivity is therefore important for conserving biodiversity and supporting commercially important fisheries. Overall, the investigation of food and space partitioning demonstrates that the high diversity of seagrass-associated commercial finfishes is maintained through a combination of habitat specialization, ecological flexibility and trophic differentiation. These ecological interactions provide a deeper understanding of the mechanisms supporting fish diversity in seagrass ecosystems and establish the basis for the subsequent objective of the study, which evaluates the ecosystem services and fisheries benefits provided by these habitats.

3. Ecosystem Services Provided by Seagrass Meadows with reference to Fisheries

The third objective of the present study was to evaluate the ecosystem services provided by seagrass meadows in Palk Bay and the Gulf of Mannar, with particular emphasis on their contribution to commercial finfish fisheries and coastal livelihoods. Although seagrass ecosystems are widely recognized for their ecological importance, quantitative information on their economic value and their role in supporting fisheries in the Indian context remains limited. The present investigation therefore integrated community perception surveys, fish market assessments and economic valuation approaches to understand the direct and indirect benefits derived from seagrass ecosystems.

Questionnaire surveys conducted across coastal villages demonstrated that local fishing communities strongly associate seagrass meadows with fisheries productivity. All respondents identified seagrass habitats as important fishing grounds, highlighting their direct role in supporting livelihoods. In addition to this primary function, respondents recognized the importance of seagrass meadows as breeding grounds, nursery habitats, feeding areas and shelter for commercially important marine species. These observations indicate that coastal

communities are closely dependent on the ecological integrity of seagrass ecosystems, although awareness of their broader ecosystem functions varies among stakeholders.

Fish market surveys provided direct evidence of the economic contribution of seagrass-associated fisheries. The market structure in Palk Bay was characterized by a locally organized value chain involving fishers, market managers, retail vendors and consumers. The majority of fish entering local markets originated from nearby fishing grounds, demonstrating a close relationship between seagrass habitats and coastal economies. The relatively short supply chain emphasizes the importance of seagrass ecosystems in sustaining local food security and generating income for small-scale fishing communities.

The analysis of target catch composition revealed that seagrass-associated fisheries support a wide range of commercially important resources, including finfishes, crabs, prawns and other marine organisms. Finfish and crabs together constituted the major share of the catch, reflecting the importance of seagrass meadows as habitats for benthic and demersal species. Fish prices varied considerably among taxonomic groups, with a small number of high-value families contributing disproportionately to market returns. Such variations indicate that species composition and habitat quality have a direct influence on the economic value generated by seagrass ecosystems.

Significant spatial variation was also observed among fish markets. Average fish prices differed across the surveyed markets, suggesting that local demand, species availability and market dynamics influence economic returns from seagrass-associated fisheries. Similarly, differences in fishing technology affected market value, with mechanized vessels generally realizing higher prices than motorized boats. These findings demonstrate that ecological productivity and socioeconomic factors jointly determine the benefits derived from seagrass ecosystems.

The economic valuation undertaken for the Dugong Conservation Reserve highlighted the substantial contribution of seagrass habitats to local fisheries. Based on conservative estimates of fish catch and market prices, seagrass-dependent fisheries were found to generate considerable annual income for fishing communities. The estimated fisheries production value per unit area emphasizes that seagrass meadows function as productive natural assets that provide measurable economic benefits. The findings therefore strengthen the argument that

seagrass conservation should be considered an investment in sustaining fisheries and coastal livelihoods.

Beyond their direct provisioning value, the study also recognized the importance of supporting and regulating ecosystem services. Nursery functions, habitat provision, trophic support, nutrient cycling and the maintenance of ecological connectivity contribute indirectly to fisheries productivity and ecosystem resilience. These services are not fully reflected in market valuations but are essential for the long-term sustainability of coastal fisheries.

The study also identified several limitations associated with ecosystem service valuation. The estimation of fisheries value relied on assumptions regarding habitat dependence, fishing effort and market prices, and did not incorporate many indirect or non-market ecosystem services. In addition, several commercially important species utilize multiple coastal habitats during their life cycle, making it difficult to attribute their total economic value exclusively to seagrass ecosystems. Future studies incorporating habitat residency indices and integrated ecosystem accounting approaches would improve the accuracy of economic assessments.

Overall, the third objective demonstrates that seagrass meadows are important ecological and economic resources that sustain fisheries, support coastal livelihoods and contribute to local food security. Their value extends beyond the direct harvest of commercially important species and includes a range of ecological processes that maintain fisheries productivity over time. The findings highlight the need to integrate ecosystem service valuation into fisheries management and coastal planning and provide the basis for the subsequent objective of the study, which examines the anthropogenic pressures affecting seagrass ecosystems and their implications for long-term conservation and sustainable resource use.

4 Anthropogenic Threats to Seagrass Ecosystems and Conservation Measures

The fourth objective of the present study was to identify the major anthropogenic threats affecting seagrass ecosystems in Palk Bay and the Gulf of Mannar and to develop appropriate conservation measures for the long-term protection of these habitats. To achieve this, field observations, point count surveys, aerial surveys and community-based interviews were integrated to assess the nature, distribution and intensity of human-induced disturbances in seagrass ecosystems.

Field observations identified fishing activities as one of the most widespread threats to seagrass meadows. Point count surveys recorded large numbers of mechanized and motorized fishing

vessels operating within shallow coastal waters, with small fishing boats being the dominant craft observed across seasons. Netting activity was particularly prominent during the monsoon season, indicating increased fishing pressure during this period. These findings suggest that fishing operations are closely associated with seagrass habitats and may increase the likelihood of habitat disturbance.

The assessment of floating litter revealed that marine pollution is another significant threat to seagrass ecosystems. Oil films constituted nearly half of all floating litter observations, while fishing gear fragments, plastic cans, bottles and other synthetic materials were also commonly encountered. Oil pollution was particularly evident near fishing harbours and landing centres, indicating the influence of fishing and vessel-related activities on coastal environmental quality.

Community perception surveys conducted across 40 coastal villages showed that awareness of seagrass ecosystems remains limited. A majority of respondents were unfamiliar with the distribution of seagrass meadows, although some recognized changes in habitat condition over time. Fishers identified both natural factors, such as cyclones and water currents, and anthropogenic activities, including trawling, drag netting and mariculture, as potential causes of seagrass decline. These observations highlight the need for greater public awareness regarding the ecological importance of seagrass habitats.

The documentation of fishing gears demonstrated the wide variety of fishing practices operating in the study area and their potential impacts on seagrass ecosystems. Drift gillnets, set gillnets, encircling gillnets, hook-and-line systems, bottom trawls and beach seines were all recorded. Bottom-contact gears such as drag nets, beach seines and trawl nets were identified as having the greatest potential to damage seagrass habitats through repeated contact with the seabed, causing shoot removal, rhizome breakage and sediment disturbance.

Anchoring activities were also identified as an important source of habitat modification. Multi-spike anchors were the most commonly used anchoring systems within the Dugong Conservation Reserve, suggesting repeated physical disturbance of shallow seagrass habitats through anchor penetration and dragging. Such disturbances may create fragmented patches within continuous seagrass meadows and reduce habitat quality.

The bycatch assessment demonstrated that fishing activities affect a broad range of non-target organisms. Sea turtles, seahorses, sea cucumbers, starfish and seagrass were among the

materials recorded in bycatch. The occurrence of seagrass itself in fishing gear indicates direct interaction between fishing operations and benthic habitats, while the incidental capture of protected and ecologically important species highlights broader ecosystem impacts associated with fishing practices.

Aerial surveys revealed clear regional differences in anthropogenic pressure between Palk Bay and the Gulf of Mannar. Boat-related activities were the dominant threat in Palk Bay, whereas litter was the major threat observed in the Gulf of Mannar. Overall threat density was significantly higher in Palk Bay, where the average number of threats recorded per transect was nearly twice that observed in the Gulf of Mannar. Fishing infrastructure, vessel movements and seaweed culture installations contributed substantially to this increased pressure.

The study further demonstrated that the composition of threats differs between the two regions. Palk Bay was characterized by intensive fishing activities and associated infrastructure, while the Gulf of Mannar was more strongly affected by marine litter accumulation. These findings indicate that seagrass ecosystems experience region-specific pressures and that conservation strategies should be adapted to local conditions.

Based on these observations, several conservation measures were identified. The regulation of destructive fishing gears, promotion of low-impact fishing practices and establishment of seagrass-sensitive anchoring zones were recognized as important steps for reducing physical habitat damage. Improvements in waste management, retrieval of abandoned fishing gear and reduction of marine litter were also identified as priorities for maintaining habitat quality. In addition, the implementation of bycatch reduction measures and regular monitoring programmes would help minimize impacts on non-target species and sensitive ecosystems.

The study also emphasized the importance of community participation in seagrass conservation. Awareness programmes, community-based monitoring and greater involvement of local stakeholders in habitat management can strengthen conservation efforts and improve long-term stewardship of coastal resources.

Overall, the fourth objective demonstrates that seagrass ecosystems in Palk Bay and the Gulf of Mannar are exposed to multiple anthropogenic pressures, with fishing activities, marine litter, anchoring and incidental bycatch representing the principal threats. The findings highlight the need for integrated management approaches that combine habitat protection,

sustainable fisheries practices and community participation to ensure the long-term conservation of seagrass ecosystems and the ecological and economic benefits they provide.

This thesis has shown that seagrass meadows in Palk Bay and Gulf of Mannar are multi-faceted ecosystems that support biodiversity, fisheries and coastal communities. Fish diversity assessment has proven that these habitats support an extensive range of economically important species and they are nursery sites. Food and space partitioning analysis has also shown that habitat heterogeneity and ecological specialization are key to keeping species alive and healthy. The ecosystem service assessment has shown that the ecological benefits of seagrass meadows translate to economic ones through fisheries and local food security. At the same time, the anthropogenic threats in fisheries, marine litter, anchoring and habitat disturbance can reduce these ecological and economic benefits if not managed.

Together, these findings indicate that seagrass ecosystem conservation can't be accomplished by preserving habitat alone. Complexity, connectivity and natural ecosystem processes in the environment must be maintained in all environments if biodiversity and fisheries production are to sustain. Conservation strategies then need to be based on ecosystem-based conservation, and the protection of habitat should be integrated with sustainable fisheries management and coastal communities should be in partnership with healthy seagrass ecosystems.

The results also emphasize that fisheries management and seagrass conservation should not be regarded as separate objectives. The long-term productivity of commercially important fish populations depends on nursery habitats and the ecological processes supported by seagrass meadows. Management interventions should therefore promote low-impact fishing, limit activities that may damage seagrass habitat and protect ecologically important sites where juvenile fishes and habitat specialists live. It should also be a key component of marine spatial planning to maintain the ecological connectivity between seagrass meadows, coral reefs and adjacent coastal habitats.

The study also emphasizes the importance of ecosystem service values to conservation and development planning. Recognizing seagrass meadows as natural assets that produce significant economic and social benefits can strengthen policy support for habitat protection and restoration. Integrated ecosystem service assessments into blue economy efforts, fisheries management plans and environmental impact assessments would offer a better scientific basis for sustainable coastal development.

Conservation will also require active participation from local communities. Developing awareness about the ecological and economic importance of seagrass ecosystems, community-based monitoring and fishers' participation in management can lead to better stewardship and better long-term sustainability of conservation programmes. These methods are especially important in situations where livelihoods are very much dependent on marine resources.

Finally, the current research and management study serves as a scientific benchmark for future research and management of the seagrass meadows of Palk Bay and Gulf of Mannar, Tamil Nadu. Long-term ecological monitoring, habitat restoration and adaptive management will be needed to address new challenges as well as increases in anthropogenic pressure and environmental change. Seagrass ecosystems should therefore be looked at as biodiversity conservation measures and sustainable fisheries, sustainable coastal ecosystems and the health of future generations.

Chapter 1: Introduction

1 Introduction

Coastal and marine ecosystems are critically important, considering productivity and species diversity. The seagrass ecosystem is one of the richest ecosystems in coastal and marine ecosystems regarding species diversity (Hori et al., 2009). The dominant vegetation community in this ecosystem is seagrass, a special type of marine flowering plant with true roots and rhizomes (Short et al., 2007). Due to the presence of rhizomes, these plants can grow in submerged photic zone patches in salty and brackish waters, which are popularly known as seagrass ecosystems. Seagrass ecosystems enhance sedimentation, reduce eutrophication problems, and establish a surface layer above benthos (Short et al., 2007). These seagrass ecosystems are highly diverse and productive as they harbor many species of vertebrates and invertebrates (Jagtap et al., 2003). The iconic species of seagrass ecosystems are the Dugong and Green turtle; both these species are exclusively used in this ecosystem as foraging grounds (Orth et al., 2006).

Seagrass Ecosystems are globally distributed except for Antarctica and serve as extensive fishing grounds across their distribution (Nordlund et al., 2017; Short et al., 2007). These ecosystems play a crucial role in providing food and shelter for littoral fish species, including many food fish species (Guidetti, 2000; Cullen & Unsworth, 2013). Seagrass ecosystems support large-scale fishery production by acting as a refuge, foraging ecosystem, and nursery grounds for many fish species (Nordlund et al., 2017). Also, fish are considered important grazers of seagrass (Heck & Valentine, 2005). Fish production largely depends on seagrass ecosystems, so it is essential to document the ecology of seagrass-associated fish and the ecosystem services provided by the seagrass ecosystem (Jones et al., 2003). Considering this fishery production, many coastal fisherman communities worldwide depend on these seagrasses for both subsistence and commercial fishery (Cullen & Unsworth, 2013). Therefore, seagrass is culturally, economically, and ecologically important for many traditional communities (Cullen & Unsworth, 2010).

The tropical Indo-Pacific bioregion of seagrass distribution is considered the most extensive and highest biodiversity region, with 24 species of seagrasses. Seagrasses generally occur on coral reef flats between the reef break and shore in this bioregion (Short et al., 2007). In India, seagrass ecosystems are generally present on mudflats and sandy shores from the lower intertidal zone to 10–15 m along the open shores and in the lagoons around islands (Jagtap et

al., 2003). So far, 14 species of seagrasses along the Indian coast have been reported, which occur in

the Gulf of Mannar and Palk Bay, which are vital seagrass ecosystems in the Indian Ocean (Thangaradjou et al., 2007; Jagtap et al., 2003). Among important seagrass ecosystems in India, the Gulf of Mannar is protected as a Marine National Park, but the Palk Bay region is not well protected by law (D'Souza et al., 2013). Like global seagrass-dependant fishery, both subsistence and commercial fishery are practiced in these critical seagrass ecosystems of India (Nordlund et al., 2017). Harboring abundant diversity, many villages near these seagrass ecosystems in Tamilnadu regions mainly depend upon fishery practices as a source of income (Thangaradjou et al., 2007). Despite having extensive coast and abundant fishery practices, seagrass ecosystems in India are not well studied compared to other countries (Jagtap et al., 2003). Significantly, the information on fish species associated with seagrass ecosystems and species interaction with seagrass ecosystems has not been studied in Indian waters.

Seagrass ecosystems

Seagrass ecosystems are important ecosystems with high structural complexity and ecological importance (Hori et al., 2009; Short et al., 2007). Seagrasses are unique submerged marine plants with true roots and rhizomes, which play a crucial role in sedimentation. They are distributed globally except in Antarctica (Short et al., 2007). According to Short et al., 2007, there are six bioregions of seagrass distribution-a) Temperate North Atlantic, b) Tropical Atlantic, c) Mediterranean, d) Temperate North Pacific, e) Tropical Indo-Pacific, f) Temperate Southern Oceans, for understanding seagrass ecology across the globe. This paper describes seagrass species and associated fauna for each bioregion. Seagrasses occupy only 0.15% of the oceanic surface with approximately 72 species, but they contribute to net oceanic ecosystem production by about 12% (Sobocinski, 2014; Cullen-Unsworth & Unsworth, 2013). Reproductive strategies for seagrasses can vary depending on environmental conditions. Seagrasses reproduce both sexually and asexually, but many seagrass populations are highly clonal, relying on asexual reproduction (Gullström et al., 2002; Short et al., 2007). Seagrasses provide an enormous carbon source to the detrital pool (Orth et al., 2016). Seagrass ecosystems play a crucial role in settling sediment, binding organic pollutants, recycling nutrients, and reducing eutrophication (Short et al., 2007). The 3- dimensional structure of seagrass beds contain a spectrum of microhabitats and niches, making them convenient as permanent and transient residences (Gullström et al., 2002). It is very well studied that most seagrass

ecosystems show a striking abundance species of associated organisms than that of unvegetated ecosystems (Orth et al., 1984; Gullström et al., 2002; Short et al., 2007; Hori et al., 2009; Jenkins et al., 1997; Jackson et al., 2001). The faunal assemblages in seagrass beds consist of animals with many different life forms and ecological characteristics (Orth et al., 1984). Seagrass ecosystems serve as nursery and spawning ground for a variety of species (Jagtap et al., 2003; Nagelkerken et al., 2002; Nordlund et al., 2017; Blandon et al., 2014; Hori et al., 2009). Also, seagrass supports grazing that varies significantly in time and space but is critically important in the grazing pathway. These grazers include Dugongs and manatees, Waterfowls, fishes, sea turtles, sea urchins, and other invertebrates. These grazers can directly graze the seagrass or epiphytic algae (Heck et al., 2006). Being one the most productive marine ecosystems, seagrass ecosystems have an important cultural and economic role in coastal human communities across the world (Cullen-Unsworth &Unsworth, 2013; Heck et al., 2006; Nordlund et al., 2017; Thangaradjou et al., 2007; Gullström et al., 2002; Short et al., 2007). Seagrass ecosystems are under threat because of habitat loss, reduced water quality driven by coastal development, physical damage by fishing activities, etc. (Cullen-Unsworth &Unsworth, 2013; Nordlund et al., 2017).

In the context of India, seagrass ecosystems are distributed over mudflats and sandy regions in lower intertidal regions to a depth of 10-15 m. Major Seagrass ecosystems in India are present in the Gulf of Mannar and Palk Bay and several islands of Lakshadweep and Andaman and Nicobar (Jagtap et al., 2003; Thangaradjou et al., 2007; D'souza et al., 2013). A vital ecosystem must be better understood at the education, research, and management levels (Jagtap et al., 2003; D'souza et al., 2013).

Seagrass-associated fish and fisheries

Seagrass habitats are considered essential habitats for fishes, including juveniles of commercially important species. These habitats provide refuge to fish species from predation and serve as feeding, nursery, and spawning grounds (Jenkins et al., 1997; Jagtap et al., 2003; Nagelkerken et al., 2002; Nordlund et al., 2017; Blandon et al., 2014; Heck et al., 2006; Hori et al., 2009). The morphological characteristics and structural complexity of seagrass meadows are essential factors for fishes associated with seagrasses. In addition to these factors, high-order factors like landscape structure and adjacent habitats also affect associated fish. Seagrass beds with high species diversity and high three-dimensional structure greatly benefit fish (Hori et al., 2009). Fish communities associated with seagrass vary according to habitat

characteristics like canopy height, seagrass species composition, density, bed heterogeneity, etc. (Hori et al., 2009; Jackson et al., 2001). Though fish species may not vary according to seagrass habitat characteristics, the ordinance of fish species and abundance changes across different characteristics of seagrass habitats (Middleton et al., 1984). Fish species associated with seagrass ecosystems can be permanent residents, temporary residents, frequent visitors, or occasional visitors (Gullström et al., 2002). Permanent residents depend on seagrass ecosystems for their entire life cycle. However, fish species categorized as temporary residents, frequent visitors, or occasional visitors depend on seagrass ecosystems for foraging, refuge from predation, and spawning (Jackson et al., 2001). It is apparent that, with fishes largely dependent upon seagrass ecosystems, fisheries are dominant in these areas across the globe (Jenkins et al., 2001; Nordlund et al., 2017). Many fishing methods are practiced in different parts of the world, ranging from handpicking to trawler fishery. The fishery practices are for many purposes: small-scale, artisanal, recreational (sport), commercial, subsistence, traditional, and industrial fisheries (Nordlund et al., 2017). Seagrass fishery is a crucial part of the livelihood of many communities across the globe; it has immense cultural value and economic importance (Nordlund et al., 2017; Cullen-Unsworth & Unsworth, 2013).

Seagrass ecosystems are believed to contribute much to fishery productivity (Nordlund et al., 2017; Cullen-Unsworth & Unsworth, 2013; Short et al., 2007). However, more detailed research is needed on the role of seagrass ecosystems in fishery production (Nordlund et al., 2017). Also, Seagrass research tends to be concentrated in particular geographical regions; latitudinal variation is essential in determining the roles and value of seagrass beds to fisheries, which is not focussed much in many studies (Jenkins et al., 2001). Considering the importance of seagrass ecosystems in fish production and fisheries, these ecosystems should be considered for conservation as a priority (Nordlund et al., 2017).

In India, around 192 fish species, including sardine, mullet, eel, cat and parrotfishes, and grouper, are reported to be associated with seagrass ecosystems (Jagtap et al., 2003). Many villages largely depend upon seagrass fishery on Indian coasts (Thangaradjou et al., 2007). The Gulf of Mannar region is protected as a marine Biosphere reserve, which implies some restrictions on fisheries. However, Palk Bay has no legal protection and no restriction on fishing activities (D'souza et al., 2013).

Ecosystem Services provided by Seagrass Ecosystems

Ecosystem services are the benefits humans take from the Earth's natural systems, including provisioning, regulating, cultural, and supporting services (Cullen-Unsworth & Unsworth, 2013). Seagrass ecosystems are vital ecosystem service providers for coastal human communities, largely dependent on seagrass ecosystems for food and livelihood. As global food production is associated with the seagrass ecosystems, they have high worldwide economic importance (Nordlund et al., 2017; Cullen-Unsworth & Unsworth, 2013; Short et al., 2007; Thangaradjou et al., 2007). Providing food resources and habitats for many commercially important species and charismatic species like dugongs, sea turtles, and seahorses is a vital ecosystem service provided by the seagrass ecosystem. Also, sediment stabilization by the seagrass ecosystem is an important ecosystem service that protects against coastal erosion. Seagrasses are biological indicators for environmental changes because they integrate environmental impacts over measurable and definable timescales. Supporting a range of diversity of organisms, seagrass ecosystems have given rise to tourism activities in many parts. All these ecosystem services can be categorized into provisioning services like fishing grounds, regulating services like sediment stabilization, cultural services like recreational values, and supporting services, which are all other services necessary for the production of all other services (Cullen-Unsworth & Unsworth, 2013; Orth et al., 2006). Quantifying these ecosystem services would help in resource management of the ecosystem (Orth et al., 2012).

Threats

In the recent past, seagrass degradation has been increasing rapidly across the world (Short et al., 2007; Cullen-Unsworth & Unsworth, 2013; Nordlund et al., 2017; Gullström et al., 2002). The global rate of decline of the seagrass area has been alarming, with a value of 7% per year since 1990 (Blandon et al., 2014). Different types of stressors, such as environmental, biological, and extreme climatological events, are behind the loss of seagrass ecosystems. Environmental stressors include rising sea levels, increasing global temperature and CO₂ concentrations, etc. Examples of biological stressors are urchin overgrazing, brown tide, etc. Extreme climatological events like storms and pulsed turbidity can subsequently affect seagrass ecosystems (Orth et al., 2006). Seagrass ecosystems are one of the coastal and marine ecosystems that humans highly impact (Short et al., 2007; Cullen-Unsworth & Unsworth, 2013; Jagtap et al., 2003). Anthropogenic activities such as anchoring and moving boats and ships, dredging and discharging sediments, landfilling, and untreated sewage disposal negatively

impact seagrass ecosystems. (Jagtap et al., 2003, Short et al., 2007). Along with these threats having destructive impacts on seagrass ecosystems, a lack of awareness of the importance of seagrass is an essential aspect of future conservation management (Orth et al., 2006).

Many advanced countries have prioritized conserving seagrass ecosystems, and rehabilitation programs have been implemented since 1945 in some areas. In India, seagrass ecosystems are included in ecologically sensitive regions and protected by the Coastal Regulation Zone Act. However, India's seagrass ecosystems are underappreciated by education, research, awareness, and management consideration compared to other ecosystems like mangroves and corals (Jagtap et al., 2003).

As there is lack of data for ecology of seagrass associated fish species in Palk bay and Gulf of Mannar, this study aims to understand and collect data about interactions between seagrass ecosystems and various fish species associated with them. This can help in managing and improving fishery practices in the region. Seagrass ecosystems is a structured community which provides high value ecosystem services which directly impact human communities dependent upon them. Therefore, it is necessary to document ecosystem services provided by seagrass ecosystems locally which can help in understanding role of this ecosystem in economy and culture of those communities. Threat assessment for these seagrass ecosystems is important for conservation management of these habits and iconic species like Dugong and sea turtles.

Objectives

1. Assess the commercially important fin fish species associated with seagrass ecosystems in Palk Bay
 - a. How many commercially important fish species which are associated with seagrass ecosystems occur in Palk Bay and Gulf of Mannar?
 - b. Is there any change in species composition of Finfish along the seagrass species diversity in these regions?
 - c. How many commercial finfish species in these regions are obligatorily associated with seagrasses?
2. Document the resource (food and space) partitioning patterns among fin fish species associated with seagrass ecosystems

- a. Which different microhabitats are utilized by obligatory seagrass associated commercial finfish species?
 - b. What kind of food resources are utilized by these commercial finfish species?
 - c. How these commercial finfish species segregate themselves by resource partitioning?
3. Evaluate ecosystem services provided by seagrass ecosystem with reference to commercial fin fish fishery
- a. What different ecosystem services are provided by seagrass ecosystem in Palk Bay and Gulf of Mannar with reference to commercial fin fish fishery?
 - b. What is the economic valuation of these ecosystem services by seagrass ecosystem in these regions?
4. Assess major threat posed by different fishing practices in seagrass ecosystem and provide option for conserving seagrass ecosystems
- a. Which are the threats posed by different fishing practices to seagrass ecosystem in Palk Bay and Gulf of Mannar?
 - b. What measures can be taken for conservation of seagrass ecosystems in Palk Bay and Gulf of Mannar?

Chapter 2: Study Area

2 Study Area

The present study was conducted in the seagrass ecosystems of Palk Bay and Gulf of Mannar, situated along the southeastern coast of Tamil Nadu, India (Figure 2.1). These two adjoining marine ecosystems represent the most extensive seagrass habitats in the country and constitute one of the most important seagrass landscapes in the northern Indian Ocean (Jagtap et al., 2003; Thangaradjou and Bhatt, 2018). Palk Bay consists of an extensively shallower habitat with relatively low wave energy, and sandy-muddy substrates makes favourable for seagrass growth. In contrast, the Gulf of Mannar is more open to oceanic influences and consists of a mosaic of coral reefs, seagrass meadows, sandy bottoms, and island ecosystems. Seasonal monsoons influence water circulation, turbidity, salinity, and nutrient availability in both regions, thereby affecting seagrass productivity and the distribution of associated marine organisms (Jagtap et al., 2003).

The Gulf of Mannar extends from Rameswaram to Tuticorin and encompasses 21 offshore islands surrounded by coral reefs and seagrass beds. Owing to its exceptional biodiversity, the area was declared the Gulf of Mannar Marine National Park in 1986 and later recognized as India's first Marine Biosphere Reserve (D'Souza et al., 2013; Jagtap et al., 2003). In contrast, Palk Bay is a shallow semi-enclosed basin located between the southeastern coast of India and northern Sri Lanka. Recognizing the ecological importance of Palk Bay and its role as one of the last strongholds of the endangered Dugong (*Dugong dugon*) in India, the Government of Tamil Nadu declared approximately 448 km² of seagrass-rich coastal waters as the Dugong Conservation Reserve in 2022 under the Wildlife (Protection) Act, 1972.

The Gulf of Mannar and Palk Bay together harbour one of the richest seagrass assemblages in the Indo-Pacific region. Extensive seagrass meadows with varying canopy heights and structural complexity create important habitats for a wide range of marine organisms. Recent remote sensing assessments estimated approximately 399 km² of seagrass meadows within Palk Bay and Gulf of Mannar, representing a substantial proportion of India's total seagrass cover (Geevarghese et al., 2018). These meadows function as important blue carbon ecosystems by capturing and storing carbon within plant biomass and sediments. Kaladharan et al. (2020) estimated blue carbon stocks in the seagrass ecosystems of Palk Bay and Gulf of Mannar, highlighting their role in climate change mitigation and coastal ecosystem resilience.

The ecological significance of these seagrass ecosystems extends beyond their floral diversity. Seagrass meadows provide important feeding grounds, breeding areas, nursery habitats, and refuge for numerous marine organisms, including fishes, crustaceans, molluscs, echinoderms, and cephalopods (Nagelkerken et al., 2002; Nordlund et al., 2016; Orth et al., 2006). The region also supports several species of conservation concern, including the Dugong (*Dugong dugon*), Green Sea Turtle (*Chelonia mydas*), and various seahorse species (*Hippocampus* spp.), all of which are closely associated with seagrass habitats (D'Souza et al., 2013; Marsh et al., 2011). The close spatial association between seagrass beds, coral reefs, and mangroves further enhances biodiversity through habitat connectivity and ecological interactions.

The coastal communities surrounding Palk Bay and the Gulf of Mannar are heavily dependent on marine fisheries for their livelihoods. Seagrass meadows support a wide range of commercially important fish, crustaceans, molluscs, and other marine resources by providing feeding grounds, shelter, and nursery habitats. Consequently, the ecological condition of seagrass ecosystems directly influences fisheries productivity and the socio-economic well-being of coastal fishing communities (Nordlund et al., 2016). Thousands of fishers residing along the coast depend directly or indirectly on seagrass-associated fisheries for income and food security (Thangaradjou and Bhatt, 2018).

Despite their ecological and economic importance, seagrass ecosystems in the region face numerous anthropogenic and environmental threats. Major threats include bottom trawling, drag-net fishing, anchoring, dredging, coastal development, sedimentation, eutrophication, marine litter, oil pollution (D'Souza et al., 2013; Jagtap et al., 2003; Nordlund et al., 2016). In Palk Bay, destructive fishing practices have been identified as one of the principal causes of seagrass degradation, whereas habitat fragmentation and declining water quality threaten several meadows across both regions (D'Souza et al., 2013). Additionally, extreme climatic events such as cyclones, storm surges, and sea-level rise associated with climate change may further affect seagrass distribution and ecosystem functioning (Orth et al., 2006).

The present study focuses on Palk Bay and the Gulf of Mannar because these regions contain India's most extensive and diverse seagrass ecosystems and support economically important fisheries and globally significant marine biodiversity. The Gulf of Mannar benefits from long-standing protection under the Marine National Park and Biosphere Reserve network, whereas Palk Bay has only recently been designated as a Dugong Conservation Reserve owing to its critical seagrass habitats and importance for dugong conservation. Despite this recognition,

Palk Bay continues to experience intense fishing pressure and other anthropogenic disturbances, highlighting challenges in implementing effective conservation and management measures. This provides an excellent opportunity to evaluate patterns of fish diversity, habitat utilization, ecosystem services, and anthropogenic threats across different conservation settings. Understanding these ecological relationships is essential for developing effective conservation strategies and sustainable fisheries management plans for India's seagrass ecosystems.

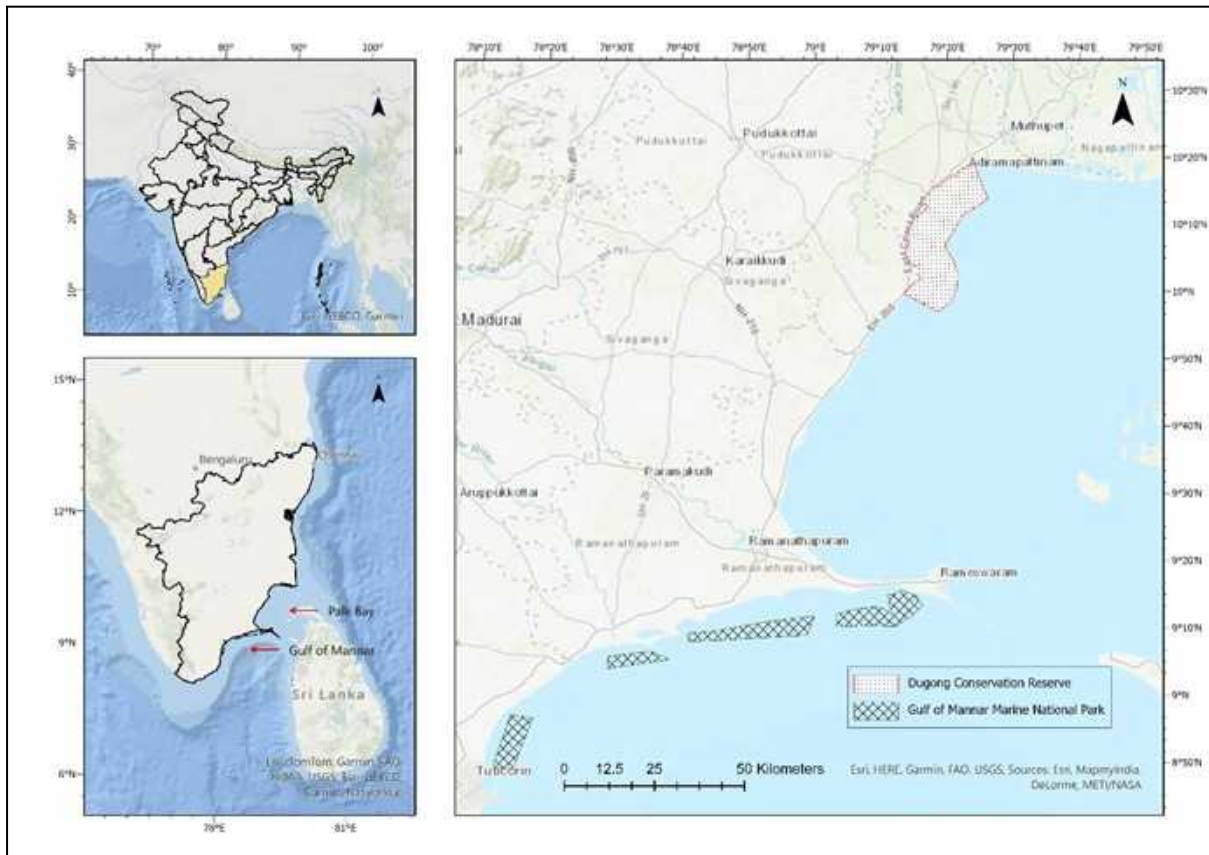


Figure 2.1: Study area map for the present study of seagrass associated fish

**Chapter 3: Commercially important
fin fish species associated with
seagrass ecosystems in Palk Bay and
Gulf of Mannar**

3 Commercially important fin fish species associated with seagrass ecosystems in Palk Bay and Gulf of Mannar

3.1 Introduction

Seagrass ecosystems serve as critical habitats for a variety of fish species, including those of commercial importance during their juvenile stages. These habitats provide essential services such as protection from predation and resources for feeding, breeding, and nursery grounds (Jenkins et al., 1997; Jagtap et al., 2003; Nagelkerken et al., 2002; Nordlund et al., 2017; Blandon et al., 2014; Heck et al., 2006; Hori et al., 2009). The unique morphological characteristics and structural complexity of seagrass meadows are vital attributes that support the diverse fauna inhabiting these environments. In addition to these intrinsic properties, extrinsic factors such as landscape configuration and the proximity of adjacent habitats significantly influence the ecological dynamics of associated fish populations.

Higher species diversity and three-dimensional structural complexity within seagrass beds are known to confer substantial advantages to fish communities (Hori et al., 2009). Various habitat traits, including canopy height, species composition, density, heterogeneity, and specific seagrass species, critically affect the life cycles of fish within these ecosystems (Hori et al., 2009; Jackson et al., 2001). Although fish species composition may not show marked variability due to seagrass habitat characteristics, the distribution and abundance of fish species do correlate with differing attributes of seagrass habitats (Middleton et al., 1984). Fish inhabiting seagrass ecosystems can be categorized as permanent residents, temporary residents, intermittent visitors, or occasional visitors (Gullström et al., 2002). Permanent residents depend on seagrass ecosystems for their entire life cycle, while temporary residents and other visiting species rely on these habitats for food, protection from predators, and spawning opportunities (Jackson et al., 2001).

Given the high dependency of fish on seagrass ecosystems, these areas are vital for fisheries globally (Jenkins et al., 2001; Nordlund et al., 2017). Fisheries practices, ranging from trawling to hand-picking, vary widely and serve diverse functions, such as artisanal, sport (recreational), commercial, subsistence, traditional, and industrial fishing (Nordlund et al., 2017). Seagrass fisheries represent a critical livelihood for numerous communities around the world and hold substantial cultural and economic significance (Nordlund et al., 2017; Cullen-Unsworth &

Unsworth, 2013). Furthermore, seagrass systems are believed to be major drivers of fisheries productivity (Nordlund et al., 2017; Cullen-Unsworth & Unsworth, 2013; Short et al., 2007). However, there is a pressing need for targeted research to better understand the impact of seagrass ecosystems on fishery production (Nordlund et al., 2017).

Current research on seagrass is predominantly concentrated in a limited number of geographical areas, and the latitudinal factors influencing the functional potential of seagrass beds for fisheries are infrequently addressed in the existing literature (Jenkins et al., 2001). Consequently, the significance of seagrass ecosystems for fish production and fisheries underscores the urgent need for these habitats to be prioritized for conservation efforts (Nordlund et al., 2017). In India, seagrass ecosystems have been documented to support a diverse array of fish species, including sardines, mullets, eels, catfish, parrotfish, and grouper, with a total of 192 species reported (Jagtap et al., 2003). Seagrass fisheries are integral to many coastal villages along the Indian coastline (Thangaradjou et al., 2007). The Gulf of Mannar has been designated as a marine biosphere reserve, which imposes certain restrictions on fishing activities; however, similar legal protections and fishing limitations are lacking in Palk Bay (D'souza et al., 2013).

The literature unequivocally establishes that seagrass ecosystems are fundamental habitats for fish and play a significant role in enhancing fisheries productivity. Factors such as habitat complexity, seagrass diversity, and ecosystem connectivity are crucial determinants of fish distribution and abundance. Numerous commercially important species rely on seagrass habitats during critical developmental phases. Despite advancements in this field, several knowledge gaps remain, particularly concerning the Palk Bay and Gulf of Mannar regions. Specifically, the total number of economically significant finfish species associated with seagrass ecosystems in these areas is not well-documented. Additionally, the influence of seagrass species diversity on finfish assemblages has not been thoroughly investigated, and the extent to which commercially valuable fish species are obligately associated with seagrass habitats remains largely unknown. The present study addresses these gaps by assessing the commercially important finfish species associated with seagrass ecosystems in Palk Bay and the Gulf of Mannar. Specifically, the study aims to:

1. How many commercially important fish species which are associated with seagrass ecosystems occur in Palk Bay and Gulf of Mannar?

2. Is there any change in species composition of Finfish along the seagrass species diversity in these regions?
3. How many commercial finfish species in these regions are obligatorily associated with seagrasses?

3.2 Standardization of Methodology for studying seagrass associated Fish

For selection of optimum method for studying fish fauna in seagrasses, comparison of point count and belt transect methods have been performed. A dataset of 13 point counts and 10 belt transects were used for this comparison with comparative factor of fish densities observed in both methods. Shannon and Simpson diversity indices and evenness index were used to compare for these two methods. T-test was used to compare densities of fish families observed in both methods. Fish species were categorized into habitat guilds, that are, bottom dwelling, Coral/ rock/ anemone associated, seagrass associated and feeding guilds, that are, carnivorous, herbivorous, omnivorous. Fish densities were also compared guild-wise observed in both the methods.

Considering results of above method, point count method was standardized for studying seagrass resource use by fish.

3.2.1 Results For Standardization of Methodology for Studying Seagrass Associated Fish

A comparison of belt transects and point count methods revealed similar estimates of fish community diversity. The Simpson's diversity index was 0.7764 for the belt transect and 0.7828 for the point count method, while the Shannon diversity index was 1.759 and 1.916, respectively. Species evenness was also comparable between the two methods, with values of 0.4147 for the belt transect and 0.3995 for the point count. The t-test indicated no significant difference between the diversity estimates obtained using the two sampling approaches ($t = 0.7458$), suggesting that both methods provide comparable assessments of fish assemblage diversity (Table 3.1).

Guild-wise analysis, however, showed differences in the estimation of fish densities between the two methods (Figure 3.1). Among habitat guilds, point counts consistently recorded higher mean densities than belt transects. Coral, rock, and anemone-associated fishes exhibited the highest densities, followed by seagrass-associated fishes, whereas bottom-dwelling fishes were recorded at the lowest densities. Although the variability was high, particularly for

coral/rock/anemone-associated species, the overall pattern indicated greater detection of habitat guilds using the point count method.

A similar trend was observed for feeding guilds. Herbivorous fishes had the highest mean densities, followed by omnivorous and carnivorous fishes. In all feeding guilds, point counts yielded higher density estimates than belt transects. The difference was most pronounced for herbivorous fishes, which also exhibited the greatest variability among observations.

Overall, while species diversity and evenness did not differ substantially between the two survey methods, point counts consistently recorded higher guild-wise fish densities than belt transects. This suggests that both methods are equally effective for assessing community diversity, but point counts may be more efficient in detecting and quantifying the abundance of different habitat and feeding guilds.

Table 3.1: Results of Diversity Indices and evenness index for fish diversity observed in Point counts and belt transects

	Simpson's Index	Shannon index	Evenness
Belt transect	0.7764	1.759	0.4147
Point count	0.7828	1.916	0.3995
T Test	0.745837		
Interpretation	Mean densities of fish observed in belt transect and point count are not significantly different		

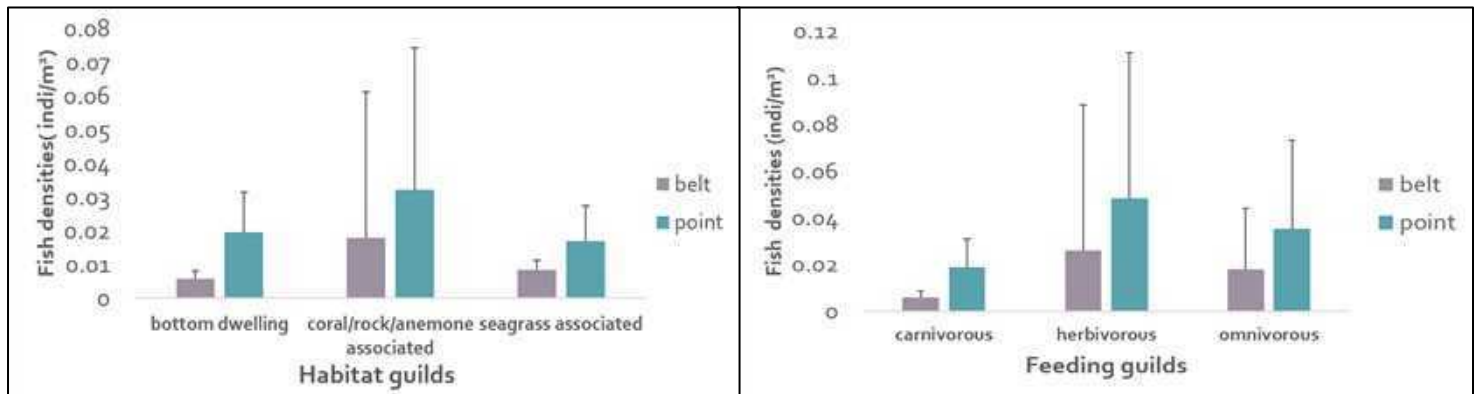


Figure 3.1: Result of comparison of guild-wise average fish densities observed in point count and belt transect

3.2.2 Fish Market Survey

A fish market survey was conducted between March 2019 and October 2024 to document the commercially important finfish species associated with seagrass ecosystems in Palk Bay. A total of 22 surveys were carried out across 13 fish markets, covering the principal landing centres in the region (Figure 3.2). Market surveys were restricted to Palk Bay, as fishers in the Gulf of Mannar predominantly exploit coral reef and offshore fishing grounds, making it difficult to distinguish catches specifically associated with seagrass habitats.

Information obtained from fishers and fish vendors was used to verify the origin of the catch, and only those species that were consistently reported to be harvested from seagrass-associated fishing grounds were included in the analysis. This approach enabled the identification and confirmation of commercially important fish species utilizing seagrass habitats and provided an independent validation of field observations.

The market surveys complemented underwater assessments by linking fish assemblages observed in seagrass meadows with species that contribute directly to local fisheries. Consequently, the survey served as an important tool for evaluating the fisheries significance of seagrass ecosystems in Palk Bay and for identifying commercially important finfish species associated with these habitats.

3.2.3 Underwater Visual census: Random Point counts by snorkelling or Diving

To understand diversity and usage of seagrass meadows by fish, random point counts were conducted at Palk Bay (n=49) and Gulf of Mannar (n=50).

a. Variable radius point counts are done by noting down distance of each sighting and then estimating the densities using distance sampling approach. Detection probability of an

individual depends upon visibility, size of the individual, seagrass cover, seagrass height and distance from the observer.

b. For size class and distance estimation reference, two tapes or ropes marked at each 1 cm of are placed on substrate in cross fashion from imaginary centre of point count circle.

c. Observer hovered not more than 2m above imaginary centre of the point.

d. Substrate, seagrass cover, seagrass height, species composition, epiphytic and non-epiphytic algal cover are noted first.

e. After noting, observer waited for 5 minutes for fish to get acclimatised to the disturbance caused in the process.

f. Observer hovered above the point for next 10 minutes. The dominant activity within every minute of every fish species individual or shoal will be noted. Their numbers are specified according to size classes (<5cm, 5-10cm, 10-15cm, >15cm) with reference to the tape.

g. Position of fish individual/ shoal in seagrass column are also be noted as benthic, in between blades or on surface of seagrass.

h. If there are too many individuals/shoals present, then activities are recorded randomly for first 5 individuals/shoals sighted in the 10-minute window. This gives an idea about how much time was spent for every activity at the meadow and will also help in segregating fishes into guilds later. Any fish swimming through the area during this time will be noted as passer-by.

i. Selection of next point is done by swimming in random direction. Distance between two points is kept minimum 20 m.

j. Number of point counts will be minimum 3 (small meadow < 100 sq. m) to maximum 5 (medium and large meadow >100sq .m).

k. Equal number of random point counts will also be conducted within 500 m of the meadow, where there is no seagrass.

3.2.4 Analysis

The fish diversity and community structure were examined using univariate and multivariate methods. For all fish markets and sampling locations, species richness and family richness were estimated, and a checklist of unique families and species was drawn from the combined dataset. Fish assemblage diversity was calculated using Simpson's diversity index (1-D) and the

corresponding dominance index (D). Diversity estimates of underwater sampling methods (belt transect and point count) were tested using a Student's t-test. Guild-wise fish densities were calculated for habitat guilds (bottom dwelling, coral/rock/anemone associated, and seagrass associated) and feeding guilds (carnivorous, herbivorous, and omnivorous) and compared between survey methods. The relative abundance of fish families was computed independently by region for Palk Bay and the Gulf of Mannar to assess taxonomic regional patterns. This was followed by SIMPER analysis based on Bray–Curtis dissimilarity index to find out which species contributed most in differences in fish assemblages between the two regions. The association between fish assemblages and environmental variables was explored by distance-based redundancy analysis (dbRDA). The approach was chosen in view of the fact that fish community data tend to be non-normal and have high number of zero values, which render linear ordination procedures less appropriate. The data of fish species abundance were converted in order to reduce the effects of higher species abundance and a Bray–Curtis dissimilarity matrix was developed. Environmental factors were seagrass cover, seagrass height, epiphytic algae cover, water depth, and the most important substrate types (sand, coral and rock). All environmental variables were standardized before analysis, and vector species and environmental variables were extrapolated to the ordination space to make sense of habitat

correlation pattern recognition. All statistical analyses and visualizations were carried out in MS-Excel and R software, with specializing in the vegan, dplyr, tidyr and ggplot2 packages.

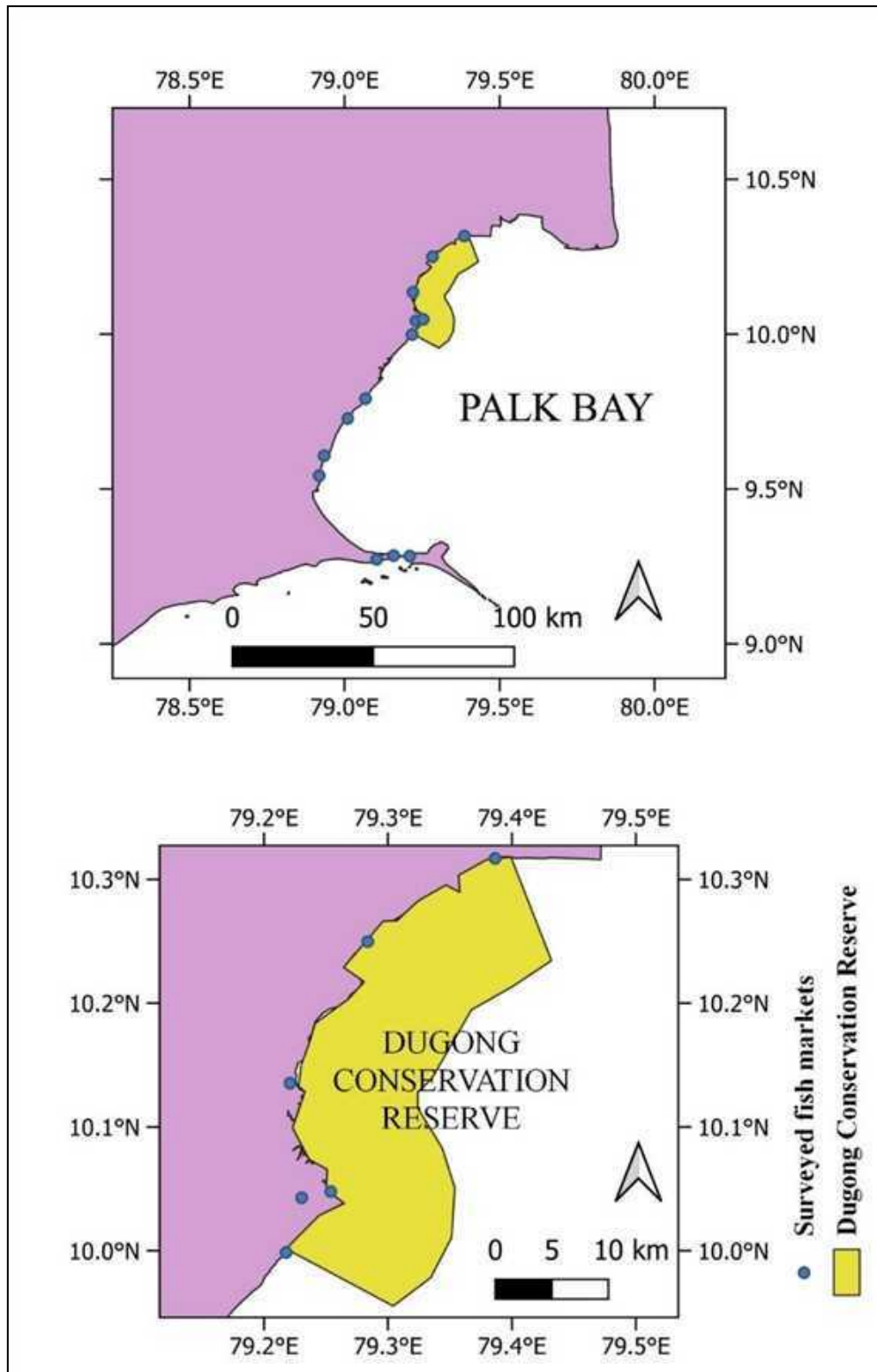


Figure 3.2: Map showing Fish markets surveyed for seagrass associated fish diversity

3.3 Results

3.3.1 Fish Market Survey

Based on repeated surveys across 13 major fish markets, a total of 161 fish species belonging to 58 families were confirmed to be harvested from seagrass-associated fishing grounds (Table 3.2).

The variety of fishes recorded in the surveyed markets varied considerably (Figure 3.3). Kattumavadi represented the most taxonomic diversity with 72 species, accounting for 37 families, followed by Manamelkudi, with 61 species and 34 families. Vadakku Pudukudi also had a high diversity with 50 species of 30 families. One of the biggest fish markets in northern Palk Bay, these landing centres serve as the hubs of catches from the seagrass environment which could explain them being relatively rich in species. Moderate diversity was classified in Therkku Pudukudi (30 species, 22 families), Adirampattinam (28 species, 24 families), Mallipattinam (27 species, 20 families) and Sethubavachatram (25 species, 21 families). Similarly, the markets of Mandapam, Tirupalaikudi, and Vedalai recorded fewer species and families, while Pamban, Tamaraipattinam, and Morappanai showed a fair level of taxonomic diversity. During the survey period, the lowest diversity was found in Nambuthalai where only two species represented two families..

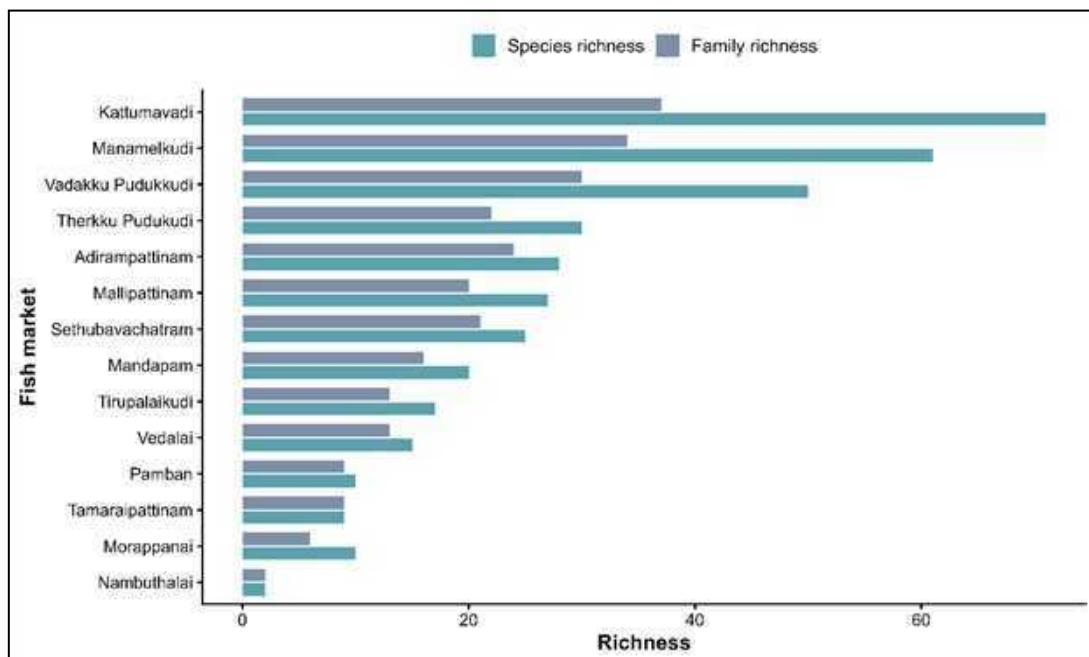


Figure 3.3: Fish species and fish family richness across 13 fish markets of Palk Bay

Table 3.2: Checklist of Fish Market Survey

Fish family	Fish species
Acanthuridae	<i>Acanthus mata</i>
Ariidae	<i>Arius maculatus</i>
Ariidae	<i>Arius sp.</i>
Atherinidae	<i>Doboatherina duodecimalis</i>
Balistidae	<i>Balistoides viridescens</i>
Belonidae	<i>Strongylura incisa</i>
Belonidae	<i>Strongylura leiura</i>
Belonidae	<i>Strongylura strongylura</i>
Belonidae	<i>Tylosurus acus melanotus</i>
Belonidae	<i>Tylosurus crocodilus</i>
Caesionidae	<i>Ephinephalus coioides</i>
Carangidae	<i>Alectis indica</i>
Carangidae	<i>Alepes djedaba</i>
Carangidae	<i>Atule mate</i>
Carangidae	<i>Carangoides praeustus</i>
Carangidae	<i>Caranx heberi</i>
Carangidae	<i>Caranx ignobilis</i>
Carangidae	<i>Caranx papuensis</i>
Carangidae	<i>Caranx sexfasciatus</i>
Carangidae	<i>Gnathanodon speciosus</i>

Carangidae	<i>Megalaspis cordyla</i>
Carangidae	<i>Parastromateus niger</i>
Carangidae	<i>Scomberoides commersonianus</i>
Carangidae	<i>Scomberoides tol</i>
Carangidae	<i>Selaroides leptolepis</i>
Carangidae	<i>Selaroides leptolepis</i>
Carangidae	<i>Carangoides sp.</i>
Chanidae	<i>Chanos chanos</i>
Chirocentridae	<i>Chirocentrus dorab</i>
Chirocentridae	<i>Chirocentrus nudus</i>
Chirocentridae	<i>Tenualosa toli</i>
Cichlidae	<i>Etroplus suratensis</i>
Cichlidae	<i>Oreochromis niloticus</i>
Cichlidae	<i>Oreochromis niloticus</i>
Clupeidae	<i>Hilsa Keele</i>
Clupeidae	<i>Hilsa sp.</i>
Cynoglossidae	<i>Cynoglossus arel</i>
Cynoglossidae	<i>Cynoglossus macrostomus</i>
Dasyatidae	<i>Dasytis zugei</i>
Dasyatidae	<i>Himantura uarnak</i>
Dasyatidae	<i>Maculobatis gerradi</i>
Dasyatidae	<i>Neotrigon kuhlii</i>
Dasyatidae	<i>Taeniura lymma</i>

Dasyatidae	<i>Telatrygon zugei</i>
Dorosomatidae	<i>Chirocentrus dorab</i>
Dorosomatidae	<i>Escualosa thoracata</i>
Dorosomatidae	<i>Etroplus suratensis</i>
Dorosomatidae	<i>Sardinella albella</i>
Dorosomatidae	<i>Tenualosa toli</i>
Drepaneidae	<i>Drepane punctata</i>
Elopidae	<i>Elops machnata</i>
Engraulidae	<i>Stolephorus indicus</i>
Ephippidae	<i>Ephippus orbis</i>
Gerreidae	<i>Gerres erythronus</i>
Gerreidae	<i>Gerres erythronus</i>
Gerreidae	<i>Gerres filamentosus</i>
Gerreidae	<i>Gerres longirostris</i>
Gerreidae	<i>Gerres macracanthus</i>
Gerreidae	<i>Gerres oblongus</i>
Gerreidae	<i>Gerres oyena</i>
Haemulidae	<i>Diagramma picta</i>
Haemulidae	<i>Plectorhinchus gibbosus</i>
Haemulidae	<i>Plectorhinchus pictus</i>
Haemulidae	<i>Pomadasys kaakan</i>
Hemiramphidae	<i>Hemiramphus far</i>
Hemiramphidae	<i>Hemiramphus lutkei</i>

Hemiramphidae	<i>Hyporhamphus sp.</i>
Hemiramphidae	<i>Hyporhamphus unicuspis</i>
Hemiscyllidae	<i>Chiloscyllium punctatum</i>
Hemiscyllidae	<i>Chiloscyllium griseum</i>
Hemiscyllidae	<i>Chiloscyllium punctatum</i>
Holocentridae	<i>Sargocentron rubrum</i>
Latidae	<i>Lates calcarifer</i>
Latidae	<i>Psammoperca waigiensis</i>
Latidae	<i>Psammoperca waigiensis</i>
Leiognathidae	<i>Eubleekeria splendens</i>
Leiognathidae	<i>Karalla dussumieri</i>
Leiognathidae	<i>Leiognathus brevirostris</i>
Leiognathidae	<i>Leiognathus dussumieri</i>
Lethrinidae	<i>Lethrinus lentjan</i>
Lethrinidae	<i>Lethrinus microdon</i>
Lethrinidae	<i>Lethrinus nebulosus</i>
Lethrinidae	<i>Lethrinus ornatus</i>
Lobotidae	<i>Lobotes surinamensis</i>
Loliginidae	<i>Sepioteuthis lessoniana</i>
Loliginidae	<i>Uroteuthis duvaucelli</i>
Lutjanidae	<i>Aprion virescens</i>
Lutjanidae	<i>Lutjanus ehrenbergii</i>
Lutjanidae	<i>Lutjanus fulviflamma</i>

Lutjanidae	<i>Lutjanus fulvus</i>
Lutjanidae	<i>Lutjanus quinquelineatus</i>
Monacanthidae	<i>Aluterus scriptus</i>
Mugilidae	<i>Crenimugil seheli</i>
Mugilidae	<i>Ellochelon vaigaiensis</i>
Mugilidae	<i>Lisa macrolepis</i>
Mugilidae	<i>Lisa pars</i>
Mugilidae	<i>Mugil cephalus</i>
Mugilidae	<i>Planiliza macrolepis</i>
Mullidae	<i>Parupeneus heptacanthus</i>
Mullidae	<i>Parupeneus indicus</i>
Mullidae	<i>Upeneus moluccensis</i>
Mullidae	<i>Upeneus sp.</i>
Mullidae	<i>Upeneus sundaicus</i>
Mullidae	<i>Upeneus tragula</i>
Mullidae	<i>Upeneus tragula</i>
Mullidae	<i>Upeneus vittatus</i>
Nemipteridae	<i>Nemipterus personii</i>
Nemipteridae	<i>Scolopsis bimaculata</i>
Nemipteridae	<i>Scolopsis vosmeri</i>
Palinuridae	<i>Panulirus homarus</i>
Paralichthyidae	<i>Pseudorhombus arsius</i>
Penaeidae	<i>Penaedus semisulcatus</i>

Penaeidae	<i>Penaeus indicus</i>
Penaeidae	<i>Penaeus semisulcatus</i>
Platycephalidae	<i>Platycephalus indicus</i>
Platycephalidae	<i>Platycephalus indicus</i>
Plotosidae	<i>Plotosus canius</i>
Plotosidae	<i>Plotosus lineatus</i>
Plotosidae	<i>Plotosus lineatus</i>
Plotosidae	<i>Plotosus sp.</i>
Polynemidae	<i>Eleuthronema tetradactylum</i>
Polynemidae	<i>Eleuthronema tetradactylum</i>
Polynemidae	<i>Kathala axillaris</i>
Pomacentridae	<i>Amphiprion sp.</i>
Portunidae	<i>Charybdis feriata</i>
Portunidae	<i>Portunus pelagicus</i>
Portunidae	<i>Thalamita crenata</i>
Pristigasteridae	<i>Ilisha megaloptera</i>
Pristigasteridae	<i>Ilisha melastoma</i>
Pristigasteridae	<i>Ilisha megaloptera</i>
Pristigasteridae	<i>Pellona ditchela</i>
Rhinobatidae	<i>Rhinobatos sp.</i>
Scaridae	<i>Scarus ghobban</i>
Scatophagidae	<i>Scatophagus argus</i>
Sciaenidae	<i>Dentrophysa russeli</i>

Sciaenidae	<i>Johnius amblycephalus</i>
Sciaenidae	<i>Johnius carouna</i>
Sciaenidae	<i>Johnius carutta</i>
Sciaenidae	<i>Nibea maculata</i>
Sciaenidae	<i>Nibea soldado</i>
Sciaenidae	<i>Nibea sp.</i>
Sciaenidae	<i>Otolithes ruber</i>
Sciaenidae	<i>Pennahia aneus</i>
Scombridae	<i>Gymnosarda unicolor</i>
Scombridae	<i>Katsuwonus pelamis</i>
Scombridae	<i>Rastrelliger brachysoma</i>
Scombridae	<i>Scomberomorus commerson</i>
Sepiidae	<i>Acanthosepion pharaonis</i>
Sepiidae	<i>Sepia officinalis</i>
Sepiidae	<i>Sepiella inermis</i>
Serranidae	<i>Ephinephalus quoyanus</i>
Serranidae	<i>Ephinephalus undulosus</i>
Serranidae	<i>Epinephalus bleekeri</i>
Serranidae	<i>Epinephalus faveatus</i>
Serranidae	<i>Pterocaesio chrysozona</i>
Siganidae	<i>Siganus canaliculatus</i>
Siganidae	<i>Siganus javus</i>
Siganidae	<i>Siganus lineatus</i>

Siganidae	<i>Siganus rivulatus</i>
Sillaginidae	<i>Sillago sihama</i>
Sparidae	<i>Acanthopagrus berda</i>
Sphyraenidae	<i>Sphyraena chrysotaenia</i>
Sphyraenidae	<i>Sphyraena jello</i>
Sphyraenidae	<i>Sphyraena obtusa</i>
Sphyraenidae	<i>Sphyraena obtusata</i>
Stromateidae	<i>Pampus argenteus</i>
Synodontidae	<i>Saurida tumbil</i>
Terapontidae	<i>Terapon Puta</i>
Terapontidae	<i>Terapon jarbua</i>
Terapontidae	<i>Terapon puta</i>
Triacanthidae	<i>Pseudotriacanthus</i>
Triacanthidae	<i>Pseudotriacanthus strigilifer</i>
Triacanthidae	<i>Triacanthus biaculeatus</i>
Triacanthidae	<i>Triacanthus nieuhofii</i>
Trichiuridae	<i>Trichiurus lepturus</i>

3.3.2 Underwater Visual census: Random Point counts by snorkelling or Diving

Underwater point monitoring surveys revealed 85 fish species belonging to 51 genera and 31 families in the seagrass systems in Palk Bay and the Gulf of Mannar (see Figure 3.4). The surveys revealed distinct regional differences in fish diversity between populations, with the Gulf of Mannar providing a richer fish diversity than Palk Bay. A total number of 23 species,

including a number of 18 genera and 16 families, were described by the survey in Palk Bay. Conversely the Gulf of Mannar supported 67 different species from 42 genera and 24 families, which showed much richness of taxonomy. When we combined the observations from both regions, the total checklist contains 85 fish species belonging to 51 genera and 31 families.

3.4.2.1 Fish diversity in Gulf of Mannar and Palk Bay

The Simpson’s diversity index (1–D) showed higher taxa diversity in the Gulf of Mannar (0.6967) than in Palk Bay (0.6485) (Table 3.3, Figure 3.5). This indicates that the Gulf of Mannar harbors a wider diversity of fish. On the other hand, the dominance index (D) is higher in Palk Bay (0.3515) compared to Gulf of Mannar (0.3033); which means that fewer species in Palk Bay contribute disproportionately to collective fish assemblage (Table 3.3, Figure 3.5). Data for both indices result in error bars indicating variability between sampling sites within each region, but the results are consistent with an almost uniform structure. The Gulf of Mannar appears more diverse in its fish assemblages than the species-dominated ones found in Palk Bay.

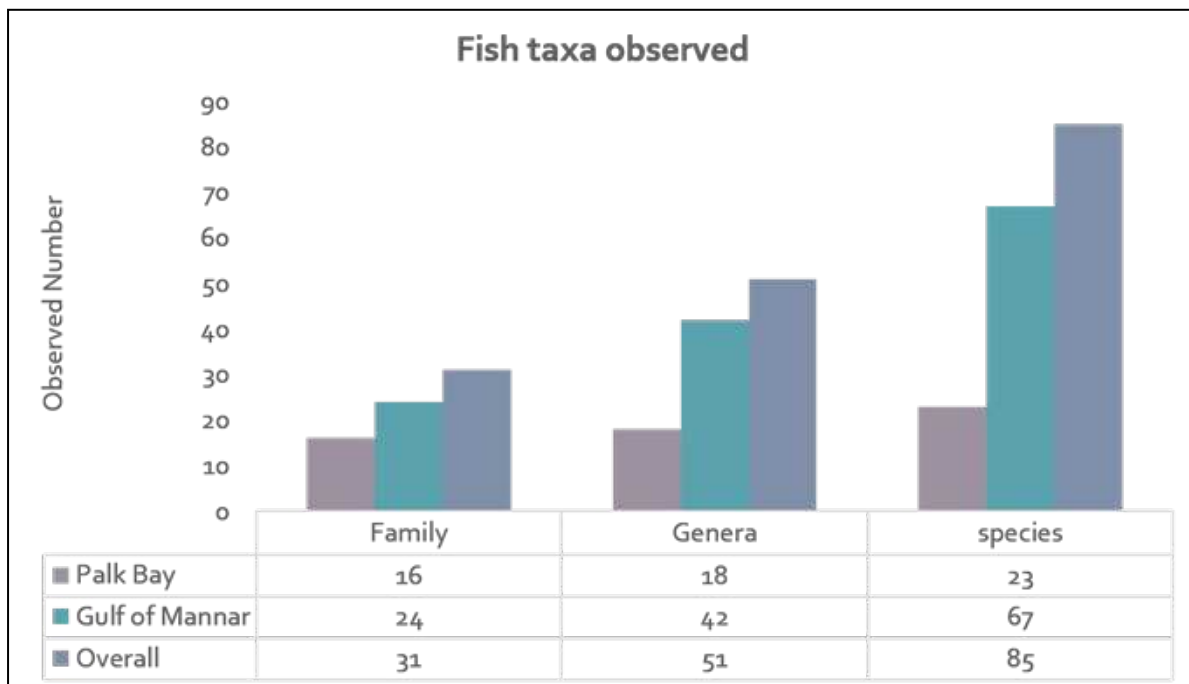


Figure 3.4: Fish taxa observed by underwater point counts in study area

Table 3.3:: Diversity indices for fish taxa observed by underwater point counts in study area

	Gulf of Mannar	Palk Bay
Simpson (1-D)	0.6967	0.6485
Shannon (H)	1.746	1.369
Dominance (D)	0.3033	0.3515
Evenness_ $e^{H/S}$	0.08075	0.1512

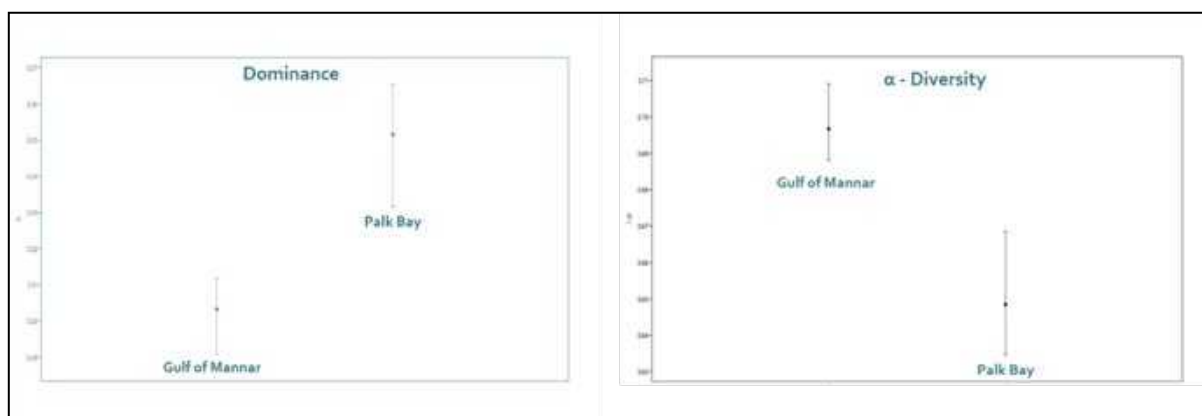


Figure 3.5:Regional variation in alpha diversity (Simpson's 1–D) and dominance (D) of seagrass-associated fish assemblages recorded during underwater point count surveys

3.4.2.2 The relative abundance of fish families in Palk Bay and the Gulf of Mannar

Several families were recorded only in one region, resulting in a complete (100%) contribution from either Palk Bay or the Gulf of Mannar (Figure 3.6). Families such as Apogonidae, Caesionidae, Chaetodontidae, Echeneidae, Haemulidae, Leiognathidae, Lethrinidae, Monacanthidae, Nemipteridae, Pempheridae, Pomacentridae, Scaridae, Serranidae, Siganidae, Sphyraenidae, Synodontidae, and Terapontidae were represented entirely by observations from the Gulf of Mannar. In contrast, Ariidae, Atherinidae, Carangidae, Engraulidae, Gerreidae,

Gobiidae, Hemiscylliidae, Mugilidae, and Syngnathidae were recorded only from Palk Bay. A few families occurred in both regions but differed in their relative contribution. Mullidae and Lutjanidae were predominantly represented in the Gulf of Mannar, whereas Monodactylidae and Tetraodontidae showed a greater contribution from Palk Bay. The family-wise composition indicates distinct regional patterns in the distribution of seagrass-associated fish assemblages.

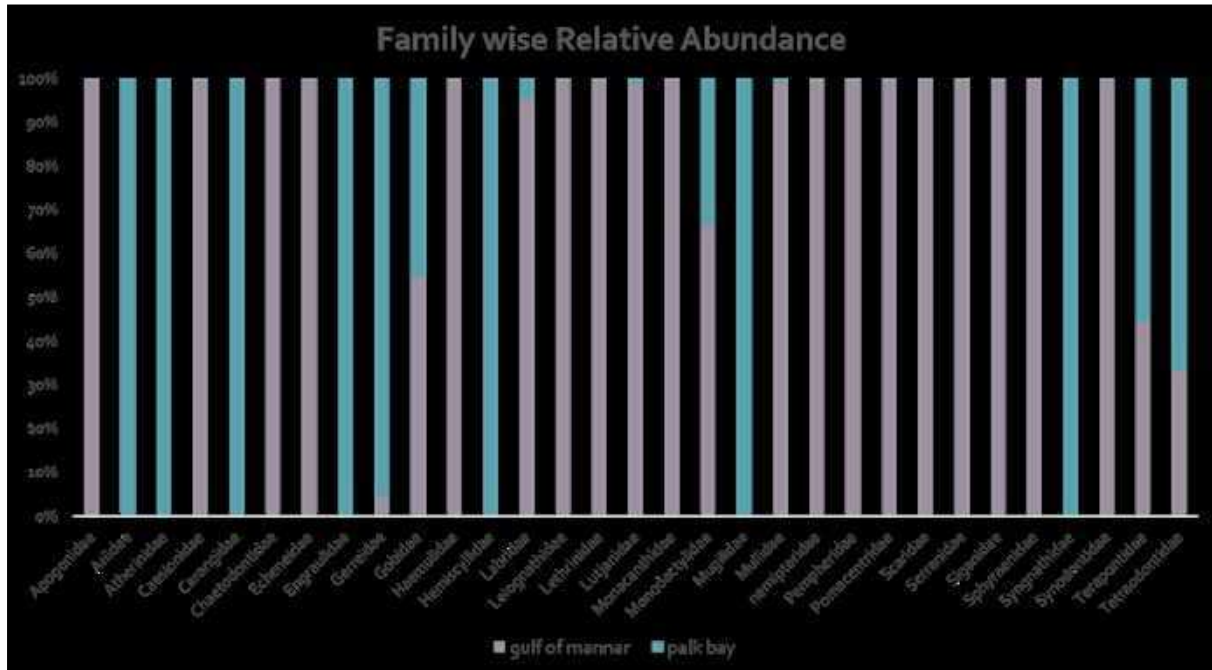


Figure 3.6: The relative abundance of fish families varied between Palk Bay and the Gulf of Mannar

3.4.2.3 Species contributing to the dissimilarity between Palk Bay and Gulf of Mannar fish assemblages

Based on the SIMPER analysis, the species primarily responsible for the compositional differences between the seagrass-associated fish assemblages of Palk Bay and the Gulf of Mannar were identified (Figure 3.7). *Terapon puta* emerged as the largest contributor, representing approximately 34% of the total dissimilarity between the two locations. *Siganus sp.* followed, accounting for nearly 12% of the variation, thus making it the second most significant contributor. Regional differences among community members attributed to various species contributed moderately to the overall dissimilarity, with *Lutjanus sp.*, *Gerres sp.*, *Parupeneus indicus*, and *Karalla daura* each contributing between 3% and 5%. Additionally, species such as *Amblyeleotris sp.*, *Cryptocentrus sp.*, *Lutjanus lemniscatus*, and *Gerres erythrourus* exhibited minimal contributions, generally less than 3%. The SIMPER results

indicate that the differences observed between the fish assemblages in Palk Bay and those in the Gulf of Mannar are predominantly driven by a relatively small number of species,

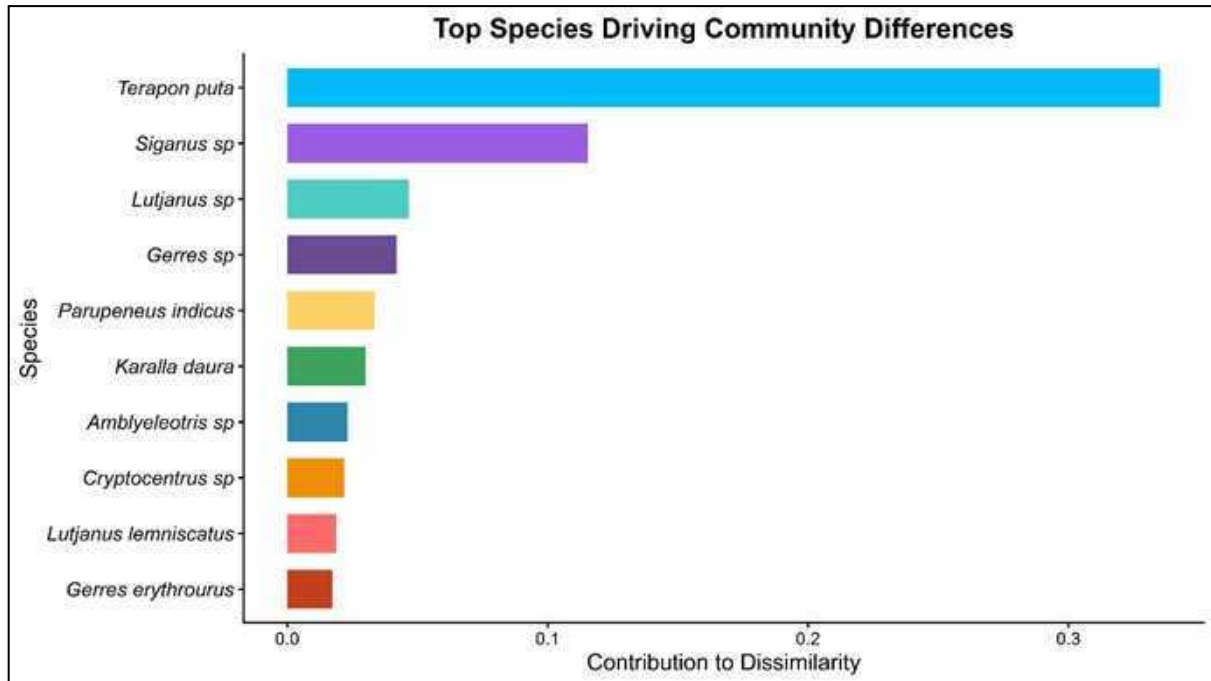


Figure 3.7: Fish genera contributing to the dissimilarity between Palk Bay and Gulf of Mannar

particularly *Terapon puta* and *Siganus sp.*, which together account for a substantial proportion of the total community dissimilarity.

3.4.2.4 Relationship between fish assemblages and environmental variables

The distance-based redundancy analysis (dbRDA) explained 22.4% and 2.7% variations along the first and second constrained axes, respectively (Figure 3.8). This ordination had a partial separation between fish assemblages of Palk Bay and the Gulf of Mannar, yet a heavy overlap was found between the two regions. The environmental vectors suggested the importance of depth, coral cover, rock substrate, seagrass height, and seagrass cover as significant factors in the dispersion of seagrass-associated fishes. In contrast, the sand and epiphytic algae were oriented in the opposite direction indicating a further pattern of species association. *Siganus sp.* and *Parupeneus indicus* were positively associated with increasing seagrass height; *Lutjanus fulvus*, *Stethojulis interrupta*, *Monodactylus argenteus* and *Sphyraena obtusa* were correlated with high coral and rock cover habitats. *Terapon puta* was found distinct off from the general group of species along the first axis, suggesting a separate configuration of habitat association. *Lethrinus sp.* and *Upeneus tragula* were situated at the opposite end of the second

axis and were more closely related to sandy habitats. In all, this dbRDA ordination indicates that habitat features such as seagrass structure and associated benthic elements may have some impact on the characteristics of seagrass-associated fish assemblages in Palk Bay and the Gulf of Mannar.

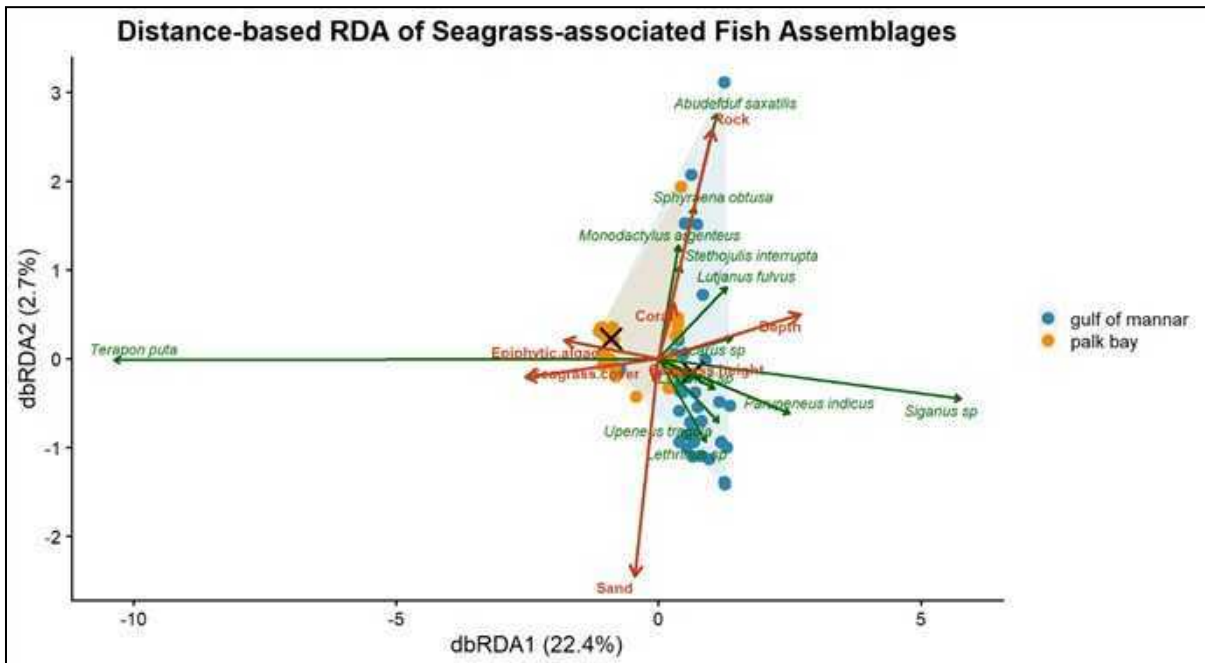


Figure 3.8: Relationship between fish assemblages and environmental variables based on dbRDA

3.4.2.5 Size class distribution of fishes in Seagrass and non-seagrass areas

The density of fishes differed among size classes between seagrass meadows and adjacent non-seagrass habitats (Figure 3.9). Juveniles, sub-adults, and adults exhibited higher densities in seagrass meadows than in non-seagrass areas across all three size classes. Among these, the most common size class within seagrass habitats was juvenile fishes, followed by sub-adults. Non-seagrass habitats supported comparatively lower fish densities, with only a few observations showing relatively high values. The variability in fish density was also greater within seagrass meadows, as indicated by wider interquartile ranges and several high-density observations across all size classes. The boxplots indicate that seagrass habitats supported a broader range of fish densities for juvenile, sub-adult, and adult fishes, whereas densities in non-seagrass habitats remained consistently low.

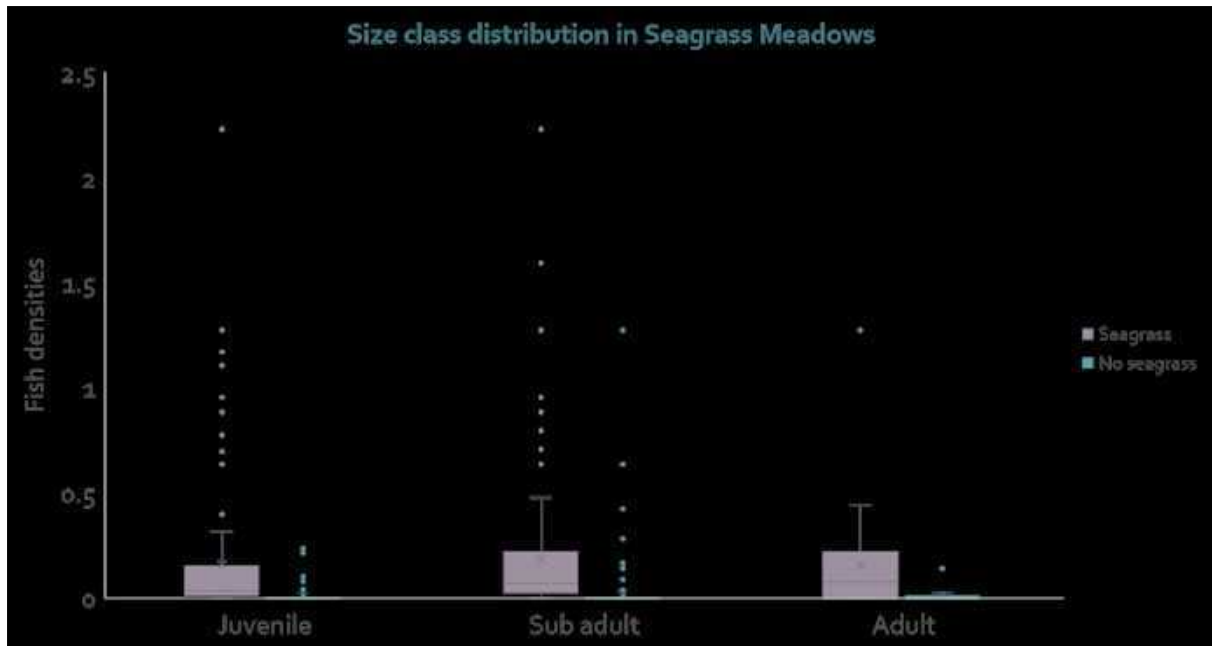


Figure 3.9: Comparison of fish density among various size classes between seagrass meadows and adjacent non-seagrass habitats

3.4.2.6 Distribution of fish densities among feeding guilds in seagrass meadows

Density of fish varied between feeding guilds and size classes (Figure 3.10). The distribution of densities was widest among carnivores and benthivores with the highest values mainly found in the sub-adult and juvenile size classes. Planktivores were represented primarily by juvenile and adult individuals, while detritivores were recorded at low densities largely confined to the sub-adult size class. Juveniles dominated herbivorous fishes, with comparatively lower numbers of sub-adults and adults observed. Omnivorous fishes were represented across all size classes, although sub-adults showed greater variability in density. We identified piscivorous fishes that have low densities and were mostly juveniles. In general, juvenile and subadult fishes accounted for a larger proportion of the densities detected throughout most feeding guilds, whereas adult fishes emerged broadly at lower densities.

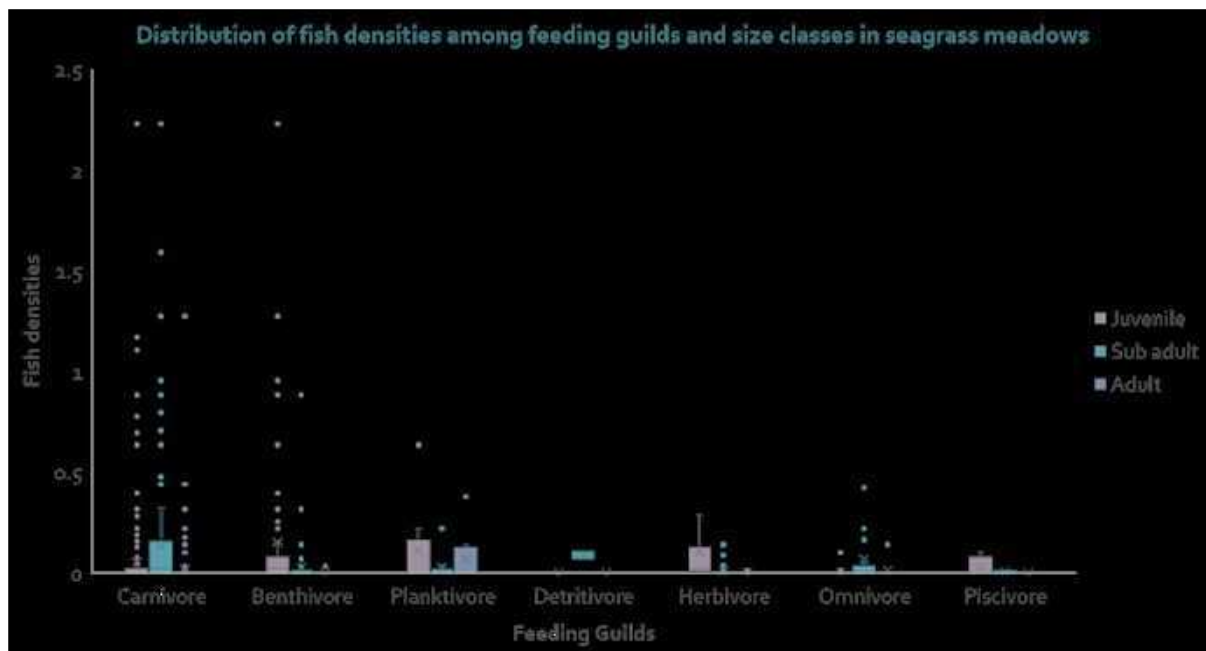


Figure 3.10: Distribution of fish densities among feeding guilds and size classes in seagrass meadows

3.4.2.7 Distribution of fish densities among habitat guilds in seagrass meadows

Fish densities were distributed among seagrass meadows' guilds and sizes (Figure 3.11). In particular, estuarine/seagrass-associated fishes showed the greatest densities and the largest variability, especially in the juvenile and sub-adult size classes. Seagrass/sandy and reef-associated guilds were also present in all levels of size, but at much lower densities. Sandy habitat-associated fishes were dominated by sub-adult and adult individuals, while reef/pelagic fishes were more frequent in the juvenile and adult size categories. Seagrass/coastal fish had higher sub-adult densities and strictly seagrass-associated species were found to have low but consistent densities within all size classes. These groups, including estuarine/coastal, sandy/reef, and reef/estuarine, were collected at relatively low densities. Juvenile and sub-adult fishes accounted for a relatively greater proportion of observed densities for most habitat guilds than adult fishes.

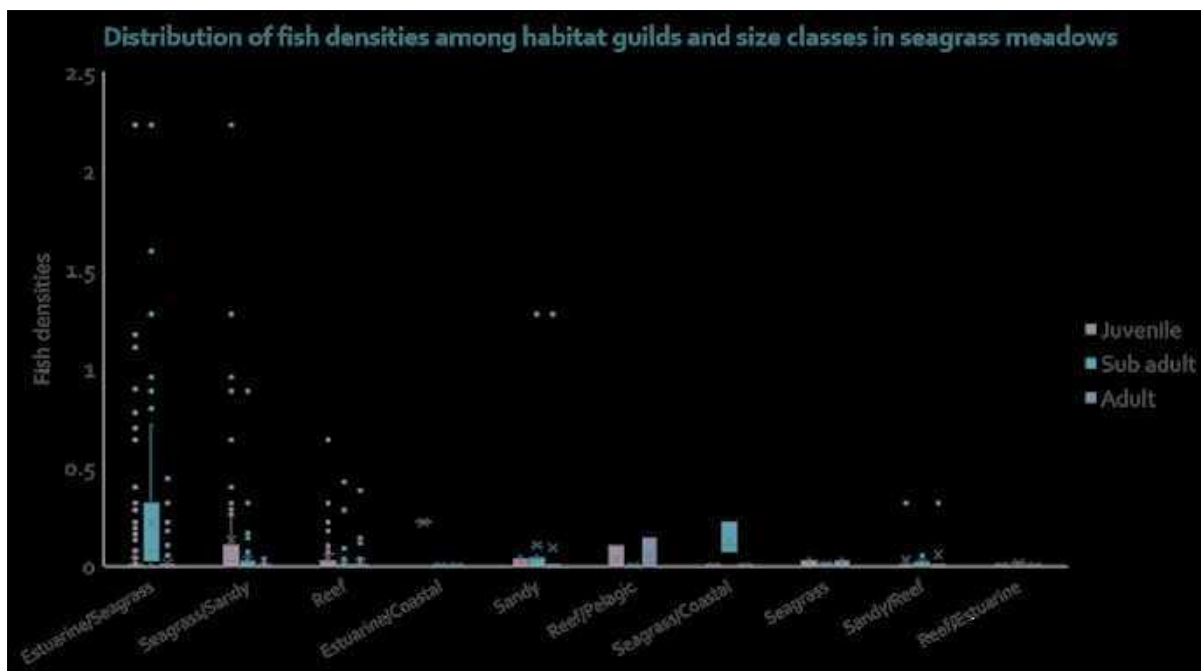


Figure 3.11: Distribution of fish densities among habitat guilds and size classes in seagrass meadows

3.4.2.8 Fish known to be associated with various habitats

The abundance of fishes associated with different habitat types varied across the three depth classes (Figure 3.12). Reef-associated fishes constituted the major proportion of the observations, and showed that the abundance was proportional to the area (86 fish in the 1–2 m depth zone, but 479 at the depth 2–4 m domain and 956 at the depth 4 to 6 m range). It found that generalist species were dominated by shallow waters, with 294 fish recovered (1–2 m) and 61 fish found at 2–4 m as well as being not present in the deepest depth class. Seagrass-associated fishes were mostly recorded in the shallowest depth class (103 of those recorded), 3 at 2–4 m and none at large depths. At 2–4 m, column water-associated fishes comprised 83 individuals, while sand-associated fishes observed relatively similar abundances in all depth classes (39, 30, 32). Most species characterized by unknown habitat associations were identified at mid-depth areas, where 202 identified individuals were recorded. Anemone-associated fishes were also seldom seen, only one fish being detected in the survey. In the end, reef-associated fishes predominated the population, especially at higher depths, and seagrass-associated and generalist fish were concentrated in shallower environments.

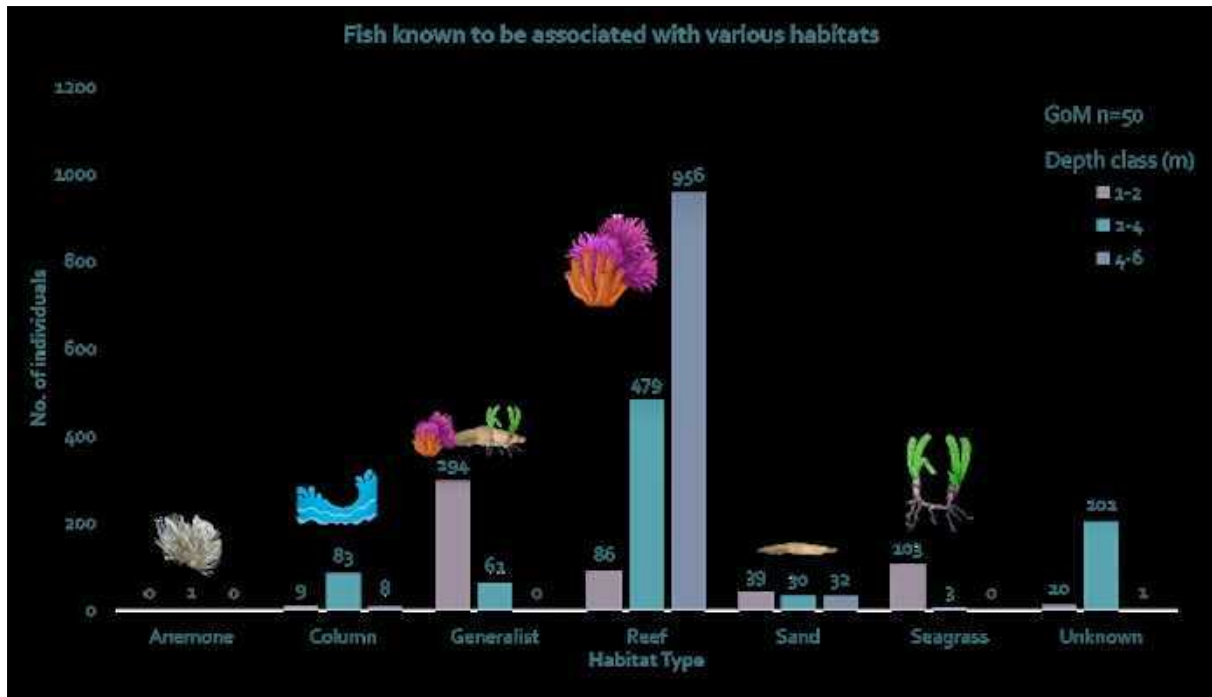


Figure 3.12: Abundance of fishes associated with different habitat types across three depth classes in the Gulf of Mannar

3.4.2.9 Juvenile Fish known to be associated with various habitats

Juvenile fishes collected in these habitat types had divergent distributions (Figure 3.13). The most abundant assemblage (1,212 individuals) were reef-associated juvenile fishes. Generalist species were the next largest group with 264 fish and seagrass-associated juveniles resulted in 103 fish. Water column juvenile fishes made up 67 individuals while sand-associated species were comparatively less abundant with 31 recorded individuals. Only two individuals belonged to species with unknown habitat associations. Reef-associated organisms were the principal source of juvenile fishes detected, but seagrass-associated and generalist organisms also played an important role in the juvenile fish assemblage.

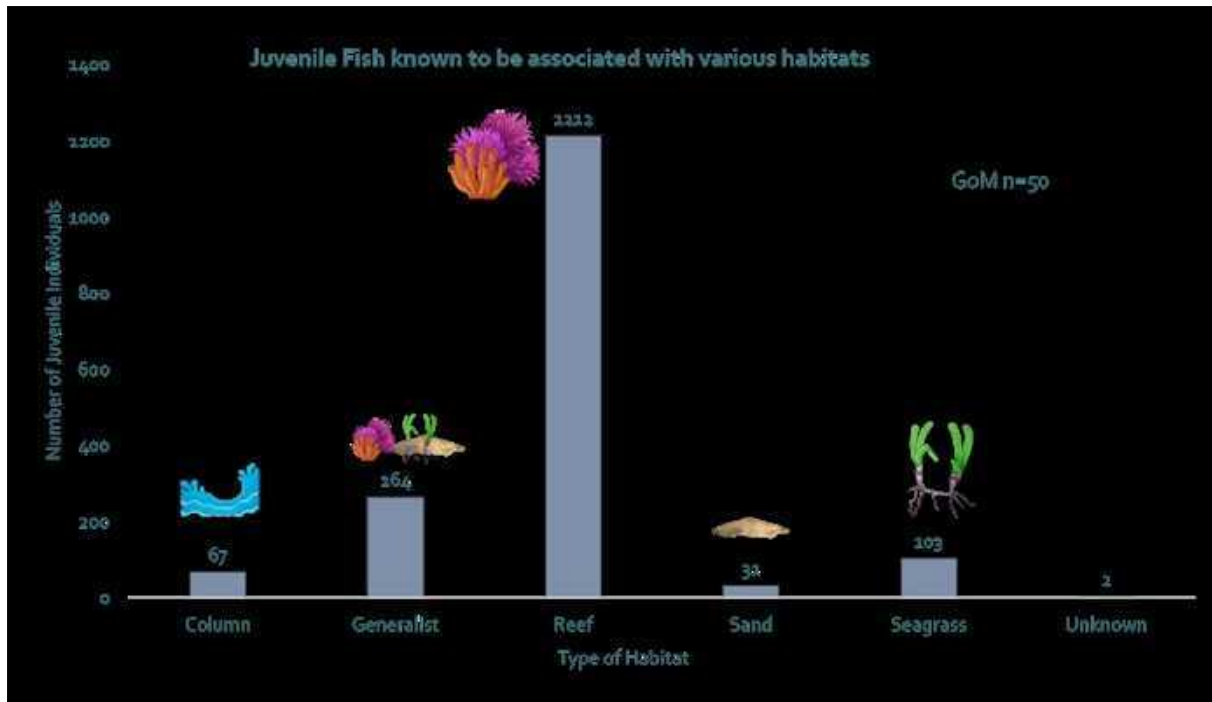


Figure 3.13: Distribution of juvenile fishes among different habitat association groups in the Gulf of Mannar

3.4 Discussion

3.4.1 Standardization of Methodology for the Study of Seagrass-Associated Fishes

Fish assemblages are vital for understanding how seagrass ecosystems contribute to their ecology, but the assessment of them is important for elucidating their value. Similar estimates for species diversity and evenness were obtained using belt transects and point count methods in this study, providing support for both methodologies to reflect accurately the broader community structure of seagrass-associated fishes. Point estimates indicated higher species densities across habitats and feeding guilds, indicating better capacity to differentiate mobile and structurally related groups of fauna. This pattern has been seen in previous studies of stationary visual census methods, which have been applied in complex habitats such as seagrass meadows and coral reefs. Many aspects of fish behavior can be changed as a function of viewer orientation, and repeated swimming of transects may result in underestimation of cryptic or cautious species (Bohnsack & Bannerot, 1986). These changes would otherwise cause noise in the observations, but point count methods mitigate this issue as the fish can acclimatize quickly, so detecting species that seek shelter in the seagrass canopy is much more effective. Harmelin-Vivien et al. (1985) and Watson et al. (1995) observed that in mixed-vegetation landscapes

with poor vegetation structure that reduces visibility, stationary counts serve a distinct purpose in heterogeneous habitats. Coral-, rock-, and anemone-associated fishes had significantly higher population densities during point counts than a standard observation but could have been the site marker due to its species presence across many neighbouring habitats. The increased detection of herbivorous and omnivorous fishes may also be due to their active foraging behavior in seagrass meadows. For the study of habitat use and ecological interactions, one of the objectives, the point count method enhanced the advantages from observing behaviors and size-class calculations. No differences in diversity level indices were seen for either analysis, hence the effectiveness of both methods in the description of species pool. The better performance of the point counts is more than the guild-wise estimators for the guild evaluation, making them desirable for long-term ecological study and ecosystem monitoring and habitat use studies. This finding is supported by Samoilys and Carlos's (2000) recommendation that survey procedures could not depend solely on quantitative information on species richness estimates but should also account for the purposes of the study. Thus, the standardising methodology adopted in this study provides a solid basis for subsequent investigation and the confidence in the ecological patterns of Palk Bay and the Gulf of Mannar has been increased.

3.4.2 Fish Market Surveys and the Commercial Importance of Seagrass Ecosystems

Fish market survey revealed 161 species of fish found to be commercially relevant and 58 fish families that were consistently linked to seagrass. This result emphasizes the essential role of seagrass ecology in Palk Bay's coastal fisheries and addresses the first research question related to the diversification of commercially-relevant seagrass-associated fishes. Seagrass habitats have been shown to be important settings for supporting fisheries production (Beck et al., 2001; Heck et al., 2003; Nordlund et al., 2017), and play an essential role in global fisheries. These provide feeding areas, nursery and refuge facilities for different species of fish, and they migrate to other ecosystems or become crucial to offshore fisheries. This argument is quite justified by the current findings that show the seagrass meadows of Palk Bay support a complex assemblage of finfishes with extremely high economic value. The variation in the species richness found in the markets is likely to be in part due to differences in habitat supplies, fishing effort, equipment, gear, and species association with the surrounding ecosystems. The taxonomic richness of fish markets like Kattumavadi and Manamelkudi fish products derive from catches fished from large seagrass complexes rich in seagrass beds and fishing grounds at many sites, resulting in higher taxonomic richness. On the other hand, markets with a lower diversity are those with lesser diversity may rely on smaller seagrass habitat or a more

fragmented seagrass community. These findings are consistent with studies published in India that suggest that fishery dependence is heavily based on seagrass ecosystems (Jagtap et al., 2003; Thangaradjou et al., 2007). Yet, the present work contributes to the existing literature by bringing to the fore one of the largest available inventories of commercially relevant seagrass-associated finfishes in the region. Market surveys confirmed that underwater observations and data also reveal the ecological significance of seagrass ecosystems for coastal communities in terms of direct economic value. The result implies that the conservation of seagrass is not only of relevance for conserving biodiversity but also should play a role in fisheries management. The destruction of seagrass habitats could reduce fish recruitment globally, with recognized consequences for subsistence (Cullen-Unsworth & Unsworth, 2013; Unsworth et al., 2019).

3.4.3 Regional Variation in Fish Diversity Between Palk Bay and the Gulf of Mannar

Regional variation in fish populations --in diversity especially --is very well-documented for the Gulf of Mannar. Subsea surveys showed relatively high species, genus and family diversity in the Gulf of Mannar vs Palk Bay. This pattern was observable in Simpson's diversity index and dominance scores, which showed that the Gulf of Mannar has a rich and diverse fish community. Higher diversity in this area implies better habitat diversity and high levels of ecological connectivity with coral reefs. Mosaic seagrass beds, coral reefs, and sandy bottoms on rocky substrates dominate the Gulf of Mannar while in the Palk Bay seagrass meadows are mostly isolated and exposed to higher levels of anthropogenic pressure. Palk Bay exhibited a slightly higher level of dominance, reflecting that a few tolerant species dominate the community structure, correlating to environmental stress and habitat simplification (Magurran, 2004). The observed community structure may be associated with fishing pressure, coastal development and habitat disturbance. These findings reflect the second research question, which argues that benthic communities, and habitat complexity, are also predictive of fish assemblages. In tropical seascapes, similarly documented regional differences exist: seagrass habitats tied to coral reefs exhibit more diversity than isolated meadows (Nagelkerken et al., 2000; Dorenbosch et al., 2005).

3.4.4 Family-Wise Composition and Regional Specialization

Family compositions in Palk Bay and Gulf of Mannar are different among coastal communities underline different family-level compositions, with unique local ecosystem elements of significance. The regional dominance by other families was clear over other parts of the island, although this was relatively constant in one region from another. The dominance of reef-

associated species (Pomacentridae, Scaridae and Serranidae) in the Gulf of Mannar suggest the extent to which coral reefs and seagrass meadows are highly ecologically connected. These environments were shown to be capable of supporting ontogenetic migrations (Nagelkerken et al., 2002; Kimirei et al., 2011). In contrast, families like Ariidae and Mugilidae were found to be mostly clustered in Palk Bay, signifying strong estuarine and shallow-coastal zones. The regional specialization of seagrass meadows indicates that they are not isolated habitats, but must also be considered elements in a wider coastal seascape. This observation leads to the conclusion that the focus on a single type of habitat may not retain ecological processes necessary for stable and uniform populations of fish.

3.4.5 Contribution of Species to Community Diversity: SIMPER Analysis Findings

SIMPER analysis indicated that limited species of fish played an important role in the divergence between the fish assemblage in Palk Bay and the Gulf of Mannar. In comparison, *Terapon puta* stood out with one-third of the total difference, followed by a range of other *Siganus spp.* That finding of high frequency suggests that regional diversity is more often driven by specialized and mostly dominant ecological specialists than a uniform spread of species. *Terapon puta* is a local species of shallow estuarine and coastal area, whereas the *Siganus species* are closely associated with highly integrated structurally complex seagrass and reef habitats where they depend on benthic algal and plant substrates. There have been some observations of similar results in tropical seagrass ecosystems, where the presence of concentrated species drives large scale community dynamics (Gullström et al., 2002; Unsworth et al., 2008). From a management perspective, these species may serve as indicators of habitat quality and ecological change.

3.4.6 Drivers Impacting Fish Assemblages in the Environment: Evidence from dbRDA

Based on the dbRDA analysis, fish compositions were grouped based on habitat factors, including seagrass height, seagrass cover, depth, coral cover, and substrate composition. The positive association of *Siganus* with the structural properties of seagrass supports previous knowledge that larger and denser seagrass canopies have a better food supply and offer protection from predators for larger organisms (Heck et al., 2003; Hori et al., 2009). Furthermore, the interspecific relationships between *Lutjanus*, *Sphyræna*, and *Monodactylus* on coral and rocky substrates strongly highlight the importance of connectivity between habitats as a dominant structure in tropical seascapes. *Terapon puta* occupies a unique benthic ecological niche, which is rarely found amongst many species associated with reefs. The

benthic composition of habitats also affects the organization of communities, as exemplified by species in the sandy substrate (*Upeneus tragula*). The results from the dbRDA analysis strongly support the second question and show that habitat heterogeneity and structural characteristics of seagrass plays an important role in the organization of fish populations.

3.4.7 *Size-Class Distribution and Nursery Function of Seagrass Meadows*

In all size groups, fish densities were consistently larger in seagrass habitats than in non-seagrass habitats. Juveniles comprised the largest part of the assemblage with sub-adults and adults next. This trend is nicely captured by the nursery role hypothesis by Beck et al. (2001) suggesting that nursery habitats have a disproportionate density of adult populations. Dense seagrass vegetation decreases risks of predation and provides many foods (necessary for juvenile survival). Increased maximum density of seagrass meadows allows them to accommodate a larger population of resident and transient fish. Similar role has been established around seagrass providing nurseries in these tropical seagrass ecosystems (Heck et al., 2003; Jackson et al., 2001; Nagelkerken et al., 2002). The results clearly relate to the third research question as it indicates that far more commercially-important fish species rely on seagrass habitats at different life history stages.

3.4.8 *Feeding Guild Structure*

Juvenile and subadult fishes predominate in the different feeding guilds, in particular carnivores and benthivores. Most herbivores were juveniles, and piscivores were rather few. The dominance of lower trophic-level consumers indicates high productivity in seagrass ecosystems which produce copious amounts of epiphytes and invertebrates and abundant detrital food web (Valentine & Duffy, 2006). This suggests that seagrass meadows facilitate complex ecological interactions (multiple feeding guilds). The juvenile herbivores are overrepresented which may indicate the seagrass meadows is a safe environment of forage, growth and development, potentially allowing fish to occupy other habitats in the later life stages. Similar ontogenetic modifications have also been observed in rabbitfishes and parrotfishes in the Indo-Pacific.

3.4.9 *Habitat Guilds and Ecological Connectivity*

Estuarine seagrass guilds showed the most species richness and variability, especially among juvenile fishes and sub-adult fishes. These guilds were the most heterogeneous species compositions among even relatively heterogeneous populations. Reef-associated and seagrass-sandy guilds also contributed to the assemblage. These findings demonstrate that multiple

habitats are not restricted to single ecosystems for a whole variety of fish during their lifetime. Connectivity to the living environment has proven particularly important in the field of coastal marine ecology (Nagelkerken et al., 2002; Sheaves, 2009). It can be inferred from the distribution data that seagrass meadows provide an intermediate habitat that connects estuaries, coral reefs and coastal waters.

3.4.10 Habitat Relationships Along Depth Gradients

Reef-associated fishes predominated in deeper areas while the seagrass-related and more generalist species were predominant in shallower waters. This trend in depth correlates with the dissimilarity in habitat species and in the structural complexity. At greater depths, coral reefs are particularly important as well, offering housing for the small-bodied, juvenile fish that benefit from shallow seagrass meadows nearby. They are in line with other observations, which have shown that the presence of depth gradients may have effect on species composition by changes in habitat structures and predator-prey interactions.

3.4.11 Juvenile habitat associations

The reef-associated juveniles represented the majority of the juvenile assemblage followed by generalist and seagrass-associated juveniles. Instead of emphasizing a reduced part played by seagrasses, these findings reinforce the strong ecological inter-relatedness between reefs and seagrass habitats. Large quantities of reef fishes utilize nursery meadows in seagrasses prior to migrating into adult reef habitats (Dorenbosch et al., 2005; Kimirei et al., 2011). The high distribution of seagrass-associated juveniles also supports the nursery status of these habitats and the importance of maintaining habitat mosaics instead of isolated ecosystems.

The present study indicates that the seagrass systems of Palk Bay and the Gulf of Mannar are key to coastal communities, fisheries, and the preservation of biodiversity. Research indicated 161 species of commercial significance to the market resources through fish market surveys, and observations underwater revealed the importance of habitat variability and environmental gradients to fish populations. Diversity analyses examining diversity and dbRDA data revealed habitat characteristics and ecosystem connectivity contribute to community composition and thus the second research question. The repeated abundance of juvenile fishes and positive relationships between commercially significant species and seagrass habitats in vulnerable life-history periods addressed the third research question. Collectively the results show how seagrass meadows also represent nurseries, feeding areas, refuges, shelter sites, and ecological corridors linking coral reefs, estuaries and coastal waters. This means that defending these

ecosystems is not just important to preserve biodiversity, but also for the continued productivity of fisheries and the livelihood of coastal families. The present study is one of the most comprehensive assessments of seagrass-associated commercial finfishes in southeastern India, and thus provides a basis for evidence-based management policy that accommodates seagrass conservation as an integral part of fisheries planning.

**Chapter 4: Resource (food and space)
partitioning patterns among fin fish
species associated with seagrass
ecosystems**

4 Resource (food and space) partitioning patterns among fin fish species associated with seagrass ecosystems

4.1 Introduction

Resource partitioning is a fundamental ecological mechanism that facilitates the coexistence of species by reducing competition for limiting resources such as food and habitat. In marine ecosystems, Schoener (1974) identified food, space, and time as the principal niche dimensions through which species minimize competitive overlap. Seagrass meadows, owing to their high structural complexity and diverse food resources, provide an ideal setting for resource partitioning among finfish assemblages. These habitats support a wide range of trophic guilds, including herbivores, omnivores, benthic invertivores, planktivores, and piscivores, allowing numerous species to coexist within relatively small spatial scales (Heck et al., 2003).

Food partitioning among seagrass-associated fishes is often driven by differences in prey selection, feeding morphology, ontogenetic shifts, and diel feeding behaviour. Many juvenile fishes exploit epifaunal crustaceans, polychaetes, and molluscs associated with seagrass blades and sediments, while larger predatory species target fish and decapod crustaceans. Hyndes et al. (1997) demonstrated that closely related sillaginid fishes inhabiting coastal seagrass habitats partition food resources according to body size, mouth morphology, and habitat preferences, thereby reducing interspecific competition. Similarly, Connolly et al. (2005) reported that seagrass-derived organic matter and epiphytic algae contribute differentially to the diets of economically important fish species, highlighting the diversity of available trophic pathways.

Spatial partitioning is equally important in maintaining fish diversity within seagrass ecosystems. Variation in canopy height, shoot density, sediment type, and proximity to mangroves or coral reefs creates a mosaic of microhabitats that support species-specific habitat preferences. Fish assemblages often segregate according to these habitat features, with some species occupying dense seagrass patches for refuge from predators while others forage in meadow edges or adjacent unvegetated areas (Bell & Westoby, 1986; Nakamura & Sano, 2004). Habitat complexity enhances niche differentiation by increasing the availability of shelter and feeding opportunities, thereby reducing direct competition among co-occurring species (Duffy, 2006).

Resource partitioning also occurs across life-history stages. Many commercially important fishes use seagrass meadows as nursery grounds, with juveniles exploiting sheltered habitats and abundant prey before migrating to coral reefs or offshore waters as adults (Nagelkerken et al., 2013). Ontogenetic habitat shifts reduce competition between age classes and contribute to the ecological connectivity of tropical seascapes. Furthermore, diel movements between mangroves, seagrass meadows, and adjacent habitats enable fishes to exploit spatially separated resources while balancing feeding opportunities and predation risk (Hammerschlag et al., 2010).

A coherent understanding of resource partitioning among seagrass-associated commercial finfishes requires integrating habitat use, feeding ecology, and species interactions. Therefore, this study first investigates the different seagrass microhabitats utilized by obligatory seagrass-associated commercial finfish species, followed by an assessment of the food resources exploited within these habitats. Building upon these observations, the study examines how species reduce potential competition by partitioning available resources through differences in habitat preference and dietary composition. By addressing these interconnected questions, the research aims to elucidate the ecological mechanisms that facilitate the coexistence of commercially important finfish species in seagrass ecosystems and to provide insights into the role of habitat heterogeneity in sustaining fish diversity and fisheries productivity with following research questions:

1. Which different microhabitats are utilized by obligatory seagrass associated commercial finfish species?
2. What kind of food resources are utilized by these commercial finfish species?
3. How these commercial finfish species segregate themselves by resource partitioning?

4.2 Methods

4.2.1 Field Methods

To understand diversity and usage of seagrass meadows by fish, random point counts were conducted at Gulf of Mannar and Palk Bay (Figure 4.1). Variable radius point counts were performed by noting down each fish sighting in the point count. Observer hovered not more than 2m above centre of the point for 10 minutes. The dominant activity within every minute of every fish species individual or shoal was noted along with seagrass characteristics. Their numbers were specified according to size classes with reference to the tape. Position of fish

individual/ shoal in seagrass column were also noted. Selection of next point was done by swimming in random direction. Distance between two points is kept minimum 20 m. Number of point counts were minimum 3 to maximum 5.

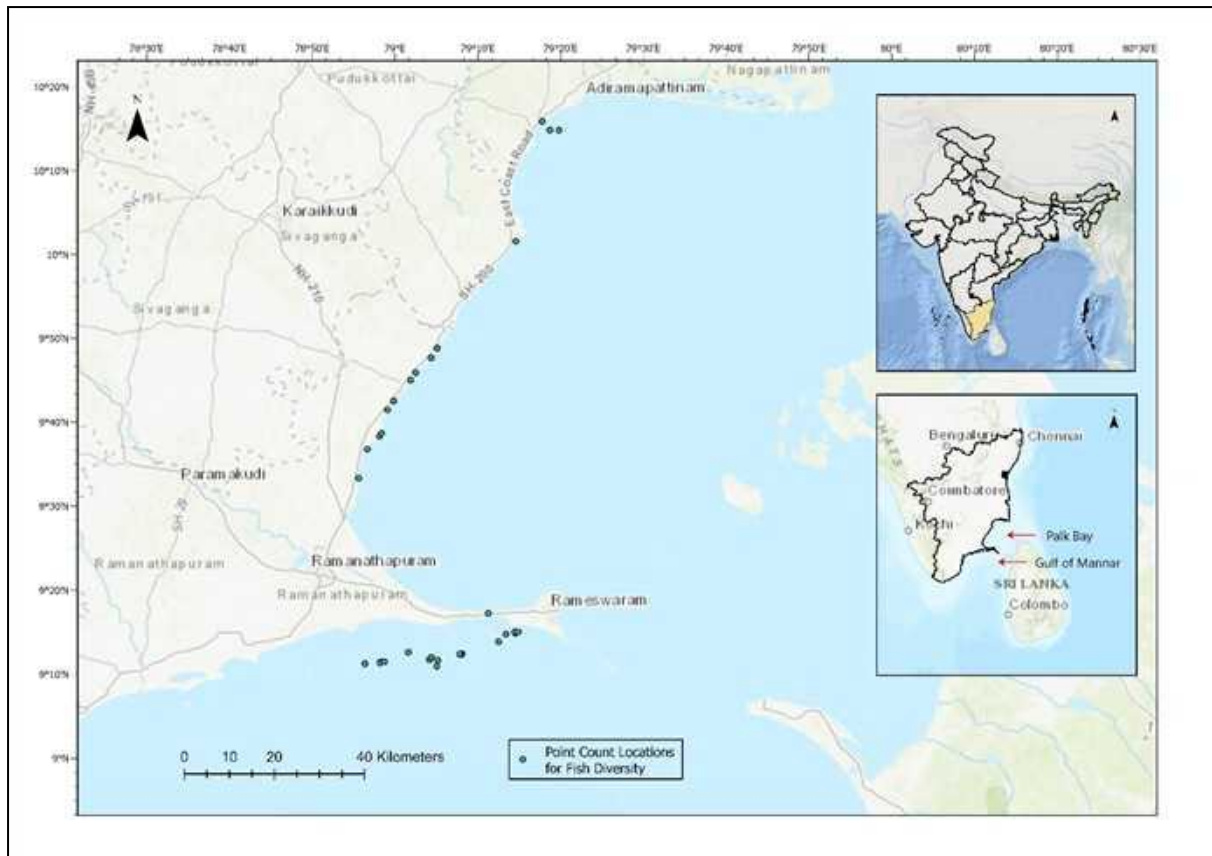


Figure 4.1: Sampling sites for underwater point counts to understand seagrass usage by fish

Field sampling was carried out between October 2021 and November 2022 to obtain information about the food resource use. Fish were collected using gill nets in 10 sampling transects in the seagrass meadows of the Dugong Conservation Reserve. The specimens were identified to the lowest taxonomic level using standard taxonomic keys immediately after collection. Each fish was dissected by making a ventral incision and the alimentary canal was carefully removed. The stomach and gut contents were removed and stored for further analysis. To determine the food resources used by the finfish species, we performed gut content analysis. We sorted food items under a stereomicroscope and identified the lowest practicable taxonomic category. The prey items were then classified into major dietary categories to understand the feeding processes and resources used by the seagrass-associated commercial fishes.

4.2.2 Analysis

Fish behavioural observations were divided into activity classes like moving, passing, feeding, hiding, guarding, and combinations of these activities. The frequency of each activity was calculated and expressed as a percentage of the total observations to characterize behaviour patterns in seagrass meadows. Behavioural data were also compared between the seagrass ecosystems of Palk Bay and the Gulf of Mannar for regional differences in habitat use. Vertical habitat utilization was determined by recording individual fishes in the seagrass meadow and dividing them into upper canopy, lower canopy, bottom, and associated microhabitats. The relative proportion of observations within each habitat was calculated to determine spatial occupancy. Habitat utilization was also measured in the two study regions to identify the variation in microhabitat use.

Habitat preferences of species were evaluated using a Habitat Utilization Coefficient (HUC), which measured the association of fish species to different seagrass density classes (dense, medium, and sparse). Habitat associations were also measured by integrating information about water depth, seagrass density, and substrate characteristics to build a habitat association matrix for the species recorded. Indicator Species Analysis was performed to identify species significantly associated with particular seagrass microhabitats. The analysis was carried out using the group-equalized indicator value index (IndVal.g) in the `multipatt()` function of the R package `*indicpecies*`. Statistical significance of species-habitat associations was evaluated using 999 permutation tests.

The diet composition was determined from gut contents for the selected commercial finfish species. The gut contents were separated into major food categories such as algae, seagrass, crustaceans, polychaetes, worms, fish remains, molluscan shells, and other miscellaneous items. The proportion of each food category was calculated and expressed as percentages to characterize the species' feeding patterns. The dietary information was subsequently used to classify fishes into functional feeding guilds and to identify the spatial and trophic resource distribution among seagrass-associated finfish species. Habitat use and dietary composition were combined to establish the spatial and trophic resource distribution among the fish population.

All statistical analyses and graphical visualizations were carried out in R software (R Core Team, 2025) with appropriate packages for data manipulation, visualization, and ecological analyses.

4.3 Results

4.3.1 Usage of seagrass space by fishes

The observed behavior of fish in seagrass meadows indicated that movement constituted the predominant activity, accounting for 32.49% of the total observations (n = 1448 fish) (Figure 4.2). Additionally, a significant proportion of fish (23.68%) were noted to traverse the meadow. Feeding behavior was recorded in 16.63% of instances, while fish were observed to conceal themselves within the seagrass canopy or adjacent microhabitats for 13.31% of the time. Instances of fish engaging in feeding while in motion were documented at a rate of 7.05%, and fish were recorded guarding their burrows or holes 4.50% of the time. Rare behaviors included fish remaining in proximity to the observer (0.98%), obscuring themselves while feeding (0.78%), and simultaneously moving and hiding (0.59%).

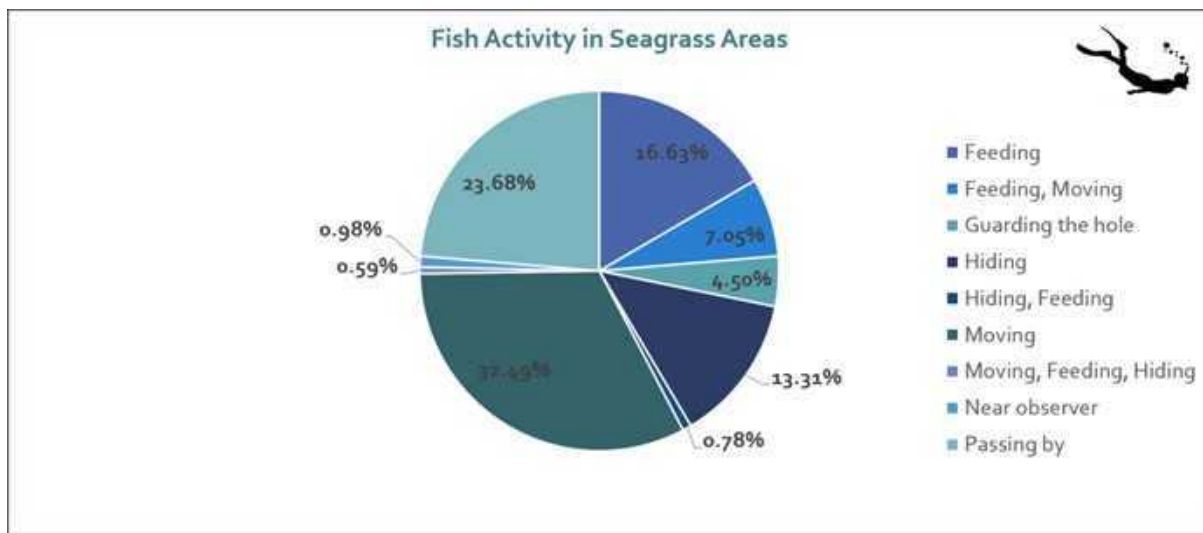


Figure 4.2: Overall fish activity observed in seagrass meadows

Distinct differences in fish activity patterns were observed between the seagrass meadows of Palk Bay and the Gulf of Mannar (Figure 4.3). In Palk Bay, passing activity was the most common behaviour (32.86% of the observations), moving (26.19%), hiding (20.48%), and feeding (17.62%) was also observed. Guarding the hole was only recorded occasionally (0.48% of all the observations). On the other hand, the seagrass meadows of the Gulf of Mannar had a much higher proportion of feeding activity (40.00% of the observations). Moving was the second most common behaviour (25.45%), followed by guarding the hole (16.36%), and hiding (12.73%). Passing was not very frequent (3.64% of the observations), hiding while feeding was made up of 1.82% of the total observations.

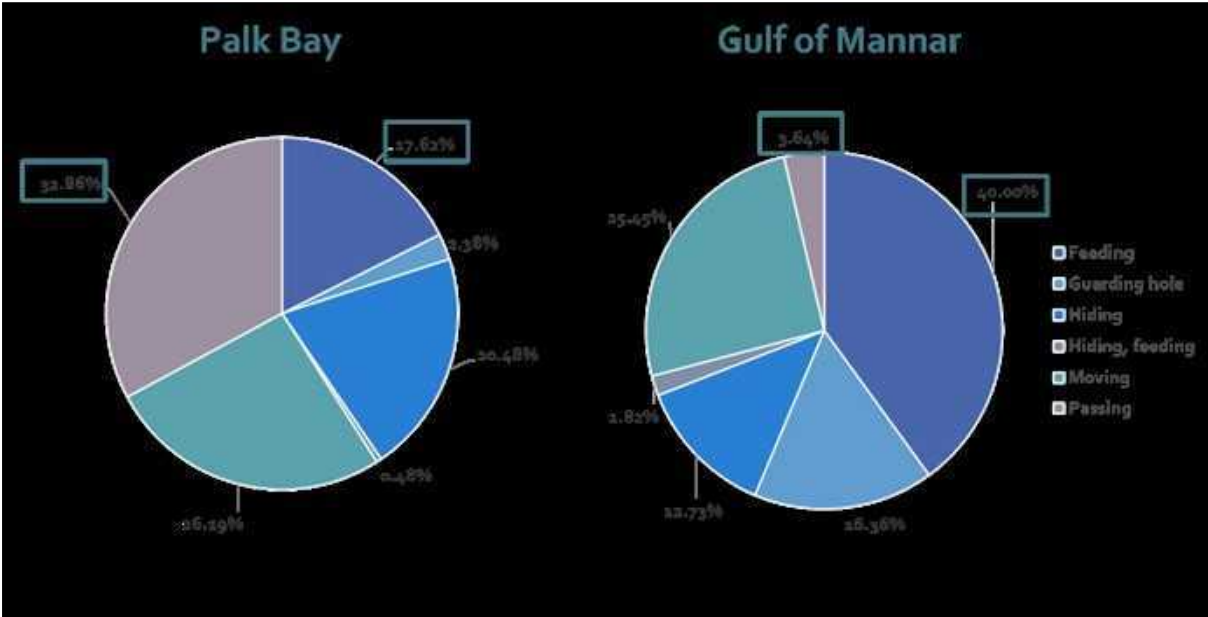


Figure 4.3: Comparison of fish activity patterns in seagrass meadows of Palk Bay and the Gulf of Mannar

The observations regarding the positional distribution of fish within the seagrass canopy indicate that the lower canopy was utilized most frequently, accounting for 68.03% of all recorded instances (Figure 4.4). Fish were also observed in the upper canopy, representing 19.95% of the total records, while the bottom canopy, despite its designation, was the least

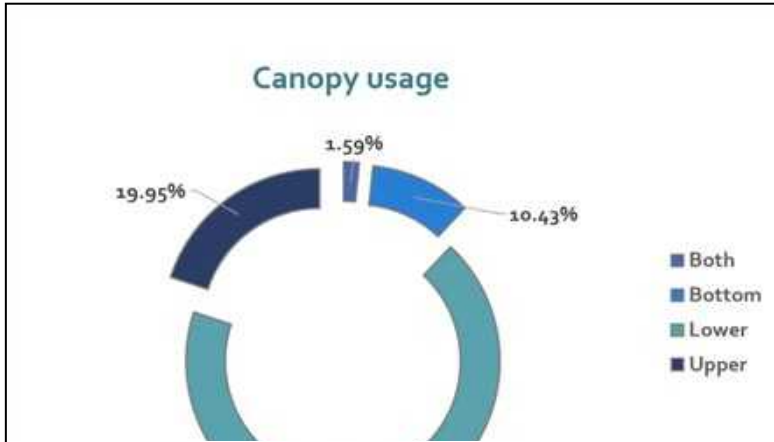


Figure 4.4: Vertical canopy utilization patterns of fishes in seagrass meadows

utilized, comprising 10.43% of all observations (Figure 4.4). Notably, concurrent usage of both the upper and bottom canopies occurred in only 1.59% of the recorded instances.

There are clear differences in habitat utilization between seagrass meadows in Palk Bay and Gulf of Mannar (Figure 4.5). In Palk Bay, the lower canopy was the most occupied habitat, accounting for 66.99% of the observations, followed by the upper canopy (19.14%). Fish near the bottom account for 9.09% of the observations while those close to the observer account for 3.83% of the observations. The whole water column is used only 0.96% of the times. The lower canopy in the Gulf of Mannar also has the highest number of observations (39.29%), and the bottom (35.17%). Fish near rocks are 10.71% and near the observer 5.36%. The habitat near coral is 3.57% of all data, the upper canopy (1.79% of all data), the algae (1.79% of all data) and around anemones (1.79% of all data) was less frequently reported.

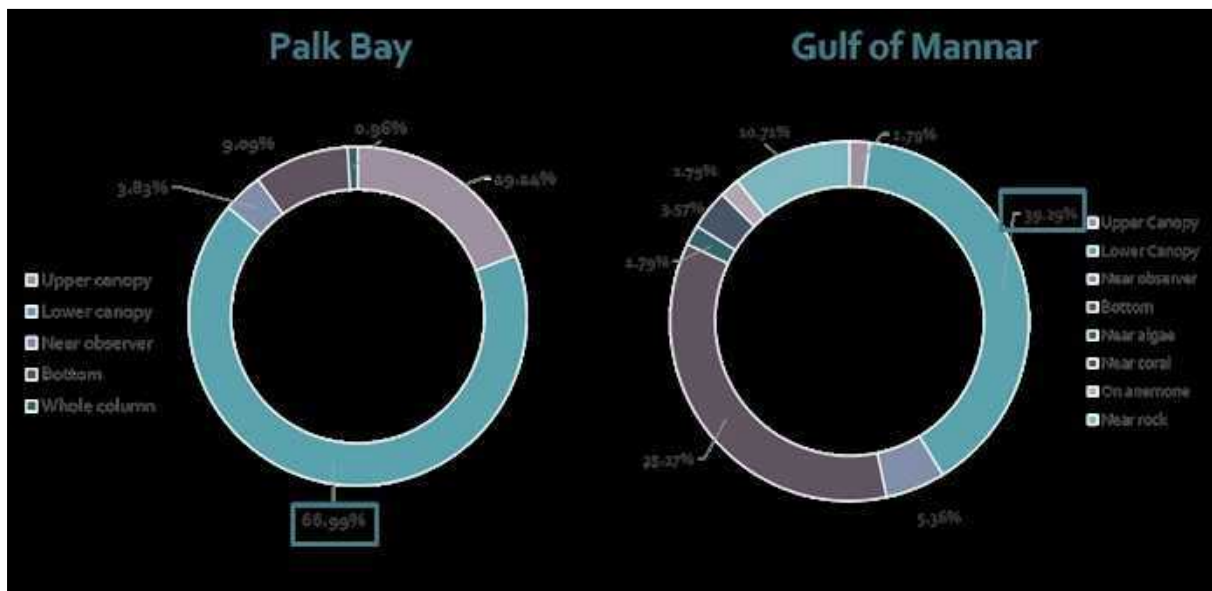


Figure 4.5: Comparison of vertical canopy utilization and associated microhabitat use by fishes in the seagrass meadows of Palk Bay and the Gulf of Mannar

We observed species-specific variations in habitat utilization across the three seagrass microhabitats (see Figure 4.6). Our findings indicate that several species, including *Acreichthys tomentosus*, *Amphiprion sebae*, *Anampses caeruleopunctatus*, *Arius maculatus*, *Arothron immaculatus*, *Atherinomorus lacunosus*, *Cheilinus oxycephalus*, and *Chiloscyllium griseum*, exhibited a strong association with dense seagrass environments. In contrast, species such as *Amblyeleotris periphthalma*, *Amblyeleotris* spp., *Caesio* spp., and a singular observation of *Chaetodon collare* demonstrated a preference for medium-density seagrass. Alternatively,

Abudefduf saxatilis and *Cheilinus chlorourus* were predominantly associated with sparse seagrass meadows. Notably, the observation of *Chaetodon collare* in sparse habitats suggests

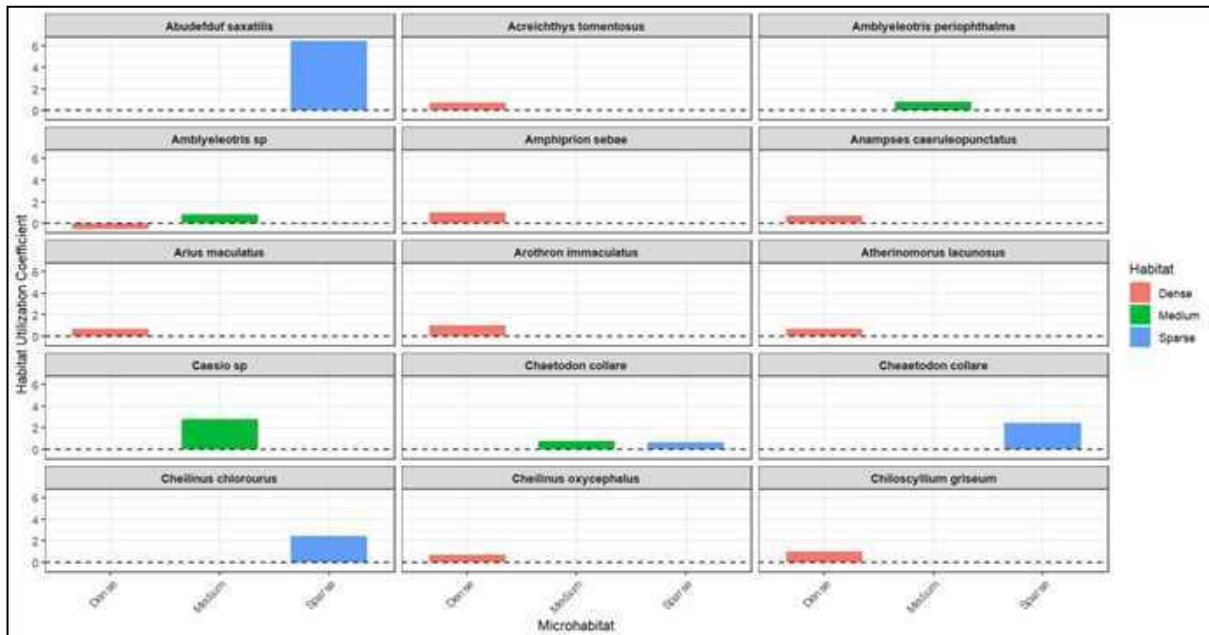


Figure 4.6: Habitat utilization coefficients of fish species across dense, medium, and sparse seagrass meadows

that this species may utilize multiple seagrass density classes.

The habitat association matrix disclosed species' preference for depth, seagrass density and substrate types among seagrass-associated fishes (Figure 4.7). Different patterns were present in the three habitat variables, indicating that the fish use different habitats. In terms of depth preference, *Abudefduf saxatilis*, *Acreichthys tomentosus*, *Amphiprion sebae*, *Caesio sp.*, *Chaetodon collare*, *Cheilinus chlorourus* and *Cheilinus oxycephalus* were associated with deeper waters (4-6 m). *Amblyeleotris periphthalma*, *Arius maculatus* and *Atherinomorus lacunosus* were associated with moderately deep habitats (2-4 m), while *Amblyeleotris sp.*, *Anampses caeruleopunctatus* and *Arothron immaculatus* were associated with shallow habitats (0-2 m). In terms of seagrass, most species were associated with dense seagrass meadows, including *Acreichthys tomentosus*, *Amblyeleotris sp.*, *Amphiprion sebae*, *Anampses caeruleopunctatus*, *Arius maculatus*, *Arothron immaculatus*, *Atherinomorus lacunosus*, *Cheilinus oxycephalus* and *Chiloscyllium griseum*. *Amblyeleotris periphthalma* and *Caesio sp.* were associated with medium density seagrass habitats. Records of *Chaetodon collare*

indicate seagrass habitats, one in the dense and the other in the sparse seagrass habitat. *Cheilinus chlorourus* was associated with sparse seagrass meadows.

Substrate preferences showed that most species were associated with sparse seagrass covered substrates. *Amblyeleotris periophthalma*, *Amblyeleotris sp.*, *Amphiprion sebae*, *Anampses caeruleopunctatus*, *Arius maculatus*, *Arothron immaculatus*, *Atherinomorus lacunosus*, *Chaetodon collare*, *Cheilinus chlorourus*, *Cheilinus oxycephalus* and *Chiloscyllium griseum* were associated with sandy substrates. *Abudefduf saxatilis* was associated with rocky substrates, and the second record of *Chaetodon collare* was associated with sandy bottoms.

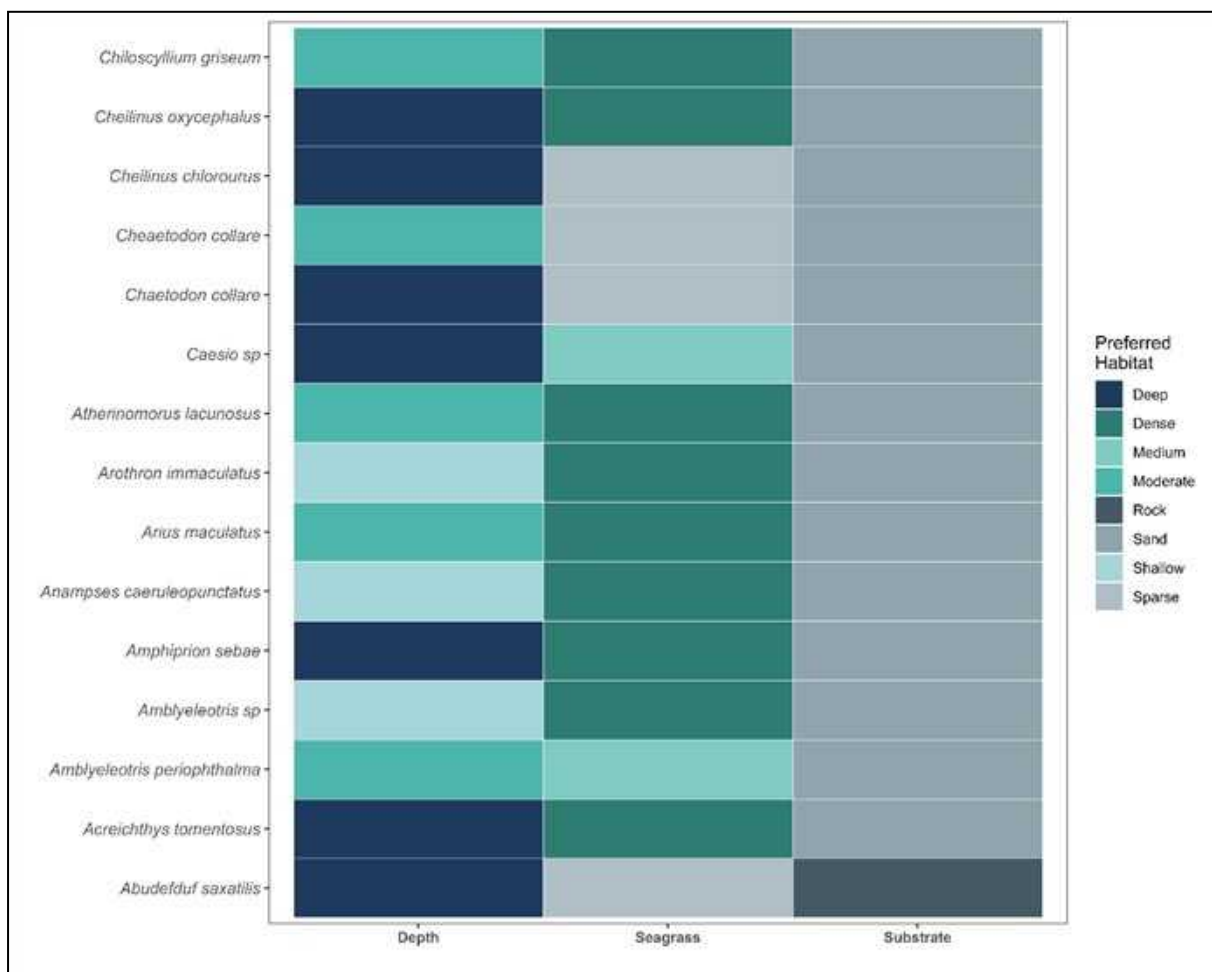


Figure 4.7: Habitat association matrix of seagrass-associated fish species based on preferred depth, seagrass density, and substrate characteristics

The indicator species analysis revealed some fish species that were highly related to certain seagrass microhabitats (Figure 4.8). The size of the circles corresponds to the indicator value and the colour gradient to the p-value. The species in the medium seagrass habitat include *Lutjanus fulviflamma* (indicator value = 0.32, $p = 0.034$) and *Oplopomus oplopomus* (indicator value = 0.18, $p = 0.050$). The medium and dense seagrass habitat was characterized by *Terapon puta*, which has the highest indicator value in all the species (indicator value = 0.70, $p = 0.002$). Several species were significantly associated with sparse seagrass habitats. *Pomacentrus sp.* (Indicator value = 0.24, $p = 0.034$), *Pomacentrus simsiang* (Indicator value = 0.25, $p = 0.028$), *Lutjanus lemniscatus* (Indicator value = 0.12, $p = 0.045$), *Lutjanus fulvus* (Indicator value = 0.35, $p = 0.002$), and *Halichoeres sp.* (Indicator value = 0.22, $p = 0.034$) among them had the highest indicator value for sparse seagrass habitats. The mixed sparse and medium seagrass habitat was represented by *Upeneus tragula*, which was found to be associated significantly with this habitat category (Indicator value = 0.26, $p = 0.048$).

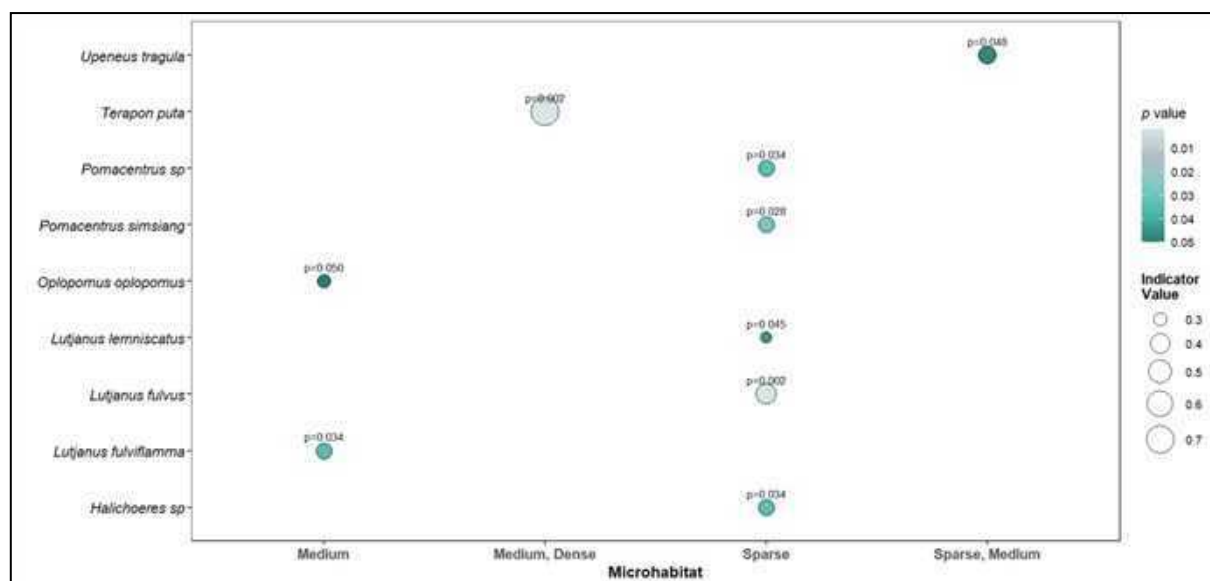


Figure 4.8: Indicator species analysis showing significant associations of fish species with different seagrass microhabitats

Regarding microhabitats, the majority of seagrass-associated finfish species exhibit distinct spatial segregation patterns (Figure 4.9). The species were associated with five identified microhabitats: the bottom, between leaves, above leaves, the water column, and near coral. Certain species demonstrate a strong affiliation with specific habitat types. Notably, *Amblyeleotris sp.*, *Cryptocentrus sp.*, *Halichoeres sp.*, and *Oplopomus oplopomus* were predominantly located in the bottom habitat, indicating a high degree of habitat specialization

among these species. *Pelates quadrilineatus* primarily inhabited the between-leaves microhabitat, while *Upeneus tragula* predominantly occupied the bottom habitat, with occasional occurrences between seagrass leaves. The Gerreidae family exhibited varied habitat utilization patterns. *Gerres sp.* was largely confined to the bottom but also utilized the between-leaves and above-leaves habitats. In contrast, *Gerres oyena* and *Gerres oblongus* showed a preference for the upper strata of the seagrass canopy. *Scolopsis taenioptera* was primarily found in the water column, with some utilization of the bottom habitat. Other commercially significant taxa, including *Terapon puta*, *Siganus sp.*, *Lethrinus sp.*, *Lutjanus spp.*, and *Parupeneus indicus*, demonstrated broader habitat usage. *Terapon puta* and *Pelates quadrilineatus* were predominantly associated with the between-leaves habitat, while *Lethrinus sp.* and *Parupeneus indicus* occupied various habitats, including the bottom, between leaves, and near coral. *Siganus* species utilized habitats both between leaves and within the water column and above-leaf areas. These patterns indicate a substantial diversity in habitat specialization and breadth among seagrass-associated finfishes.

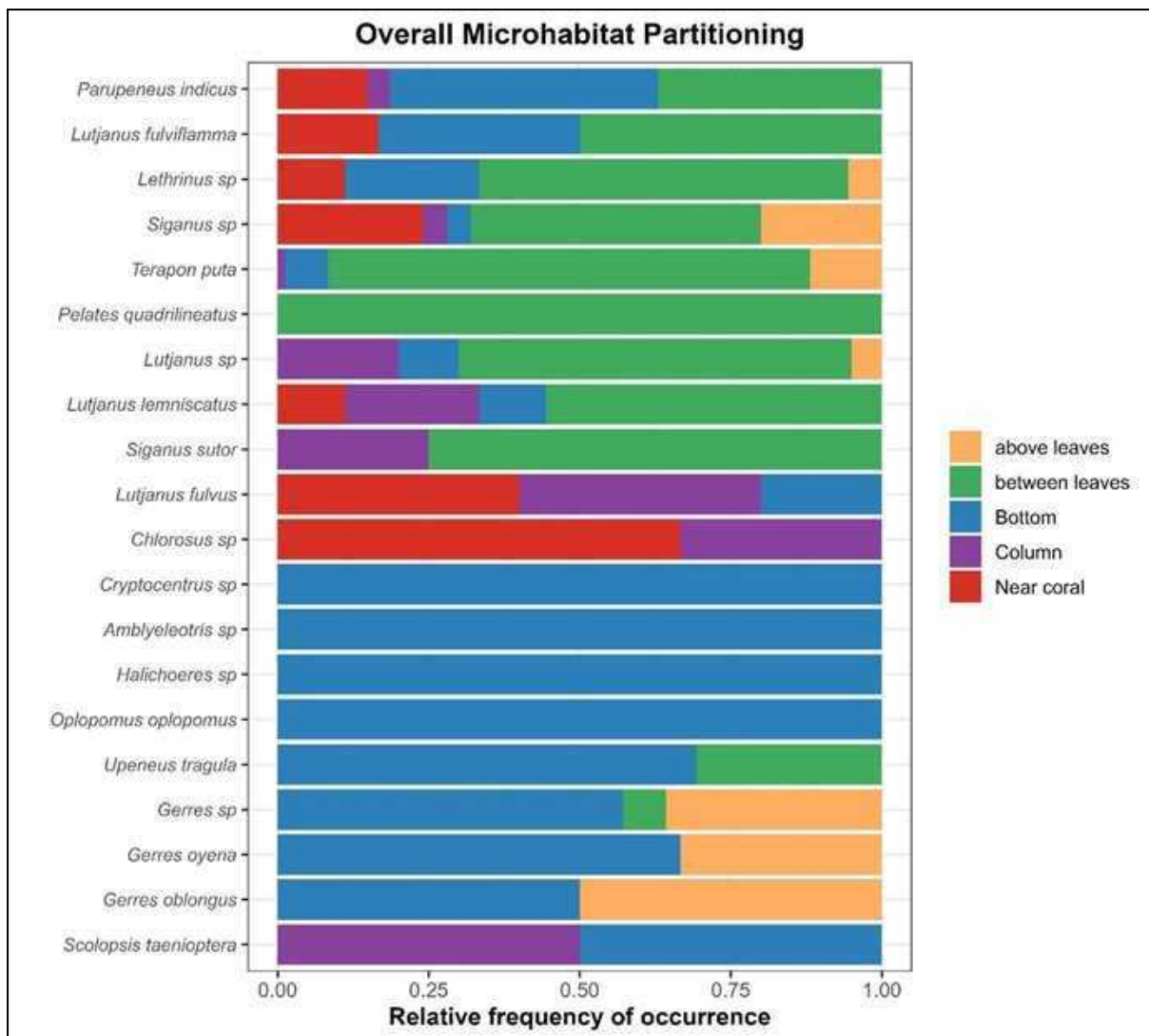


Figure 4.9: Microhabitat partitioning in the most commonly occurring seagrass associated fish of Palk Bay and Gulf of Mannar

In Palk Bay, gobiid fishes such as *Amblyeleotris periophthalma*, *Amblyeleotris sp.* and *Cryptocentrus sp.* all were found to be restricted to bottom habitats, indicating a high degree of habitat specialization. *Pleurosicya mossambica* and *Moolgarda seheli* were also found to occupy a low habitat use. In contrast, Gerreidae species used multiple habitats. *Gerres erythrourus*, *Gerres oblongus*, *Gerres oyena* and *Gerres sp.* ranged in bottom, above-leaf and between-leaf habitats, whereas *Terapon puta* was mainly associated with between-leaves habitat (Figure 4.10)

At the Gulf of Mannar, there was broader habitat utilization among several commercially important species. *Siganus sp.*, *Parupeneus indicus*, *Lutjanus lemniscatus* and *Lutjanus fulviflamma* occupied several habitat types, including bottom, canopy and near-coral habitats. *Amblyeleotris sp.* and *Cryptocentrus sp.*, in contrast, were still strongly associated with bottom habitats, indicating limited microhabitat preference (Figure 4.11)

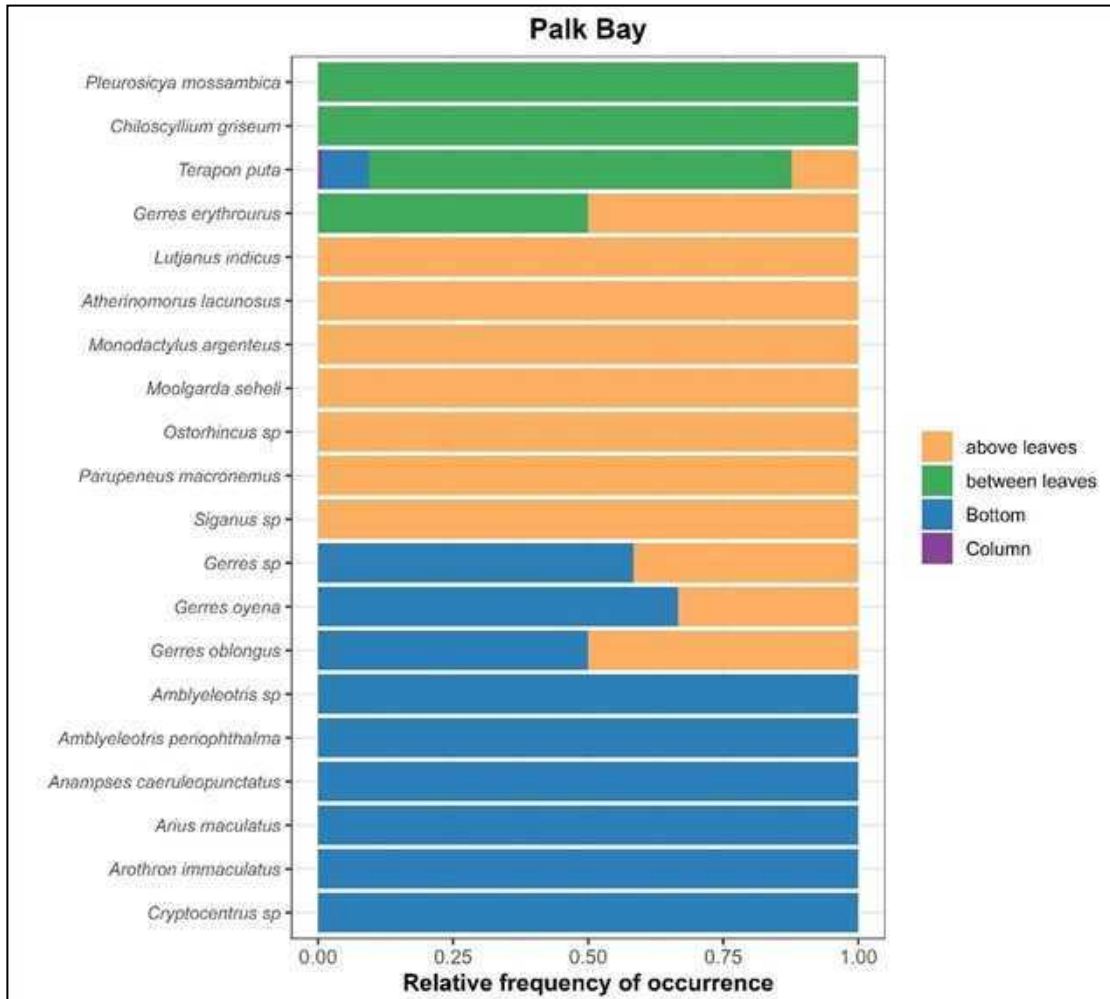


Figure 4.10: Microhabitat partitioning in the most commonly occurring seagrass associated fish of Palk Bay

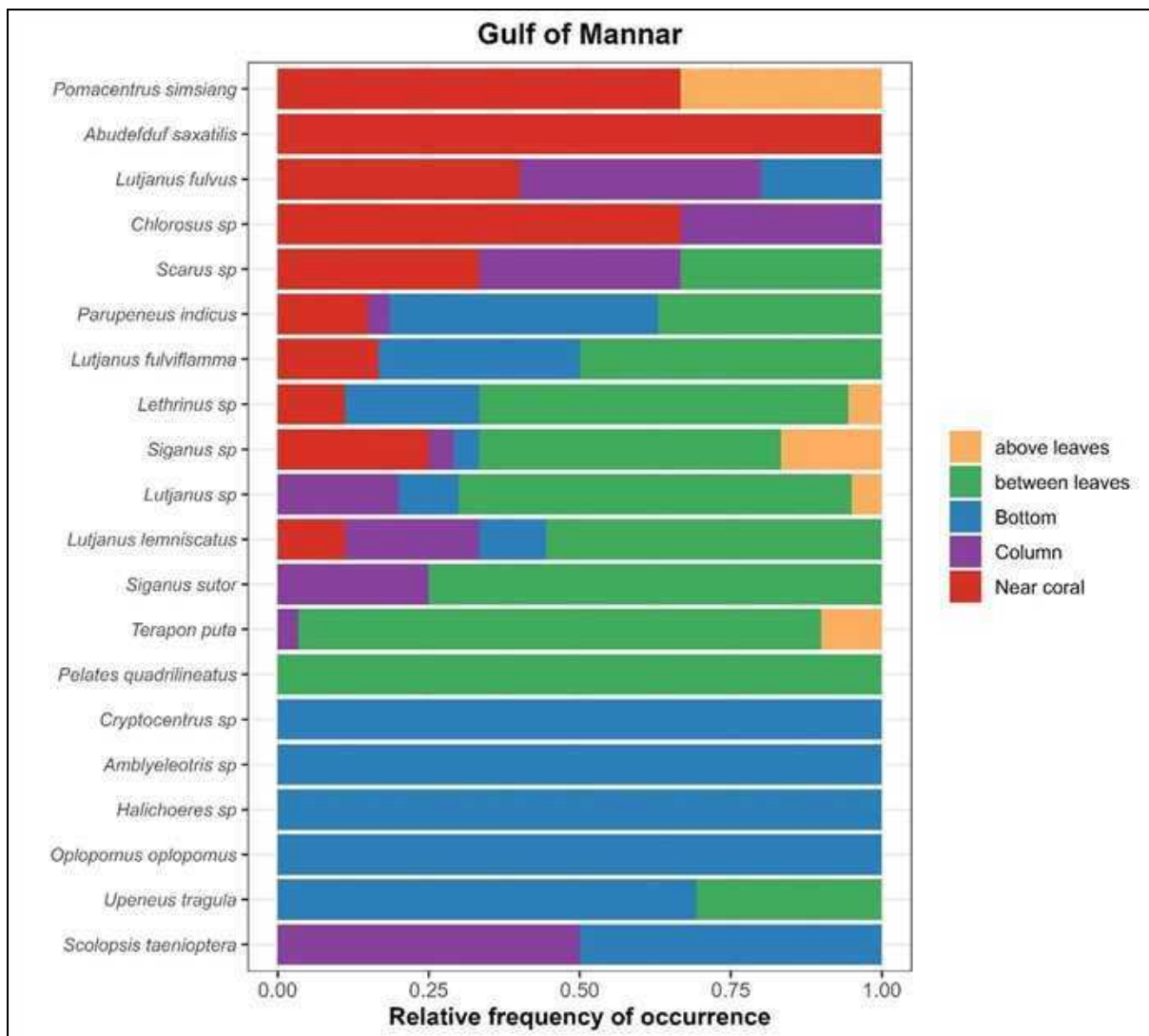


Figure 4.11: Microhabitat partitioning in the most commonly occurring seagrass associated fish of Gulf of Mannar

4.3.1.1 Pianka's habitat niche overlap

A comparison of the two regions suggests that both Gulf of Mannar and Palk Bay support species groups with strong habitat overlap; however, Palk Bay exhibits more clearly defined habitat-use clusters, particularly among gobiids and gerreids. In contrast, the Gulf of Mannar shows broader habitat sharing among lutjanids, lethrinids, and mullids, alongside distinct habitat separation of benthic gobiid species. These patterns indicate that seagrass ecosystems in both regions facilitate coexistence through a combination of habitat sharing and ecological partitioning.

The Pianka niche overlap matrix for Palk Bay shows distinct clustering patterns, with species forming groups with either large habitat sharing or strong habitat segregation (Figure 4.12). The highest habitat overlap was found for the gobiid species *Cryptocentrus sp.*, *Amblyeleotris periophthalma*, and *Amblyeleotris sp.* All of them show Pianka's index close to 1.0, while the gerreid fishes (*Gerres sp.*, *Gerres oyena*, and *Gerres oblongus*) showed very high overlap (in fact, they almost all use the same seagrass habitats). The most highly overlapped species are *Pleurosicya mossambica* and *Terapon puta*, which almost overlap the whole habitat. The lowest habitat overlap was between gobiid (*Cryptocentrus sp.*, *Amblyeleotris periophthalma*, and *Amblyeleotris sp.*) and *Pleurosicya mossambica* and *Terapon puta*, with overlap values almost zero. *Moolgarda seheli* was found with little overlap with the gobiid group and thus had different habitat utilization patterns. These results indicate high habitat partitioning between various functional groups of seagrasses in Palk Bay. We observed moderate habitat overlap between gerreid species and *Moolgarda seheli*, especially between *Gerres oyena* and *Moolgarda seheli* and *Gerres oblongus* and *Gerres erythrourus*. *Gerres erythrourus* also showed intermediate overlap with *Pleurosicya mossambica*, indicating some habitat sharing. The moderate overlap values suggest that although all species are able to exploit the same habitats, they may compete with each other for resources due to their choice of habitats or behavior.

The Pianka niche overlap matrix for the Gulf of Mannar revealed a wide range of habitat use among the main seagrass finfish species (Figure 4.13). The assemblage could be broadly divided into two groups, i.e. species with high habitat overlap and/or species with relatively different habitat preferences. Most habitat overlap was found between the lutjanid and predatory fishes. *Lutjanus sp.*, *Lutjanus lemniscatus*, *Lethrinus sp.*, *Siganus sp.*, and *Terapon puta* also had very high number of pairwise overlap (Pianka's index was close to 1.0), so these species probably enjoyed similar habitats in the seagrass environment. Similarly, *Parupeneus indicus* and *Upeneus tragula* also had a high number of overlaps with each other and *Lutjanus fulviflamma*, suggesting that both species tend to prefer similar microhabitats.

In contrast, the lowest habitat overlap was found between the gobiid species (*Amblyeleotris sp.* and *Cryptocentrus sp.*) and several of the larger predatory fishes along with *Terapon puta*, *Siganus sp.*, *Lutjanus sp.*, and *Lutjanus lemniscatus*. For these pairwise comparisons, Pianka's index values were close to zero and therefore very different habitats are found. Such low overlap implies that these species occupy different ecological niches or exploit different

structural components of the seagrass meadow. However, there was moderate habitat overlap between *Amblyeleotris sp.* and *Lethrinus sp.*, and *Cryptocentrus sp.* and *Lutjanus fulviflamma*. Intermediate overlap was also found between the gobiid species and *Parupeneus indicus*, indicating some kind of spatially partitioned habitat sharing across all species. In general, the Gulf of Mannar assemblage exhibited a mosaic of strong habitat sharing between several commercially important species and clear habitat differentiation between benthic gobiids and large mobile predators.

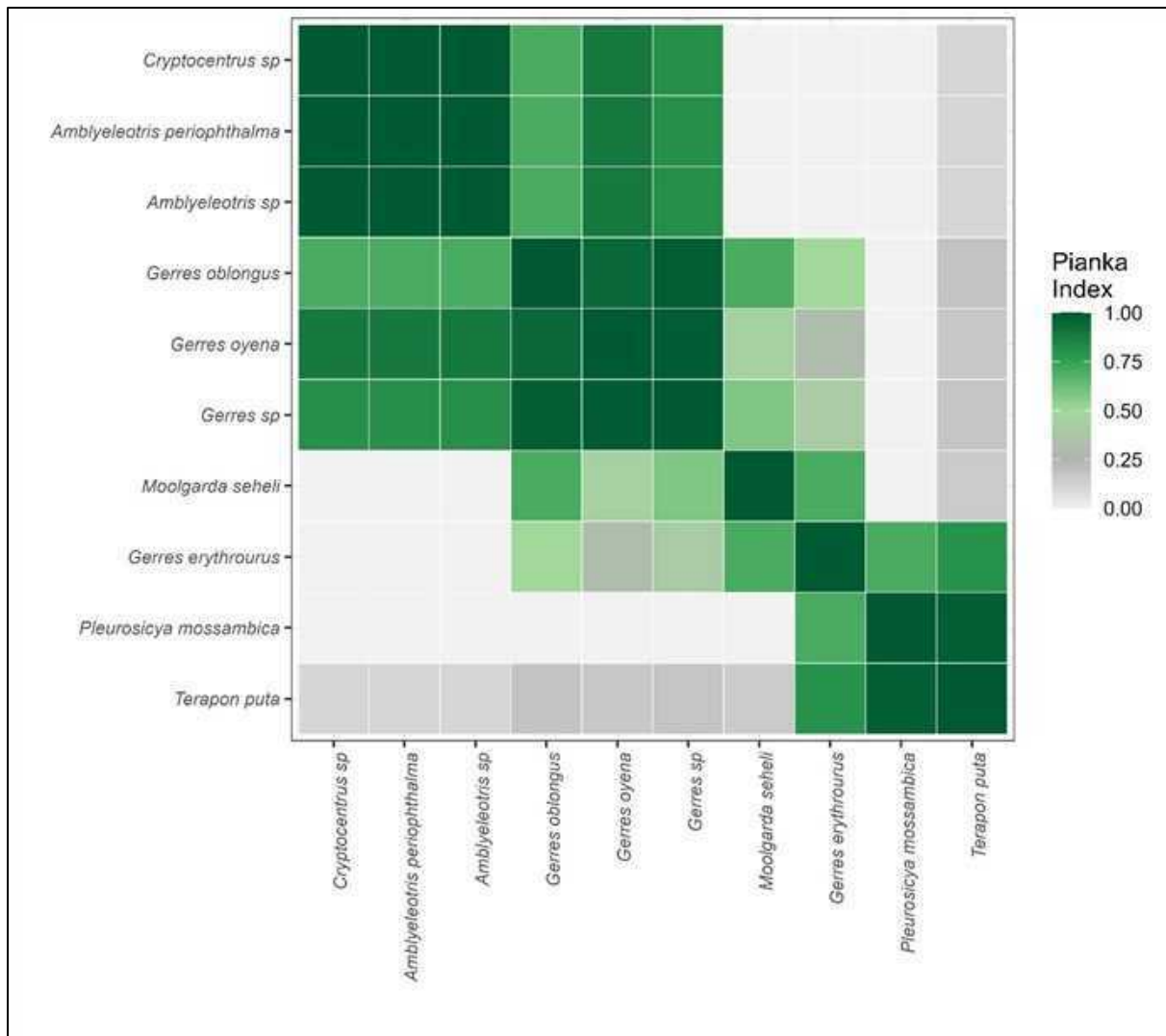


Figure 4.12: Pianka's habitat niche overlap between the most commonly occurring seagrass associated fish of Palk Bay

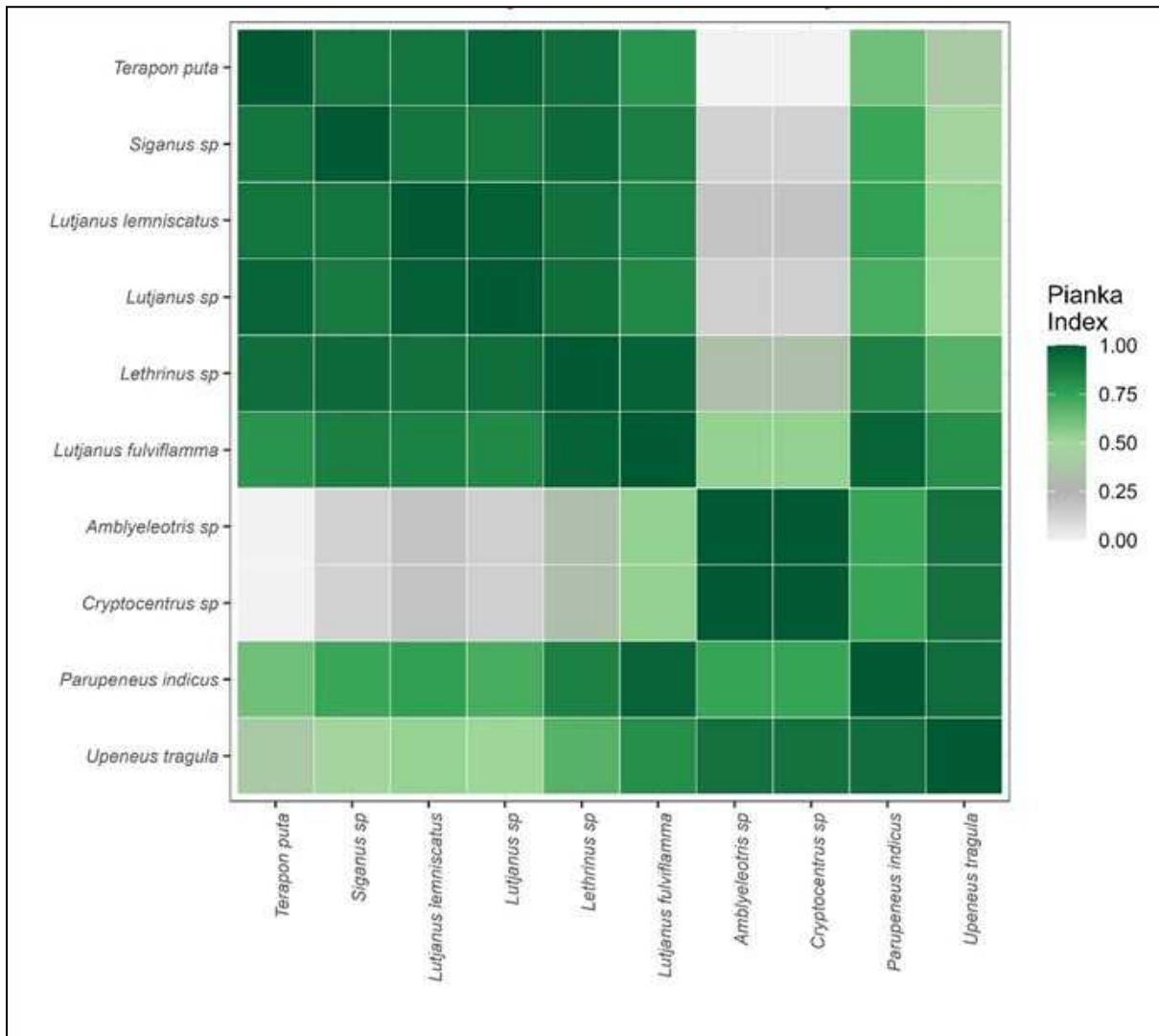


Figure 4.13: Pianka's habitat niche overlap between the most commonly occurring seagrass associated fish of Gulf of Mannar

4.3.1.2 Habitat niche breadth based on Levins' standardized index

Compared to the two seagrass ecosystems, the two species have very different habitat uses. In the Gulf of Mannar, there are very wide habitat niches for *Siganus sp.*, *Parupeneus indicus* and lutjanids and very narrow habitat niches for gobiids. In Palk Bay, gerreid fishes have the widest habitat niches and gobiids, mullets and clingfishes have very narrow habitats. These results suggest that the coexistence of the ecosystems is a result of habitat generalism in some species and habitat specialization in others, where the competition between the species is not great.

The Levins' standardized niche breadth analysis for Palk Bay also showed marked differences in habitat utilization among species (Figure 4.13). The highest habitat niche width was found

for *Gerres oblongus* and *Gerres erythrourus* (BA \approx 0.33), followed by *Gerres sp.* (BA \approx 0.31). *Gerres oyena* also found a relatively wide habitat niche (BA \approx 0.26). The high values in the genus *Gerres* indicate that these species exploit a variety of seagrass habitats and are habitat generalists. We observed moderate habitat niche breadth for *Terapon puta* (BA \approx 0.19), suggesting the species has some degree of habitat flexibility, compared to the other species in the group. The lowest habitat niche breadth was for *Amblyeleotris periophtalma*, *Amblyeleotris sp.*, *Cryptocentrus sp.*, *Moolgarda seheli* and *Pleurosicya mossambica*, all of which had values close to zero. These species appear to be very specialized and likely depend on specific structural or environmental characteristics of the seagrass meadow.

The Levins' niche breadth index exhibited large variation in habitat utilization for seagrass-associated finfishes in the Gulf of Mannar (Figure 4.14). Lower values of the Levins' niche breadth index were associated with more habitat use. The highest habitat niche breadth was for *Siganus sp.* (BA \approx 0.47), followed closely by *Parupeneus indicus* (BA \approx 0.45), *Lutjanus lemniscatus* (BA \approx 0.41), and *Lutjanus fulviflamma* (BA \approx 0.40) in order to be considered as habitat generalists that utilize a wide range of available seagrass microhabitats. The species with moderate habitat niche breadth included *Lethrinus sp.* (BA \approx 0.32), *Lutjanus sp.* (BA \approx 0.26), and *Upeneus tragula* (BA \approx 0.18). These fishes seem to thrive in a subset of habitats while maintaining some degree of ecological flexibility. The lowest habitat niche breadth was observed for *Terapon puta* (BA \approx 0.08), implying that they were mostly using a special habitat. In contrast, *Amblyeleotris sp.* and *Cryptocentrus sp.* exhibit values of close to zero, indicating that they are associated with very specific habitat conditions in the seagrass ecosystem.

4.3.2 Usage of food resources in seagrass meadows by fishes

The food partitioning could be only studied for 2 species as they were opportunistically caught by the fishing method.

The gut contents of *Gerres erythrourus* showed that fish scales form the most relevant food source (51.95% of total gut contents) (Figure 4.14). Algae is the second most abundant food source (18.18%), and invertebrates make up 10.39% of the diet. Miscellaneous food items are 7.79% and worms are 4.55%. Minor dietary components included seagrass material (3.25%), shells (2.60%), and polychaetes (1.30%). The gut contents were in fact a mixture of food and the food of animals and fish scales were the main food source. Overall, gut content of *Gerres erythrourus* showed a wide range of foods in the seagrass ecosystem, fish scales, algae and invertebrates with the most food.

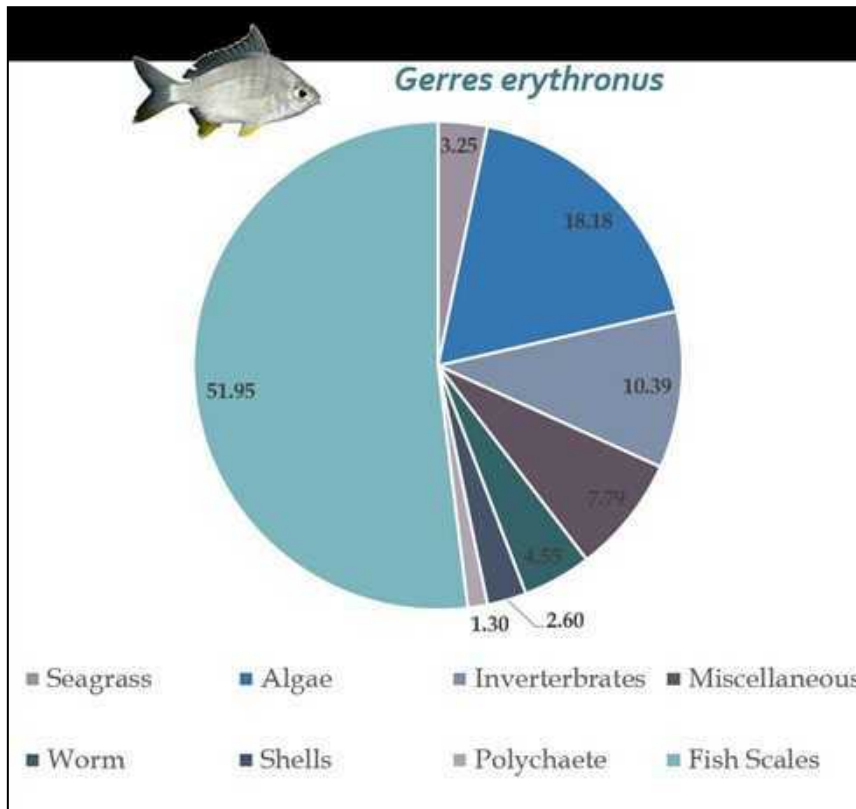


Figure 4.14: Gut content composition of *Gerres erythronus* collected from seagrass meadows

The gut contents of *Psammoperca waigiensis* showed that shrimps were the most abundant food sources (82.33% of the gut contents in total) (Figure 4.15). Miscellaneous food items contributed to 6.60% of the diet and crabs were 3.83% of the diet. Amphipods were the least abundant food source and only 0.94% of the gut contents. The diet of *P. waigiensis* was dominated by crustacean prey, mainly shrimps, with crabs and amphipods being less numerous. The presence of other food sources suggests that in seagrass habitats, food species are occasionally eaten.

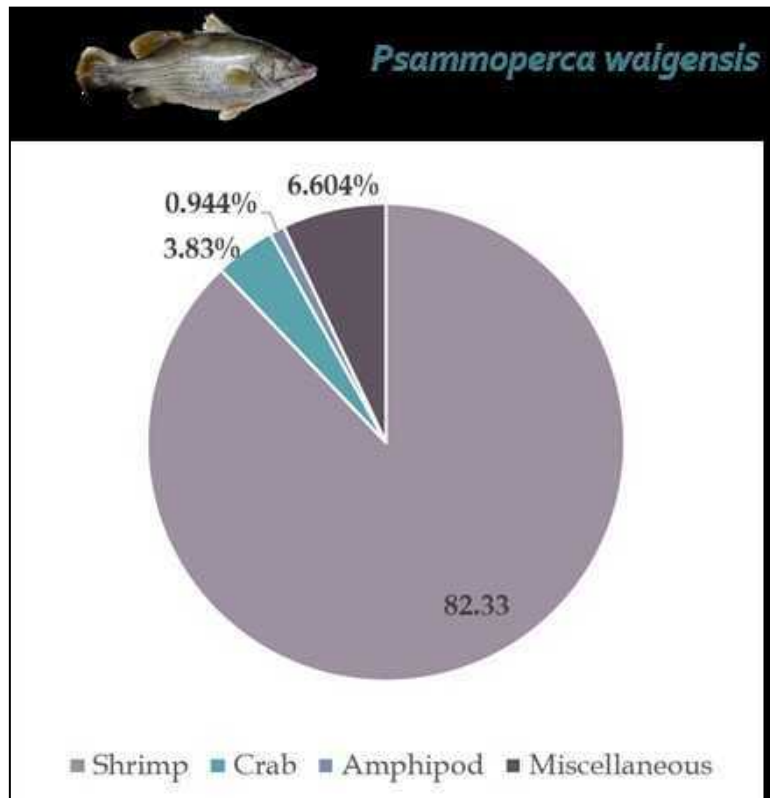


Figure 4.15: Gut content composition of *Psammoperca waigiensis* collected from seagrass meadows

4.4 Discussion

4.4.1 Resource partitioning as a mechanism for coexistence in seagrass ecosystems

Resource partitioning is a fundamental ecological process that makes species with similar habitats able to coexist by reducing niche overlap. According to Schoener (1974), differentiation in food, space and time reduces competition between individuals and maintains community stability. Seagrass meadows are one of the most heterogeneous coastal ecosystems with diverse microhabitats and abundant trophic resources that allow for such ecological segregation. Our analysis demonstrates that commercial finfish species from the seagrass ecosystem of Palk Bay and the Gulf of Mannar partition resources based on behaviour, use of habitat and diet preferences.

Unlike homogeneous habitats, seagrass meadows have a wide range of canopy structure, shoot density, substrate composition and connectivity with the surrounding ecosystem. This structural diversity in meadows increases the number of ecological niches for fishes and leads to less competition between coexisting species (Duffy, 2006). The segregation of species across different seagrass density classes and habitat types in our study is consistent with this ecological picture and demonstrates that niche differentiation is an important mechanism that makes seagrass fish assemblages structural.

4.4.2 Behavioural and spatial partitioning within seagrass meadows

The abundance of movement, feeding and hiding behaviors in the underwater surveys suggests that fishes exploit seagrass meadows to play a variety of ecological roles. The high number of movement associated activities suggest that seagrass habitats serve as ecological corridors in the linking ecology of adjacent coastal areas. Similar phenomena have been observed in tropical seascapes, where fishes move daily between mangroves, seagrass beds and coral reefs to maximize feeding opportunities and reduce the risk of predation (Nagelkerken et al., 2015).

The present study also revealed clear regional differences in habitat usage. Fish populations in Palk Bay were more transit and refuge-related, whereas feeding behaviour was more pronounced in the Gulf of Mannar. Such differences might be a result of local variations in habitat complexity and resources. Nakamura and Sano (2004) also showed that fish distribution in Japanese seagrass ecosystems was strongly influenced by the structure of adjacent habitats.

Vertical partitioning of the seagrass canopy was another important mechanism to reduce spatial overlap. Most of the fishes settled in the lower canopy, with the few remaining in the upper canopy and the bottom. The lower canopy offers protection from predators and abundant benthic prey organisms, so is a good habitat for many seagrass species. Bell and Westoby (1986) showed that even small changes in canopy height and shoot density have a significant impact on the abundance and distribution of fishes and decapods and highlight the importance of habitat structure.

4.4.3 Habitat specialization and niche differentiation

Based on habitat utilization coefficient and habitat association, it was found that fishes do not use seagrass habitats randomly but they have clear preference for specific combinations of seagrass density, water depth and substrate properties. Some species showed strong affinity for

dense seagrass habitats while others were associated with medium or sparse meadows. Similar specialization was observed in different depth zones and substrate types.

Habitat specialization reduces interspecific competition by allowing species to exploit different parts of the habitat. Hyndes et al. (1997) showed that coastal sillaginid fishes partition habitats based on body size, feeding morphology and movement patterns. The current results suggest that commercial finfishes in the Indian seagrass ecosystem do so as well to reduce ecological overlap. Indicator species analysis confirmed this conclusion by determining which species were most closely associated with specific habitats. The species with high indicator values can be considered habitat specialists, while species with more than one habitat class are ecological generalists. This habitat fidelity suggests that changes in seagrass structure could lead to substantial changes in the fish community composition.

4.4.4 Microhabitat partitioning

It is evident that the species are clearly separated by bottom, between-leaf, above-leaf, water column and near-coral habitats and microhabitat complexity is a key factor for the organization of the community. Some groups of gobiid fishes, such as *Amblyeleotris periphthalma*, *Amblyeleotris sp.* and *Cryptocentrus sp.*, are associated with bottom habitats and thus are demersal animals and dependent on benthic habitats. Similar habitat preferences have also been found for gobiids living in seagrass beds and sandy soils, where sediment and shelter availability are important in distribution patterns (Bell & Westoby 1986; Horinouchi 2007). In contrast, species such as *Siganus sp.*, *Parupeneus indicus* and lutjanid fishes live in a range of habitats, which suggests that they are more flexible. Rabbitfishes feed on seagrass canopies and move to other habitats during daily activity, and goatfishes and snappers often migrate regularly between benthic feeding and more complex habitats in the marine ecosystem (Unsworth et al., 2008; Nagelkerken et al., 2015). The marine habitats that have been found in the Gulf of Mannar near-coral habitat as well with fish species have been shown to be connected on a deep and close level between seagrass meadows and reef habitats. Such habitat interrelationships are recognized as a key ecological mechanism for the production and maintenance of reef fisheries. The greater habitat utilization of commercially important species may also reflect changes in habitat requirements due to evolution of the fish. Many tropical fishes use seagrass meadows as nursery habitats in the early years and then develop their habitat range as they grow (Heck et al., 2003). As a result, the existence of habitat specialists and habitat generalists in the same meadow seems to reduce direct competition and make maximum

use of space. Pianka's habitat niche overlap. Pianka's habitat niche overlap analysis revealed high habitat sharing and high habitat segregation among species. The full overlap between *Amblyeleotris periophthalma* and *Amblyeleotris sp.*, *Amblyeleotris periophthalma* and *Cryptocentrus sp.* in Palk Bay and *Amblyeleotris sp.* and *Cryptocentrus sp.* in the Gulf of Mannar suggests that these species have very similar habitat landscapes. At first sight, such high overlap might indicate that the species are in great competition. Yet, in many cases closely related or functionally similar species survive by splitting other ecological dimensions like prey selection, feeding times, body size differences or subtle microhabitat features not measured in this study. In classical niche theory, several niche axes are present in the ecosystem and ecologically similar species can coexist as far as the space is concerned. Similarly, the high overlap between *Parupeneus indicus* and *Upeneus tragula* in the Gulf of Mannar probably shows that the two species are related to benthic feeding habitats. Both are members of the Mullidae family and have barbels that are used to locate infaunal prey in the sediment. So their collaboration might be due to differences in prey size, feeding efficiency or habitat use rather than on a very large scale. Gerreids are known to occupy shallow coastal areas and often use seagrass meadows for feeding and sheltering. The high overlap among gerreid fishes in Palk Bay is also ecologically important. Their similar habitat preferences may mean that these habitats have sufficient resources to support more than one species. Resource-rich habitats allow more niche overlap because food and shelter are not necessarily limited at once. There are also pairs of species that overlap very little or not at all. As *Terapon puta* and *Amblyeleotris sp.* are found to have a very large habitat segregation in the Gulf of Mannar, this may be a mechanism for reducing interspecific competition. Likewise, these patterns were observed for species with very different habitats - bottom-dwelling gobies and species that use the upper seagrass canopy or water column. This segregation is strong evidence that spatial partitioning is an important aspect of seagrass fish groupings. The differences in habitat structure and landscape configuration between Palk Bay and Gulf of Mannar may also be related to different habitat types. The Gulf of Mannar has greater heterogeneity due to its proximity to coral reefs and the patchy seagrass meadows, and this may have a greater diversity of habitat-use strategies. The more homogeneous meadows of Palk Bay can therefore create greater overlap for species that play similar ecological roles. Levin's habitat niche breadth. Levin's habitat niche breadth analysis further supports the niche overlap results by distinguishing between habitat specialists and habitat generalists. Some species with broad habitat niches, such as *Siganus sp.*, *Parupeneus indicus* and lutjanid fishes in the Gulf of Mannar, may be able to

exploit multiple habitat types and therefore are likely to be more plastic. Habitat generalists are more resilient to local habitat disturbances because they can switch among habitat types in response to environmental change. On the other hand, the very narrow niche breadths of *Amblyeleotris periphthalma*, *Amblyeleotris sp.*, *Cryptocentrus sp.* and several other benthic fishes indicate a high degree of habitat specialization. Specialist species are often dependent on specific substrate conditions, shelter structures or prey groups and thus can be particularly affected by habitat loss. Loss of bottom habitat through sediment intrusion, fishing activities or seagrass diminishment can be catastrophic for such species. The relatively broad habitat niches of gerreid species in Palk Bay suggest that these fishes play a general role in the seagrass ecosystem as well. Their ability to exploit several habitats can be part of what makes them successful and may be a reason for the high habitat overlap among species in this family. Similarly, the large niche range of *Siganus sp.* in the Gulf of Mannar reflects its feeding ecology and mobility so that it is able to take advantage of a large number of available resources. Specialists and generalists in seagrass fish communities might help to maintain ecosystem organization. Generalist species can maintain ecological functions in a wide range of environmental conditions while specialist species can contribute to biodiversity by occupying unique ecological niches.

4.4.5 Trophic partitioning and dietary specialization

Food resource utilization was also a major area of niche differentiation among the fishes studied. The gut content analyses showed a wide range of diets from broad-spectrum feeders to very specialized predators. The diverse range of food items, including algae, seagrass material, crustaceans, worms, polychaetes, molluscan remains and fish tissues, reflects the high trophic diversity that seagrass ecosystems provide. The wide diet observed in *Gerres erythrourus* suggests an opportunistic feeding strategy which allows the species to exploit several benthic resources depending on their local availability. Opportunistic feeding behaviour is advantageous in dynamic coastal environments as it decreases reliance on any single prey resource. In contrast, *Psammoperca waigiensis* showed a high dietary specialization with shrimps dominating the gut contents. This leads to less trophic overlap with generalist feeders and is an important mechanism for resource partitioning. Connolly et al. (2005) showed that in seagrass systems there are multiple trophic pathways running at once, meaning that different fish species can exploit and eat different sources of energy in the same habitat. The coexistence of generalist and specialist feeding strategies in the present study indicates that trophic segregation is critical for maintaining fish diversity in seagrass ecosystems.

4.4.6 Integration of food and space partitioning

The main contribution of this study is the fact that resource partitioning occurs simultaneously on different spatial and trophic scales. Different species that share the same habitats often have different food resources. The species that eat similar prey have different habitat strata or seagrass density classes. This multi-dimensional niche segregation prevents direct competition and allows many commercial fish species to live together in relatively small areas.

These findings are consistent with Schoener's (1974) niche partitioning theory and provide support for the idea that ecological communities are structured through the differential use of available resources. Similar patterns have been observed in other coastal ecosystems where habitat complexity and trophic diversity co-dictate community organization (Heck et al., 2003; Duffy, 2006).

4.4.7 Implications for seagrass conservation and fisheries management

The results of this study have important implications for the management of the study area. The pattern of habitat specialization suggests the conservation of seagrass ecosystems is not only about the meadow but also about maintaining heterogeneity. Seagrass habitats between dense and medium and sparse also supported different fish communities and indicator species, and it is important to avoid any patchwork of habitats. Similarly, the diversity of trophic pathways supported by seagrass ecosystems drives the productivity of commercial fisheries. Habitat degradation due to coastal development, destructive fishing practices, sedimentation, or seagrass loss may simplify habitat structure and reduce the opportunities for resource partitioning, ultimately resulting in declines in fish diversity and fisheries yield.

The study demonstrates that the seagrass meadows of Palk Bay and Gulf of Mannar support commercial finfish populations through spatial and trophic resource partitioning. Different species used different layers of seagrass canopy, habitat types, seagrass density, and food resources to avoid niche overlap and coexist within the same ecosystem. The presence of habitat-specific indicator species and feeding strategies again supports heterogeneity in seagrass diversity and ecosystem functioning. These seagrass meadows are also the source of artisanal fisheries and are important habitats for endangered species such as the dugong, so any change in seagrass structure will affect ecology and fishery productivity. As a result, the recovery of biodiversity in seagrass microhabitats and ecological processes that drive resource partitioning will be critical to the long-term sustainability of the seagrass meadows of the study areas and fishery resources that are developed there in the future.

The integration of microhabitat partitioning, Pianka's habitat niche overlap and Levin's habitat niche width supports the hypothesis that spatial resource partitioning is an important mechanism for the organization of seagrass-associated finfish communities. Although some species share habitats widely, some species are highly habitat-specialized, and it is likely that species coexist in a combination of habitat sharing and habitat segregation. These findings have conservation implications. Seagrass meadows provide fish species with a broad diversity of ecological strategies, from extremely specialized benthic taxa to habitat generalists that move between seagrass, water column and coral-associated habitats. Habitat degradation may impact species differently, and specialists are particularly vulnerable to the loss of specific microhabitats. As such, conservation and management strategies should aim to preserve not only seagrass extent, but also the structural complexity and habitat connectivity that underpin spatial resource partitioning and sustain the biodiversity and fisheries productivity of tropical seagrass ecosystems.

Chapter 5: Ecosystem services provided by seagrass meadows in reference to fisheries

5 Ecosystem services provided by seagrass meadows in reference to fisheries

5.1 Introduction

5.1.1 *Economic Contributions of Seagrass Meadows to Global and Local Fisheries*

Seagrass meadows are globally recognized as fishing grounds owing to their intricate structural framework, elevated primary productivity, and trophic interconnectivity. Increasing evidence indicates that seagrass ecosystems significantly strengthen both commercial and artisanal fisheries, thereby directly impacting food security and coastal livelihoods across the globe (Unsworth et al., 2019; Nordlund et al., 2018).

Globally, over 20% of the principal fisheries species rely on seagrass habitats at one or more stages of their life cycle (Unsworth et al., 2019). This underscores the interplay between habitat functionalities and fisheries sustainability from both economic and ecological perspectives. However, the escalating loss of seagrass due to human-induced pressures jeopardizes the continuity of these ecosystem services. Therefore, elucidating the extent and mechanisms through which seagrasses enhance fisheries is vital for effective coastal management and policy development.

5.1.2 *Direct Economic Contributions to Fisheries*

In addition to serving as nurseries, seagrass meadows function as active fishing grounds, particularly within tropical regions. Artisanal and small-scale fisheries often target diverse assemblages of species affiliated with seagrass habitats, including finfish, crustaceans, mollusks, and bait organisms (Nordlund et al., 2018).

Employing a Seagrass Residency Index (SRI), Jackson et al. (2015) estimated that species associated with seagrass contribute approximately 30–40% of the value of commercial fisheries landings in certain Mediterranean contexts. Despite occupying a relatively minor fraction of coastal territory (<2%), Mediterranean seagrass meadows were assessed to generate between €58–91 million annually for commercial fisheries and around €112 million for recreational fisheries (Jackson et al., 2015). Local-scale valuation studies validate their economic importance. For e.g., *Cymodocea nodosa* meadows in Gran Canaria were assessed at €866 ha⁻¹ yr⁻¹ concerning fisheries-related services (Tuya et al., 2014). These data illustrate that seagrass habitats yield economic advantages in terms of fishery production.

5.1.3 Indirect Contributions to Fisheries Productivity

While the direct enhancement of fisheries is broadly acknowledged, the indirect ecosystem services rendered by seagrasses also play a crucial role in supporting fisheries sustainability. Seagrasses play a pivotal role in sediment stabilization, and reduction of turbidity, which collectively improve habitat conditions for fish and invertebrates (Nakaoka et al., 2014). By mitigating wave energy and curtailing coastal erosion, they safeguard adjacent ecosystems, such as coral reefs and mangroves, which are frequently ecologically intertwined with seagrass systems (Tuya et al., 2014).

Seagrass meadows also work for nutrient retention and cycling, which boosts primary productivity and enhances trophic transfer efficiency. These processes support higher trophic levels and contribute to the sustained fisheries (Kaladharan et al., 2018).

Seagrasses have increasingly been acknowledged as vital blue carbon ecosystems. By facilitating long-term carbon sequestration, they assist in climate mitigation efforts and buffer coastal habitats against acidification (Doolan & Hynes, 2023). The stable environmental conditions fostered by seagrasses indirectly support fisheries by maintaining ecosystem resilience. These indirect services are seldom comprehensively represented in economic evaluations; however, they are essential for the long-term sustainability of fisheries.

5.1.4 Regional Perspectives on Economic Contributions in Asia and the Indo-Pacific

In the regions of Southeast Asia and the Indo-Pacific, seagrass meadows play a crucial role in sustaining artisanal fisheries that are essential for food security and income for countless coastal communities (Fortes, 2018; Ambo-Rappe, 2020). The degradation of these systems, attributed to coastal development, unsustainable fishing practices, and seaweed cultivation, has raised significant concerns about long-term economic viability (Blankenhorn & Asmus, 2006).

Within the Mediterranean, the seagrass meadows of *Posidonia oceanica* are integral to fisheries, tourism, and coastal protection (Rigo et al., 2021). Economic repercussions related to the decline of seagrass in the Gulf of Gabes (Tunisia) have been estimated to surpass €750 million over a span of twenty years (Zrelli et al., 2020; Pruckner et al., 2022). These financial losses underscore the concrete economic ramifications of habitat degradation. In the southwestern region of Madagascar, fisheries associated with seagrass are essential for both protein security and household revenue (Wallner-Hahn et al., 2022). Approaches centre around community-based governance and participatory management have yielded beneficial outcomes

in maintaining fish stocks and bolstering local economies (Budzich-Tabor, 2014; García & Antelo, 2019).

In India, the economic value of seagrass ecosystems has been approximated at ₹259,434 ha⁻¹ yr⁻¹, indicating their significant contribution to local fisheries and ecosystem services (Ramesh et al., 2024). Enhancing conservation and governance frameworks in these areas is imperative for ensuring both ecological integrity and economic resilience.

5.1.5 Valuation Approaches and Methodological Challenges

Despite an increasing acknowledgment of the ecosystem services rendered by seagrass, economic assessments frequently underplay their actual value. Value-transfer methodologies may inadequately encompass the ecological determinants that underpin service provision (Dewsbury et al., 2016). Innovative approaches in natural capital accounting and biophysical modeling aim to more effectively integrate ecological structures with economic outcomes (Rigo et al., 2021). Advanced tools such as the Seagrass Residency Index (Jackson et al., 2015) offer more precise estimates of fisheries dependence by assessing habitat utilization across various life stages. Enhancing the interconnections between ecological and economic factors is vital for sound policy formulation.

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The objective of this study is to systematically evaluate the ecosystem services provided by seagrass meadows in the Palk Bay and Gulf of Mannar, with specific reference to their role in supporting commercial finfish fisheries with the following research questions:

- i) What different ecosystem services are provided by seagrass ecosystem in Palk Bay and Gulf of Mannar with reference to commercial fin fish fishery?

ii) What is the economic valuation of these ecosystem services by seagrass ecosystem in these regions?

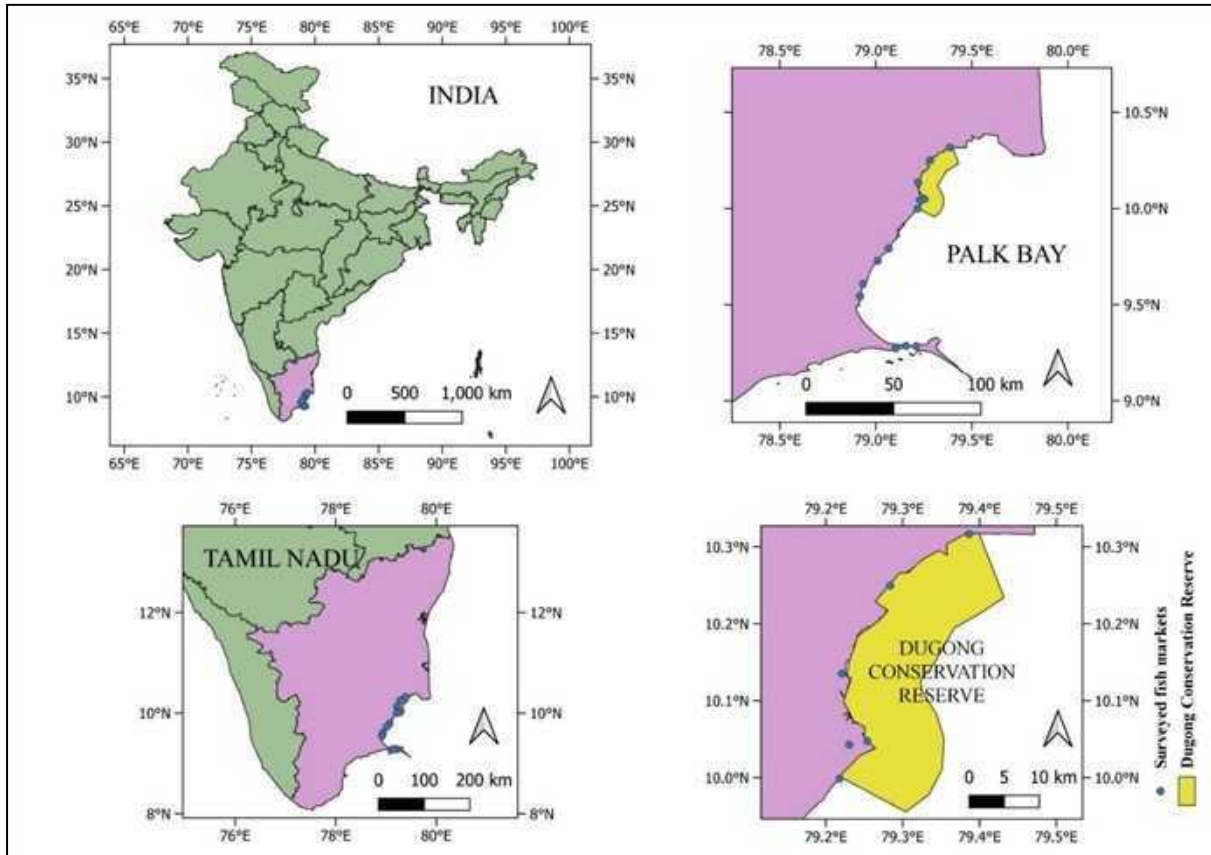


Figure 5.1: Map showing fish markets survey conducted in Palk Bay for economic evaluation

5.2 Methods

5.2.1 Field method

A semi-structured questionnaire survey was conducted across 40 villages in North Palk Bay during the period 2018–2019, with a total of 882 interviews aimed at assessing local community perceptions regarding seagrass ecosystems, their ecological significance, the extent of community dependence, and perceived threats to seagrass meadows. The survey instrument also included detailed inquiries into fishing practices, encompassing methods employed, types of fishing gear utilized, and vessel specifications. The geographic focus of the study encompassed regions adjacent to the Dugong Conservation Reserve, highlighting the conservation relevance of the survey area. In addition to community-based assessments, fish markets-linked with local fish landing centre surveys were conducted to quantify the economic benefits derived from seagrass-associated fisheries. These surveys aimed to identify key

stakeholders benefiting from seagrass fisheries and to determine the market valuation of commercially significant fish species linked to these ecosystems.

From 2019 to 2024, in months of March to October, fish market surveys were systematically carried out across 13 markets in Palk Bay (Figure 5.1), with a specific focus on assessing the economic valuation of fish species harvested from seagrass meadows. Given that seagrass-associated fisheries are not actively targeted in the Gulf of Mannar, the valuation study was confined to small-scale markets in Palk Bay, where fishers predominantly employ motorized boats. Each surveyed fish market documented wholesale auctioned catches as well as transactions involving individual retail vendors. For each recorded sale, the fish species sourced from seagrass meadows were identified, and the respective market prices per kilogram were meticulously recorded to facilitate an economic evaluation of seagrass-dependent fisheries.

In addition to field data collection, quantitative demographic data was acquired from Department of fisheries in August 2025 for the fishing gears operated in the Dugong Conservation Reserve, North Palk Bay for evaluation of per day earning for a motorized boat fisher.

5.2.2 Analysis

The questionnaire survey data was analysed by MS-excel to understand the dependency of fisherfolk on the seagrass meadows. Various ecosystem services were documented through these questionnaire surveys with reference to fisheries. The fish market data was analysed by MS-excel to understand the strata in fish markets, fish cost per kilogram and average cost per market surveyed.

5.3 Results

5.3.1 Ecosystem services provided by seagrass meadows in Palk Bay

The questionnaire survey assessed the significance of seagrass meadows in relation to fisheries, with all respondents (100%) acknowledging their role as fishing grounds, making this the most important ecosystem service provided by the seagrass meadows of Palk Bay. This acknowledgment underscores the direct economic contributions these ecosystems offer by underpinning local fishing endeavours. The evaluation of stakeholder perspectives (Figure 5.2) illustrates that seagrass meadows are acknowledged as multifunctional ecosystems. In addition to functioning as vital fishing areas, seagrass habitats are esteemed for their ecological contributions, which encompass habitat provision, support for biodiversity, and facilitation of fish recruitment.

However, beyond their primary function as fishing grounds, the survey revealed gaps in awareness regarding other ecological benefits—60% of respondents were unaware of additional roles, while 9% believed seagrass meadows had no importance beyond fishing. In contrast, 29% of respondents recognized their broader ecological contributions, highlighting several critical ecosystem services.

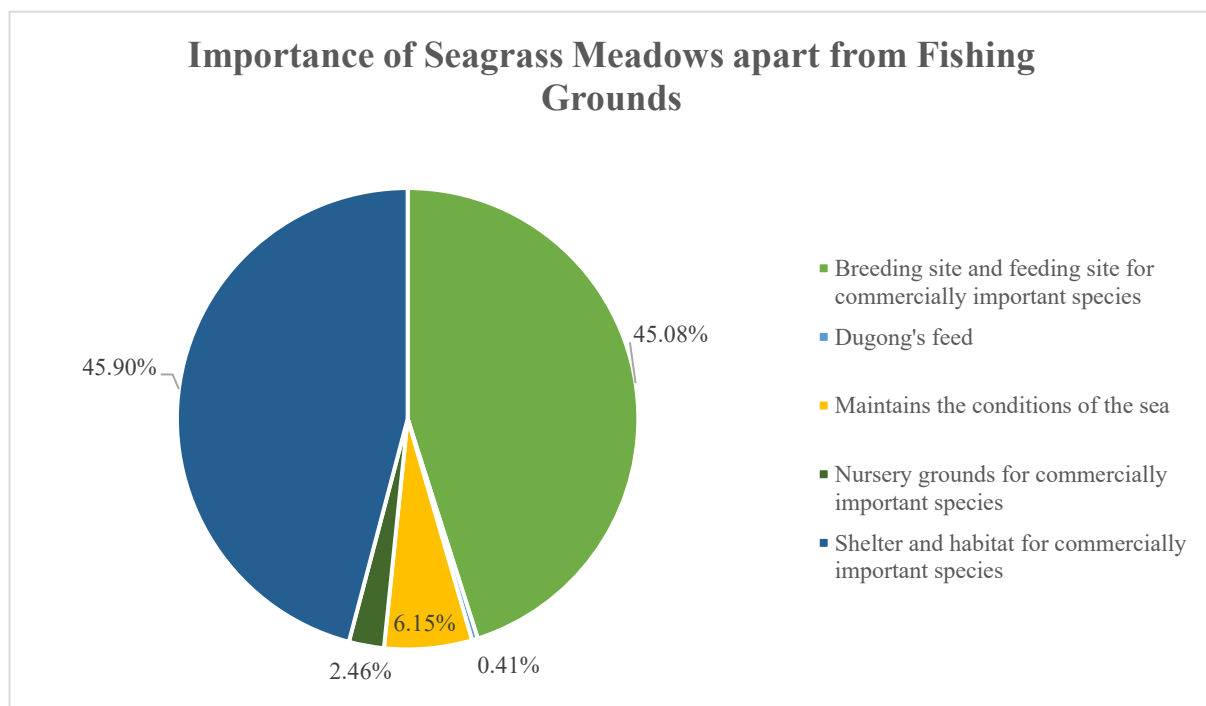


Figure 5.2: Importance of Seagrass Meadows apart from Fishing Grounds

Among these recognized services, seagrass meadows serve as breeding grounds, where marine species spawn and ensure population stability, supporting healthy fish stocks. They also function as feeding grounds, providing nutrient-rich environments and structural complexity that attract a variety of marine organisms reliant on seagrass beds for sustenance. Additionally, they offer nursery grounds, where juvenile fish and invertebrates find shelter and protection from predators, allowing them to mature before moving into open waters. Lastly, they provide shelter for commercially important species, enhancing survival rates by offering refuge within their dense underwater structure, which directly benefits fisheries by maintaining viable populations of marketable species. The responses indicate a strong linkage between ecosystem integrity and fishery productivity. The recognition of ecological functions alongside direct fishery benefits highlights the dependence of local livelihoods on healthy seagrass ecosystems.

The recognition of these additional ecosystem services underscores the need for broader conservation awareness, particularly among stakeholders who rely on seagrass meadows for economic and ecological sustainability. Understanding and promoting these roles can contribute to more informed fisheries management and habitat protection efforts, ensuring the long-term health of seagrass ecosystems and their associated marine life.

5.3.2 Economic evaluation of provisioning ecosystem service

To evaluate the most important ecosystem service provided by seagrass meadows—namely their role as fishing grounds—fish market surveys were conducted in Palk Bay to assess how seagrass-associated fisheries contribute to the local economy and seafood supply chain. These surveys aimed to capture the structure of the market, the key stakeholders involved, and the flow of fish products from capture to consumption.

The fish marketing system in Palk Bay follows a semi-structured value chain (Figure 5.3). These fish markets primarily operate through two distinct types: auction markets and retail markets, each playing a crucial role in distributing marine resources harvested from seagrass meadows. The market structure is pioneered with fishers, who actively harvest fish and trade their catch through multiple channels. The system reflects a partially organized yet locally confined market structure typical of small-scale fisheries. The supply chain remains short and spatially concentrated within coastal settlements.

Auction Markets

Auction markets function as a direct sales conduit for fishers, facilitating the transaction of their catch either to intermediaries or to end purchasers. Fish market managers or intermediaries operate as facilitators, acquiring fish directly from fishers and subsequently distributing it to retail vendors while retaining a commission for their services. Nevertheless, this operational framework is restricted to specific markets such as Sethubawachhatiram in North Palk Bay. Intermediaries frequently encompass wholesale traders who procure fish in substantial quantities for further redistribution, whereas direct purchasers may include suppliers for restaurants, processing facilities, or larger retail establishments. The auction mechanism guarantees competitive pricing and effective bulk transactions, typically occurring in designated venues equipped with established bidding protocols. This market architecture enables fishers to expeditiously offload their catch and obtain immediate remuneration, thus rendering auctions an essential component of the local fishery economy. However, the presence of commission-based intermediaries indicates a degree of value capture extending beyond primary production, although the lack of additional processing phases signifies constrained post-harvest value enhancement.

Retail Markets

Retail markets, on the other hand, cater directly to consumers and are structured around middlemen who acquire fish from auction markets before distributing them to retail sellers. These sellers operate stalls or shops where individual consumers purchase seafood for household consumption. Retail markets provide accessibility and convenience for buyers, offering a diverse range of fish species at varied price points depending on demand and seasonality. Since seagrass-associated fish species are often valued for their commercial importance, their presence in retail markets highlights the direct contribution of seagrass ecosystems to food security and local nutrition.

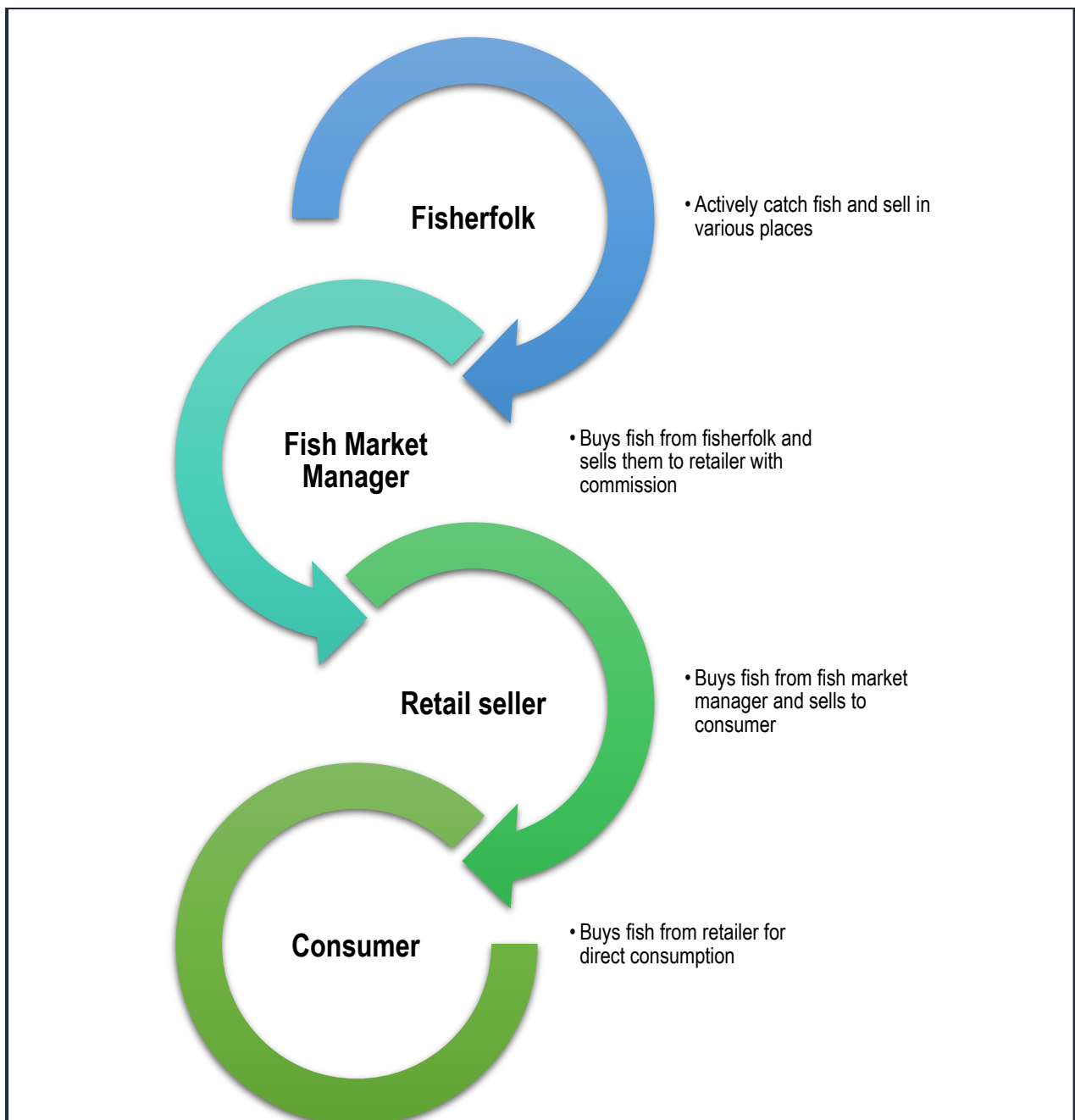


Figure 5.3: Fish Market structure in Palk Bay and Gulf of Mannar

The target catch composition in Palk Bay's seagrass-associated fisheries is shown in Figure 5.4. Crabs (34%) and finfish (33%), which together account for roughly two-thirds (67%) of all target landings, dominate the catch structure. At 24% of the total catch, prawns make up the third major component. Squid (3%) and pomfret (3%), on the other hand, made only minor contributions, and Indian salmon (2%) and barracuda (1%) together made up less than 5% of the entire target catch. The abundance of finfish and crabs indicates that seagrass meadows

serve as vital habitats for benthic and demersal species, which are the main sources of revenue for regional fisheries.

Considering the fin fishery catch, there are significant fluctuations in both average and maximum fish prices (₹/kg) across various fish families documented in the markets of Palk Bay (Figure 5.5). A significant heterogeneity in pricing was identified among the selling price of fish families, mirroring variations in market demand, species diversity, and economic value. The average prices across the families typically spanned from ₹40/kg to ₹300/kg, with multiple families congregating within the ₹80–150/kg bracket, thereby indicating a moderate and stable market demand. On the contrary, maximum prices displayed a considerably broader range, surpassing ₹500/kg in numerous instances and attaining peak figures exceeding ₹1,500/kg for specific high-value families. However, high value catches are rare instances indicating the average catch value per kg restricted at Rs. 257 (Table 1).

Families such as Sphyraenidae, Polynemidae, Siganidae, and select pelagic groups displayed relatively elevated maximum price spikes compared to their average values, indicating strong market premiums during specific landings (Figure 5.4). With average prices exceeding ₹450/kg and maximum prices approaching ~₹580/kg, Polynemidae had the highest market values. Additionally, Sillaginidae and Latidae showed comparatively high maximum prices (>₹500/kg), along with correspondingly high average and minimum values. Sphyraenidae, Carangidae, Belonidae, and Paluridae are among the commercially significant families that have shown moderate average prices (~₹250–350/kg) and maximum prices that typically range between ₹350 and 450/kg.

Average prices for mid-range families, including the Lutjanidae, Sciaenidae, Serranidae, Gerreidae, and Lethrinidae, were generally between ₹180 and 250/kg, with moderate variations between the lowest and maximum values. Families like Ariidae, Terapontidae, Engraulidae, and Pomacentridae recorded maximum prices below ₹150/kg at the lower end of the distribution, with average prices frequently falling below ₹100/kg. It is notable that the pelagic fish landings are likely happening from mechanized boats which operate over long distances offshore. In contrast, families such as Ariidae, Terapontidae, and Trichiuridae have shown comparatively low and less variable price ranges, suggesting low but commercial valuation (Figure 5.5). These catches are artifact of small-scale motorized fishery happening in near shore seagrass meadows of Palk Bay.

The difference between average and maximum price underscores the fluctuations in market dynamics and the stratification of prices within the multi-species seagrass-associated fishery. Families exhibiting wider error margins indicate greater price variability, which may be affected by factors such as seasonal availability, size of the fish, freshness, and consumer preferences.

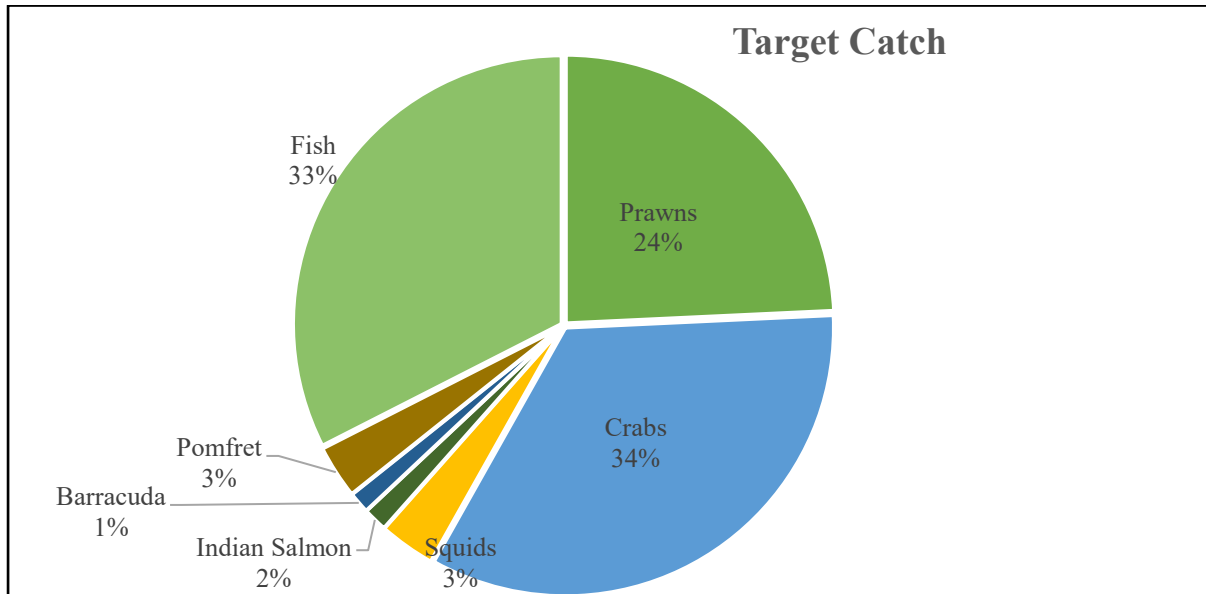


Figure 5.4: Target Catch in seagrass meadow fishery in Palk Bay, Tamil Nadu

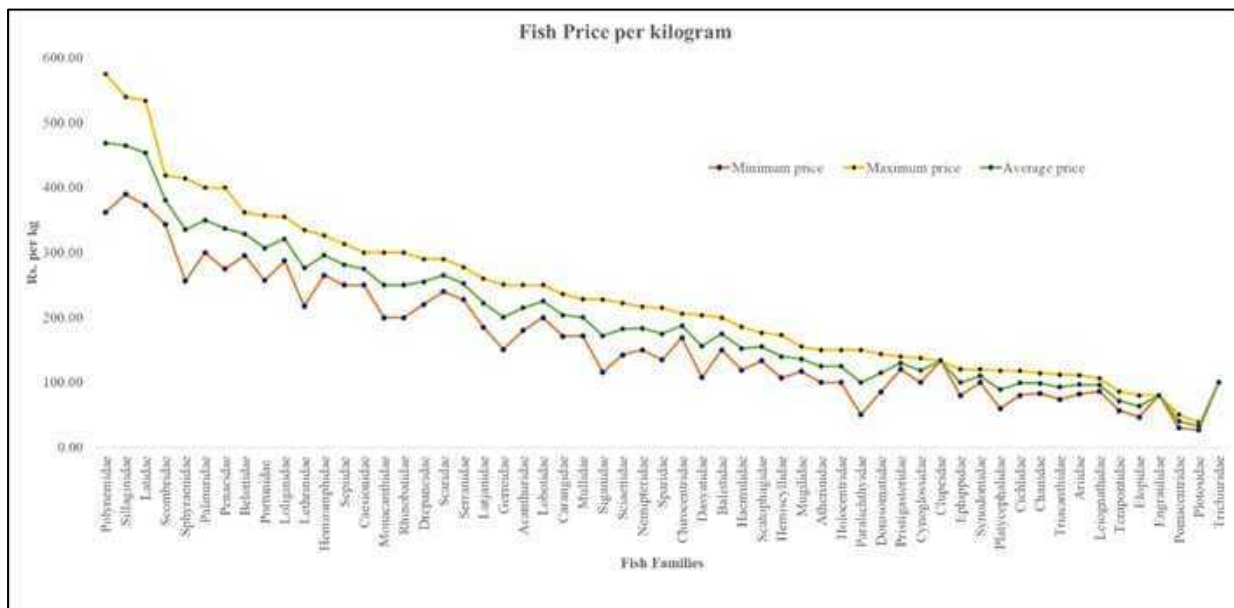


Figure 5.5: Species wise fish selling price in Palk Bay

Analysis of fish supply pathways (Figure 5.6) indicates that small markets in Palk Bay rely predominantly on locally harvested catches. The majority of fish entering markets originates directly from nearby artisanal fisherfolk, with limited dependence on distant landing centers.

This localized sourcing pattern suggests minimal supply-chain elongation and reinforces the spatially tight coupling between fishing grounds and consumption centers. Such proximity reduces transportation costs but may also increase vulnerability to localized stock fluctuations and habitat degradation.

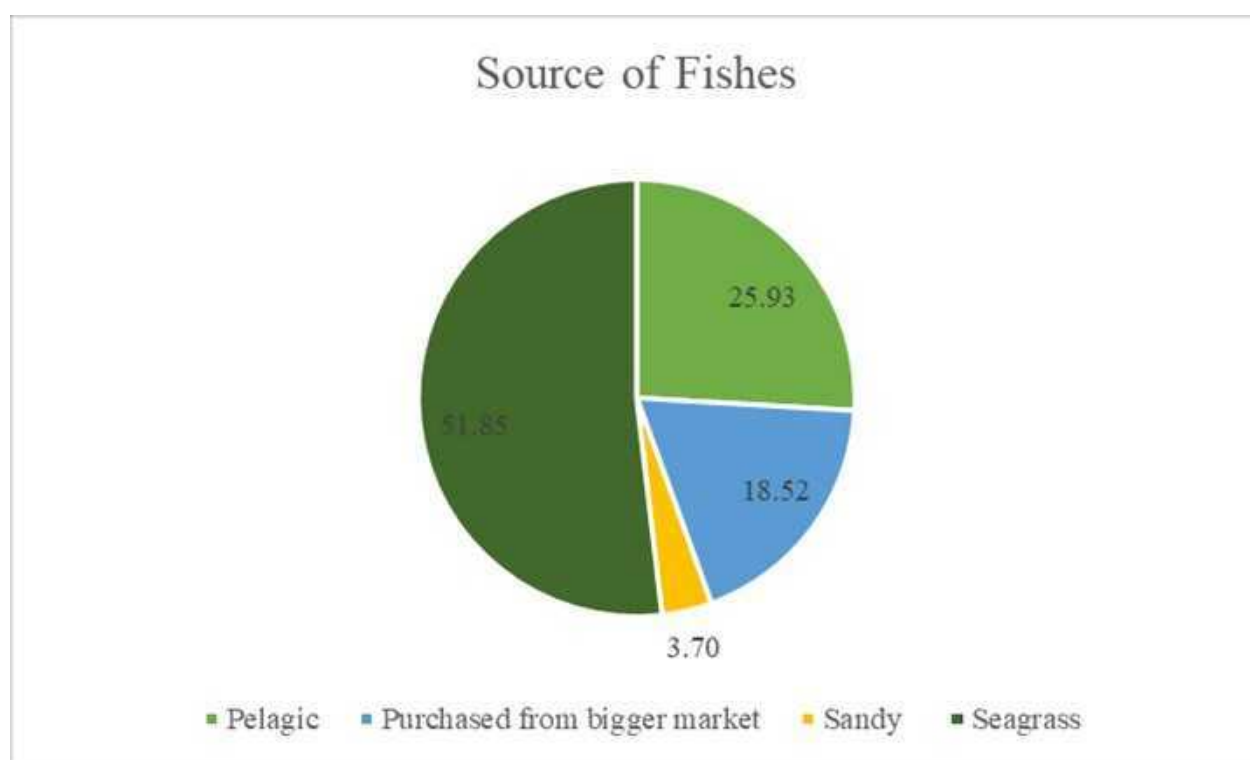


Figure 5.6: Sources of fish coming for sell in small markets of Palk Bay

Spatially, average fish prices in seagrass-associated fisheries varied considerably across 13 small markets in Palk Bay (Figure 5.7). The overall mean price across markets was approximately ₹172/kg. Marked spatial heterogeneity was observed among markets, with prices ranging approximately from ₹130/kg to ₹400/kg.

Pamban recorded the highest average fish cost (~₹400/kg), followed by Morappanai (~₹300/kg) and Sethubavachatram (~₹275/kg). Adirampattinam (~₹250/kg) also exhibited

relatively elevated prices compared to most other markets. In contrast, Tamarai (₹130/kg) and Mandapam (₹140/kg) showed the lowest average prices. Intermediate price levels were observed in Kattumavadi, Nambuthalai, Tirupalaikudi, and Manamelkudi (₹200/kg), as well as Vadakku and Therkku Pudukudi (₹170–180/kg) and Vedalai (₹150/kg). The coefficient of variation among various markets was approximately ₹124/kg, signifying a high degree of spatial heterogeneity in fish pricing. Markets that display elevated mean prices may indicate a greater availability of high-value species, diminished supply volumes, or intensified localized demand. In contrast, markets with lower pricing might be linked to increased volumes of low-value species or heightened competition among vendors.

The detected spatial variability emphasizes that the economic returns derived from seagrass-associated fisheries are not homogeneous throughout Palk Bay as other habitats may affect the fishery. The market dynamics critically affect fisher income independently of aggregate catch levels.

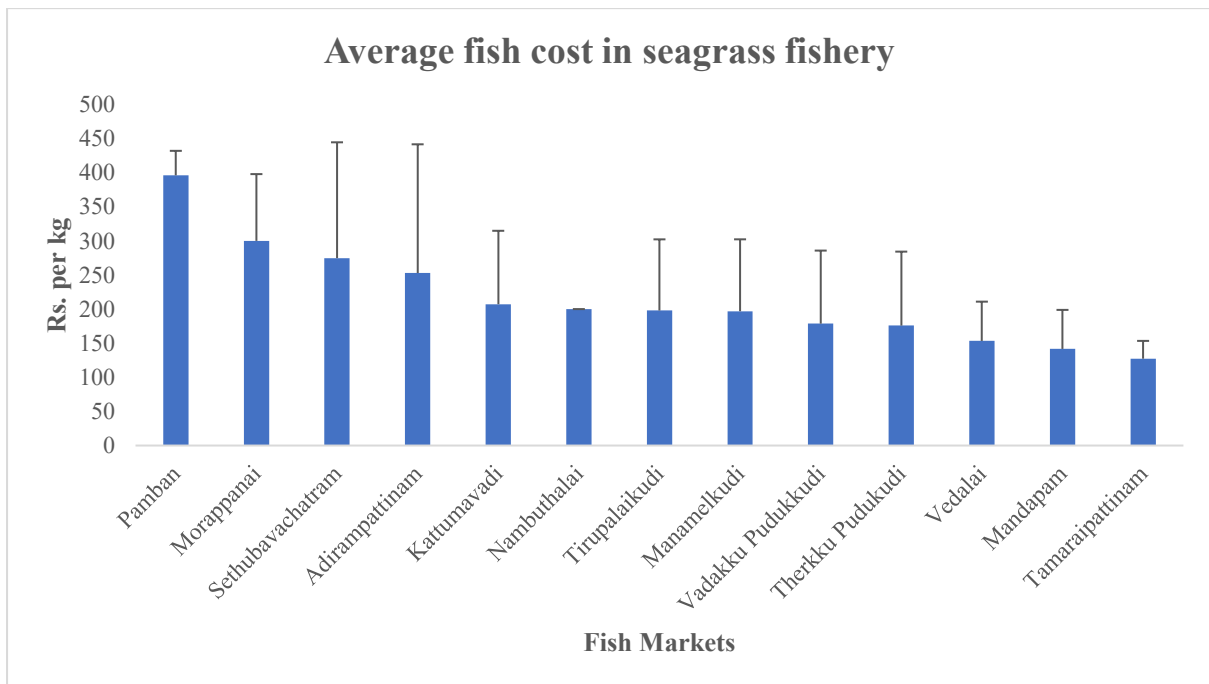


Figure 5.7: Average fish cost in seagrass fishery in Palk Bay markets

In terms of type of fishing gears, Table 1 delineates the mean maximum retail price per kilogram of fishing commodities traded in Palk Bay markets, systematically classified by the type of fishing vessels. Mechanized vessels documented the most elevated mean maximum

price (₹332.30/kg), while motorized vessels manifested a diminished mean maximum price (₹250.52/kg). The aggregated average across various vessel categories amounted to ₹257.95/kg. The price disparity between the mechanized and motorized classifications was approximately ₹81.78/kg, signifying a 32.6% higher mean maximum price for fish harvested by mechanized boats. This considerable discrepancy implies that the catches from mechanized vessels may encompass a higher proportion of economically valuable species, larger specimens, or substantial landings that significantly affect market dynamics and price realization. The overall mean price (₹257.95/kg) encapsulates the consolidated market conditions prevailing across vessel types but conceals the significant stratification linked to fishing technology. These findings underscore the assertion that the type of vessel exerts a quantifiable influence on retail price determinations within Palk Bay markets, potentially impacting the distribution of income among various fishing cohorts.

Table 5.1: Average Retail Price of Fish per Kilogram sold by retail vendors in Palk Bay Markets

Boat type	Average of Max price / kg (INR)
Mechanized	264.87
Motorised	205.40
Average	210.10

5.3.3 Evaluation of earnings of seagrass dependent fishery in Dugong Conservation reserve

In the surveyed markets, Sethubavachatram, Adirampattinam, Kattumavadi, Vadakku Pudukkudi, Therkkku Pudukudi are situated in the Dugong conservation reserve (DCR). According to the data acquired from fisheries department, there are total of 1,638 motorized boats (Table 2) in Dugong conservation reserve. According to the average motorized boat income specifically in the markets in DCR is Rs. 217 per kg. In Southeast Asia, small-scale seagrass fishers report average landings of **10–30 kg/day** depending on gear (Unsworth & Cullen-Unsworth, 2016; Nordlund et al., 2018).

Considering a conservative estimate of 10 kg catch per day,

Average earning per fishing boat per day= 217 x 10= Rs. 2170

Average earning per fishing boat per month= 2170 x 30= Rs. 65,100

Average earning of all fishers in DCR per year= 65,100 x12 x 1638 = Rs. 1,27,76,40,000 (~ 127 crore INR)

According to the Environment, Climate Change and Forest Department G.O. (Ms). No. 165 (2022), the total seagrass cover within the Dugong Conservation Reserve is approximately 122.5 sq. km (Johnson et al., 2026).

Therefore, the direct fishery production from seagrass is as follows:

Fishery production value of 1 sq. km of seagrass per year= Rs. 1,27,76,40,000 /122.5= Rs. 1,04,29, 714 (~1.04 crore INR)

The substantial economic value of seagrass ecosystems to coastal communities is evidenced by the fact that each square kilometer of seagrass meadow within the Dugong Conservation Reserve generates approximately ₹1 crore INR annually through direct fisheries production. This quantifiable yield underscores the function of seagrass meadows as high-return natural capital assets, reinforcing the economic rationale for their restoration and conservation within marine protected and sustainably managed areas.

Table 5.2:Details of active fisherfolk in Dugong Conservation Reserve

Village	Full time active fishers	Fishermen Families	Average No of boats engaged in fishing
Adaikathevam	165	165	78
Alaganvayal	127	94	#N/A
Ammanichathiram	30	30	36
Ammapattinam	89	80	18
Annanagar Pudutheru	145	146	90

Anthonyarpuram	242	229	75
Arasanagaripattinam	42	105	85
Arumugakittangi	163	110	#N/A
Athipattinam	106	72	35
Ayyampattinam	167	102	#N/A
Chellanenthal	795	573	31
Chinnamanai	139	120	54
Embavayal	168	133	50
Enathi	115	103	75
Eripurakkarai	504	384	28
Gandhinagar	223	232	17
Ganeshapuram	139	180	44
Gopalapattinam	137	339	9
Jagathapattinam	83	92	50
Kalimankuda	138	168	60
Kallivayalthottam	734	750	44
Kandanivayal	0	45	28
Karaiyoor Street	835	675	#N/A
Karankuda	100	117	105
Kattumavadi	184	187	60
Keezhakudiyiruppu	71	111	55
Keezhathottam	257	240	#N/A
Kollukadu	167	168	17

Kottaipattinam	1268	1063	35
Krishnarajipattinam	225	227	14
Kumarappam Vayal	138	98	10
Mallipattinam	470	465	#N/A
Manora Colony	97	105	#N/A
Manthiripattinam	171	133	#N/A
Maravakkadu	427	435	#N/A
Melasthanam	97	104	#N/A
Mettupalayam	21	21	42
Mimisal	26	26	7
Mudukkan Vayal	97	87	17
Mumbalai	113	124	60
Muthanenthal	99	75	#N/A
Muthukuda	478	454	#N/A
Palakkudi	202	134	#N/A
Pattangadu	76	75	#N/A
Pillaiarthidal	127	100	#N/A
Ponnagaram	308	291	#N/A
Prathabiramanpattinam	156	155	63
Pudukudi	548	491	14
Pudupattinam	405	358	#N/A
Pudutheru	34	50	47
R. Pudupattinam	228	500	#N/A

Sambaipattinam	157	147	18
Seetharamanpattinam	0	53	19
Sembiyan Madevipattinam	73	80	#N/A
Senthalaipattinam	716	604	#N/A
Sethubavachatram	503	450	#N/A
Somanathanpattinam	90	52	7
Subbamal Chathiram	69	45	58
Thambikottai	298	315	#N/A
Tharagar Street	105	105	#N/A
Thirumangalapattinam	33	33	15
Thulasiyapattinam	15	15	2
Vadakku Ammapattinam	194	315	#N/A
Vadakku Manamelkudi	47	60	63
Vallavanpattinam	120	120	3
Grand Total	14296	13715	1638

5.4 Discussion

5.4.1 Seagrass-Dependent Fisheries as Coupled Social–Ecological Systems

The findings indicate that the fisheries associated with seagrass in Palk Bay generate measurable economic variations that are affected by factors such as market location, fishing technology, species composition, and the condition of the habitat. According to Cullen-Unsworth et al. (2014), this reinforces the notion that seagrass meadows function as natural capital assets rather than merely serving as passive ecological habitats.

Through their trophic support, nursery roles, and complex habitats, seagrass ecosystems are recognized for enhancing fisheries productivity (Nordlund et al., 2018; Unsworth et al., 2019). Seagrass meadow-dependent small-scale fisheries in Southeast Asia and the Western Indian

Ocean play a crucial role in enhancing local markets, increasing household income, and improving food security (Nordlund et al., 2018). These broader trends align with the spatial differences noted in fish prices within Palk Bay and the taxonomic factors influencing value, indicating that ecological health directly affects economic outcomes. In the Western Indian Ocean, studies from Tanzania and Mozambique have similarly confirmed that seagrass meadows contribute substantially to local fisheries landings and household income, particularly in small-scale, nearshore fisheries (Nordlund et al., 2018). These parallels suggest that the ecological–economic coupling observed in Palk Bay reflects broader Indo-Pacific patterns.

5.4.2 Spatial Price Heterogeneity and Market Structuring

The bifurcated disparity in the mean prices of fish across various markets (₹124.71–₹258.38/kg) signifies a moderate yet significant degree of spatial heterogeneity. Akin market fluctuations have been observed in the coastal fisheries of Southeast Asia, where local demand, species availability, and access to infrastructure critically influence price realization (Unsworth et al., 2019). Economic evaluations of the services rendered by seagrass ecosystems reveal that provisioning values can exhibit considerable variability across different locations, contingent upon species composition and local market dynamics (Campagne et al., 2015; Tuya et al., 2014).

In Indian Ocean small-scale fisheries, localized supply chains with limited cold-chain integration create price structures closely tied to daily landings and habitat productivity (Cullen-Unsworth et al., 2014). The moderate coefficient of variation observed in Palk Bay suggests semi-integrated market functioning, yet persistent spatial inequities imply that geographic location and species mix influence fisher income beyond total catch volume. This spatial heterogeneity underscores the importance of integrating ecological productivity into regional fisheries management, particularly where certain seagrass patches may disproportionately support high-value taxa.

5.4.3 Fishing Technology and Income Stratification

The approximately 32% higher average maximum price realized by mechanized vessels compared to motorised boats suggests technological stratification in economic returns. Globally, mechanization has been associated with expanded spatial access, altered species composition, and differentiated market integration (Kurien, 1998).

In South and Southeast Asia, mechanized fleets often access offshore or deeper habitats, potentially landing larger-bodied or higher-value taxa relative to small-scale artisanal vessels operating in nearshore seagrass habitats (Nordlund et al., 2018). However, while mechanization can increase gross revenue, it may also raise operational costs and intensify fishing pressure, potentially undermining long-term sustainability (Kurien, 1998).

The Palk Bay findings reflect this broader pattern: higher price realization linked to vessel type likely reflects differences in catch composition and market segmentation rather than purely efficiency gains. This underscores the need to evaluate net economic benefits and ecological impacts simultaneously.

5.4.4 Taxonomic Drivers of Market Value

Family-level price analysis revealed pronounced skewness, with most taxa clustered in moderate price ranges but a minority exhibiting extreme maximum price spikes. This pattern mirrors global multi-species fisheries associated with seagrass ecosystems, where a small subset of high-value species contributes disproportionately to income (Nordlund et al., 2018).

Studies from Southeast Asia have shown that episodic landings of high-value species—such as groupers, snappers, and certain invertebrates—can significantly influence short-term fisher income, even when overall catch volume remains stable (Unsworth et al., 2019). Similar patterns have been reported in Western Indian Ocean seagrass fisheries, where invertebrate taxa (e.g., sea cucumbers) contribute disproportionately to economic value relative to biomass (Nordlund et al., 2018).

The divergence between average and maximum prices in Palk Bay therefore reflects market volatility typical of tropical multi-species artisanal systems. Such skewed distributions imply that conservation of nursery habitats may disproportionately affect upper-tier market species, thereby influencing both income variability and resilience.

5.4.5 Ecosystem Service Valuation and Policy Implications

Economic valuation studies consistently show that seagrass meadows generate substantial provisioning service values, often exceeding several thousand USD per hectare annually depending on context (Campagne et al., 2015; Tuya et al., 2014). While valuation methods vary, the central conclusion is robust: fisheries-related services constitute a major share of total seagrass economic value.

The Palk Bay results reinforce this conclusion at a localized scale. Spatial price heterogeneity, technological differences, and taxonomic stratification collectively demonstrate that seagrass ecosystems underpin measurable economic gradients within coastal markets.

In Southeast Asia and the Indian Ocean, habitat degradation has been shown to reduce fisheries productivity and disproportionately affect small-scale fishers dependent on nearshore habitats (Unsworth et al., 2019). Given that seagrass systems are declining globally at significant rates, failure to conserve these habitats risks compressing high-value price ranges and eroding income stability.

The projected direct fishery production value of approximately ₹2.10 crore per km² annually (derived from DCR fisher counts, conservative daily landings, and an average price of ₹250/kg) signifies a substantial and policy-relevant contribution of seagrass meadows to local coastal economies. This level of value aligns with the trends observed in seagrass valuations conducted globally: seagrass provisioning services often yield significant economic returns per area, although the reported figures are highly dependent on specific contexts (Tuya et al., 2014; Campagne et al., 2015).

Global syntheses underscore two key points that provide context for the Palk Bay estimate. Firstly, the values associated with seagrass fisheries differ significantly across regions due to variations in species composition, market prices, fishing intensity, and socio-economic conditions (Nordlund et al., 2018; Jänes et al., 2020). Secondly, numerous site-specific studies (such as valuations of Mediterranean *Posidonia* and case studies from the Canary Islands) reveal that a relatively small portion of habitat area or a minority of species can contribute to a disproportionately large share of fisheries value — a trend that corresponds with the skewed, high-value occurrences observed in the Palk Bay data (Campagne et al., 2015; Casas et al., 2021; Rigo et al., 2021).

Collectively, the figure for Palk Bay falls within the spectrum of documented site-level estimates where productive seagrass meadows generate annual fisheries values that can be significantly impactful at management levels (Tuya et al., 2014; Nordlund et al., 2018). Notably, regional comparisons (between the Indian Ocean and Southeast Asia) emphasize that small-scale seagrass fisheries often form the basis of household incomes and food security, thereby adding further policy significance to the monetary estimate presented here (Unsworth & Cullen-Unsworth, 2016; Fortes, 2018).

Thus, integrating seagrass conservation into fisheries management and coastal policy is not only an ecological imperative but also an economic necessity. Blue economy frameworks that recognize seagrass meadows as natural capital assets are increasingly advocated globally (Cullen-Unsworth et al., 2014), and the present findings provide empirical market-level evidence supporting such approaches in the Indian context.

5.4.6 Key limitations and sources of uncertainty

1. **Attribution of catches to seagrass:** the calculation assumes that the conservative daily landing (20 kg/fisher) is entirely attributable to seagrass-dependent fishing. In reality, many fishers exploit mosaics of habitats (seagrass, reef, sand) and not all landed biomass originates from seagrass nurseries. This likely **over-attribute** value to seagrass if not corrected by a residency/apportionment index (Jackson et al., 2015; Jänes et al., 2020).
2. **Assumption of uniform dependence across fishers:** the estimate treats all 14,296 traditional fishers as equally dependent on seagrass. In practice, gear types, target species, and fishing grounds vary; some fishers may rarely fish seagrass areas. This assumption can **inflate total attributed value**.
3. **Daily catch and fishing effort assumptions:** using a constant 20 kg/day and 30 days per month ignores seasonality, periodic closures, bad weather days, and variability in fishing effort. Real annual fishing days are usually lower than 360 days; assuming full-month effort likely **overestimates annual revenue**.
4. **Price and market dynamics:** the ₹250/kg price is an average; prices vary by species, season, and market. The calculation uses gross revenue (price × weight) and does not deduct costs (fuel, gear, labour shares, commissions), so it **overstates net income** accruing to fishers.
5. **Spatial scaling issues:** scaling total fishers' earnings to per-km² by simple division assumes even spatial distribution of fishing benefits across all seagrass area. In reality, some meadows (recruitment hotspots) contribute disproportionately, so the per-km² figure represents an **average** that masks heterogeneity.
6. **Exclusion of indirect and non-market values:** the estimate includes direct provisioning value only. It omits supporting, regulating and cultural services (e.g., nursery spillover, coastal protection, recreation), so the **total ecosystem value** of

seagrass is substantially higher than the reported fisheries figure (Campagne et al., 2015; Cullen-Unsworth et al., 2014).

7. **Data quality and temporal mismatch:** fisher counts, price data and seagrass area may come from different years or reporting systems; mismatches can introduce error in annualization and per-area calculations.
8. **Double counting and overlap with other habitats:** some species utilize multiple habitats during their life cycle; attributing full market value to seagrass risks **double counting** the contribution if other habitats (mangroves, reefs) also subsidize the same catch.

This research illustrates that the fisheries linked to seagrass in Palk Bay function as closely interconnected social-ecological systems, where the condition of the habitat directly influences species composition, market trends, and economic gains. By applying conservative estimates for catch and prices, the direct production value of fisheries associated with seagrass ecosystems within the Dugong Conservation Reserve was approximated at around ₹2.10 crore per km² annually, highlighting the significant economic role of seagrass meadows in supporting coastal livelihoods.

This level of value corresponds with global findings indicating that seagrass ecosystems offer vital fisheries provisioning services, especially in small-scale tropical systems (Nordlund et al., 2018; Unsworth et al., 2019). Valuation studies conducted at various sites in the Mediterranean, Atlantic islands, and Southeast Asia similarly indicate that productive seagrass meadows can yield considerable economic returns per area, frequently influenced by nursery-dependent and high-value species (Campagne et al., 2015; Tuya et al., 2014; Casas et al., 2021). The disproportionate value structure noted in Palk Bay—where a small number of species significantly impact market returns—reflects global trends (Jänes et al., 2020; Nordlund et al., 2018).

Crucially, economic valuation bolsters the case for conservation by rendering ecosystem services visible within policy and development planning frameworks. Converting the ecological functions of seagrass into quantifiable monetary metrics facilitates their integration into cost-benefit analyses, marine spatial planning, and blue economy accounting systems (Cullen-Unsworth et al., 2014). In this regard, seagrass meadows ought to be recognized as valuable natural capital assets rather than merely passive coastal habitats.

Nonetheless, the valuation presented here has significant limitations. The estimate presumes that all registered fishers uniformly depend on seagrass habitats and assigns all daily landings solely to production derived from seagrass. Fishing efforts were annualized based on constant daily catch and price estimates without considering seasonal fluctuations, non-fishing days, operational expenses, or habitat diversity. Additionally, the per-km² value reflects an average across total seagrass coverage and does not take into account the spatial variability in productivity. As shown in global methodological advancements, more sophisticated approaches—such as habitat residency indices or production function models—would enhance attribution accuracy (Jackson et al., 2015; Jänes et al., 2020).

Despite these constraints, even conservative modifications would likely affirm that seagrass ecosystems in Palk Bay produce substantial fisheries value. Consequently, habitat degradation could shrink high-value landings, diminish income variability, and weaken livelihood resilience, particularly for small-scale fishing communities (Nordlund et al., 2018; Unsworth et al., 2019).

In summary, the conservation and restoration of seagrass meadows within the Dugong Conservation Reserve is not merely a biodiversity goal but an economic necessity. Integrating seagrass valuation into fisheries management and coastal governance frameworks will be crucial for ensuring long-term ecological integrity, income stability, and the sustainable development of the blue economy.

**Chapter 6: Assess major threat posed
by different fishing practices in
seagrass ecosystem and provide
option for conserving seagrass
ecosystems**

6 Assess major threat posed by different fishing practices in seagrass ecosystem and provide option for conserving seagrass ecosystems

6.1 Introduction

Seagrass ecosystems are among the most productive coastal habitats and provide nursery grounds, feeding areas, spawning habitats, and shelter for a wide range of fish species. Recent studies have shown that habitat complexity, environmental quality, and ecosystem connectivity strongly influence fish abundance, diversity, and recruitment in seagrass meadows (Lattanzi et al., 2024; Gomis et al., 2024). Structurally complex seagrass habitats generally support greater fish diversity and abundance than degraded habitats (Mwaluma et al., 2022; Malesa et al., 2022).

Seagrass ecosystems are increasingly threatened by habitat degradation, coastal development, pollution, nutrient enrichment, and other anthropogenic disturbances. Seagrass loss can reduce fish abundance, alter community structure, and impair nursery functions (O'Leary et al., 2021; Rees et al., 2023). Pollution from fishing, aquaculture, and land-based activities can further affect seagrass health and associated biodiversity (Litsi-Mizan et al., 2024; Smulders et al., 2022).

Seasonal changes in environmental conditions influence fish assemblages, particularly larval and juvenile stages (Ngisiange et al., 2024; Tarimo et al., 2022). Connectivity between seagrass meadows and adjacent habitats such as mangroves and coral reefs is also important for sustaining fish populations and supporting recruitment processes (Gilpin, 2023; Ren et al., 2022).

Healthy seagrass meadows play a vital role in maintaining fish populations and supporting coastal fisheries. However, increasing fishing pressure and other human activities continue to threaten these ecosystems. Understanding the nature and extent of these threats is essential for developing effective conservation and management strategies.

This chapter examines the major threats posed by different fishing practices within seagrass ecosystems and explores potential conservation measures for safeguarding these habitats. Specifically, the chapter addresses the following research questions:

:

1. Which are the threats posed by different fishing practices to seagrass ecosystem in Palk Bay and Gulf of Mannar?
2. What measures can be taken for conservation of seagrass ecosystems in Palk Bay and Gulf of Mannar?

6.2 Methods

6.2.1 Field method

To understand threats, from Adirampattinam to Ammapattinam over ten transects perpendicular to the shore were conducted placed at a 5 km distance from each other. Hundred (Ten points per transect) points were sampled by point count method to observe threats (Figure 6.1). Ten-minute point counts were performed at each sampling point to record boats, nets and floating litter.

A semi-structured questionnaire survey was conducted in 40 villages in North Palk Bay from 2018-19 (Figure 6.2). 882 interviews were conducted to understand the perception of local communities towards seagrass ecosystems, their importance, community dependence on seagrass and threats to the seagrass meadows. The questionnaire entailed details about fishing methods, gears and vessels used. The questionnaire survey was conducted in the North Palk Bay in the adjoining areas of Dugong conservation reserve.

Additionally, A total of 96 aerial transects were laid systematically parallel to the coastline covering the entire study area (Figure 6.3). Each transect measured approximately 3 km in length with an effective observation width of 0.130 km. The surveys were carried out using low-altitude aerial reconnaissance, during which all visible anthropogenic and environmental threats were recorded along the transects. Observations included fishing activities, marine debris, coastal modifications, vessel movements, and other potential disturbance sources. Geographic coordinates of each observation were documented for spatial analysis and mapping.

To quantify the relative occurrence of threats, encounter rates were calculated for each threat category using the number of observations recorded per transect distance surveyed. This approach enabled standardized comparison of threat intensity across different sections of the study area. The spatial distribution of transects and recorded threats was further visualized using GIS-based mapping techniques.

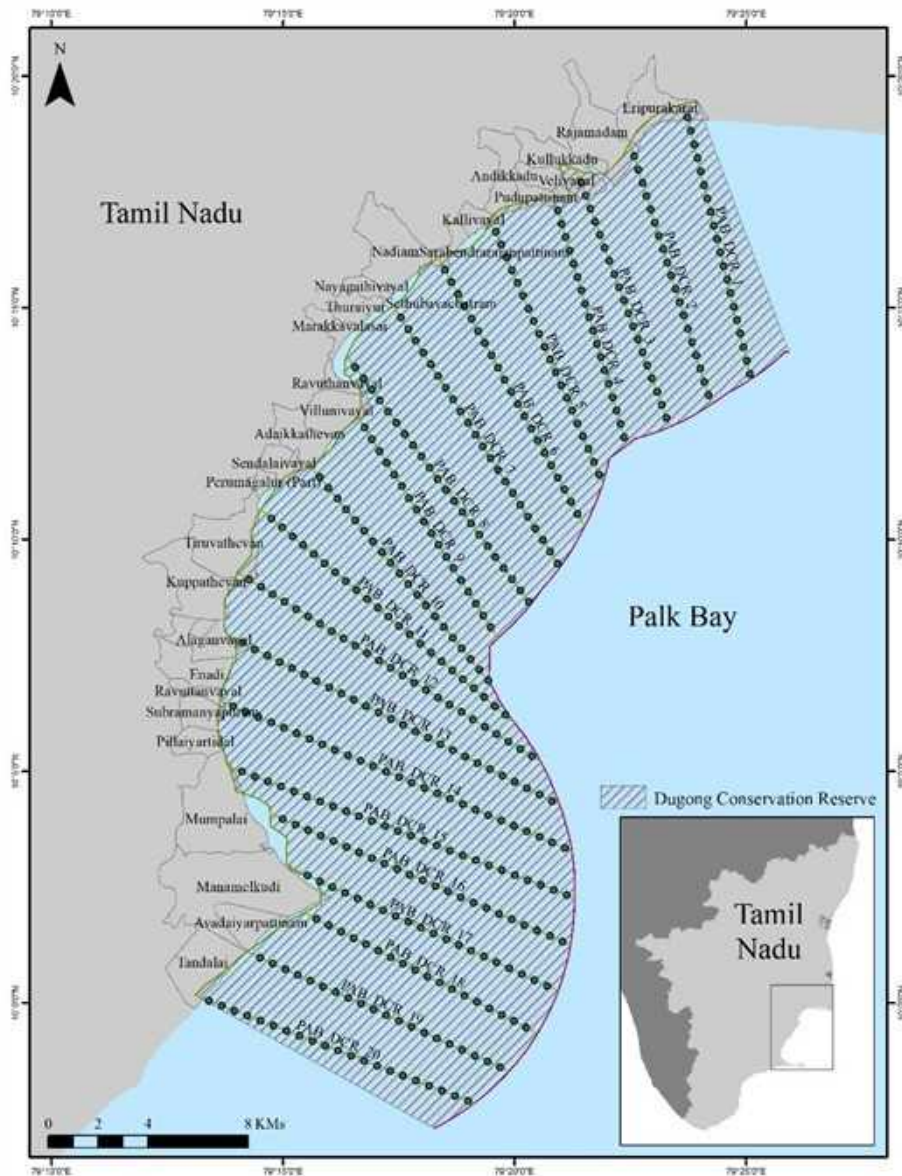


Figure 6.1: Transects for threat detections in Dugong Conservation Reserve

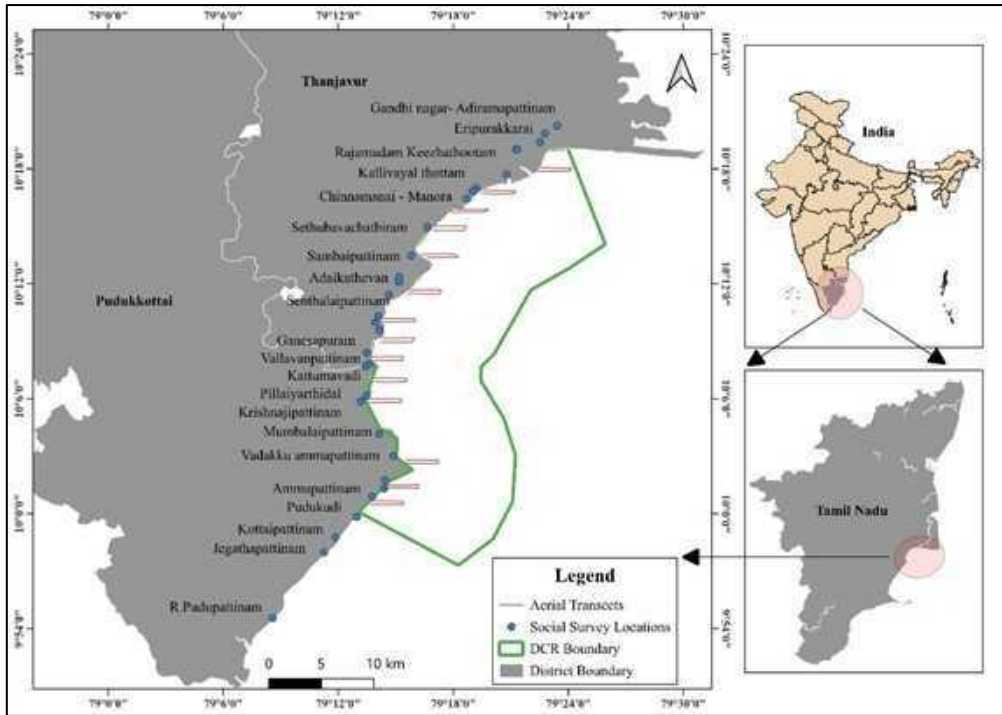


Figure 6.2: Surveyed Villages for threat documentation and dependency on seagrass meadows in Dugong Conservation Reserve

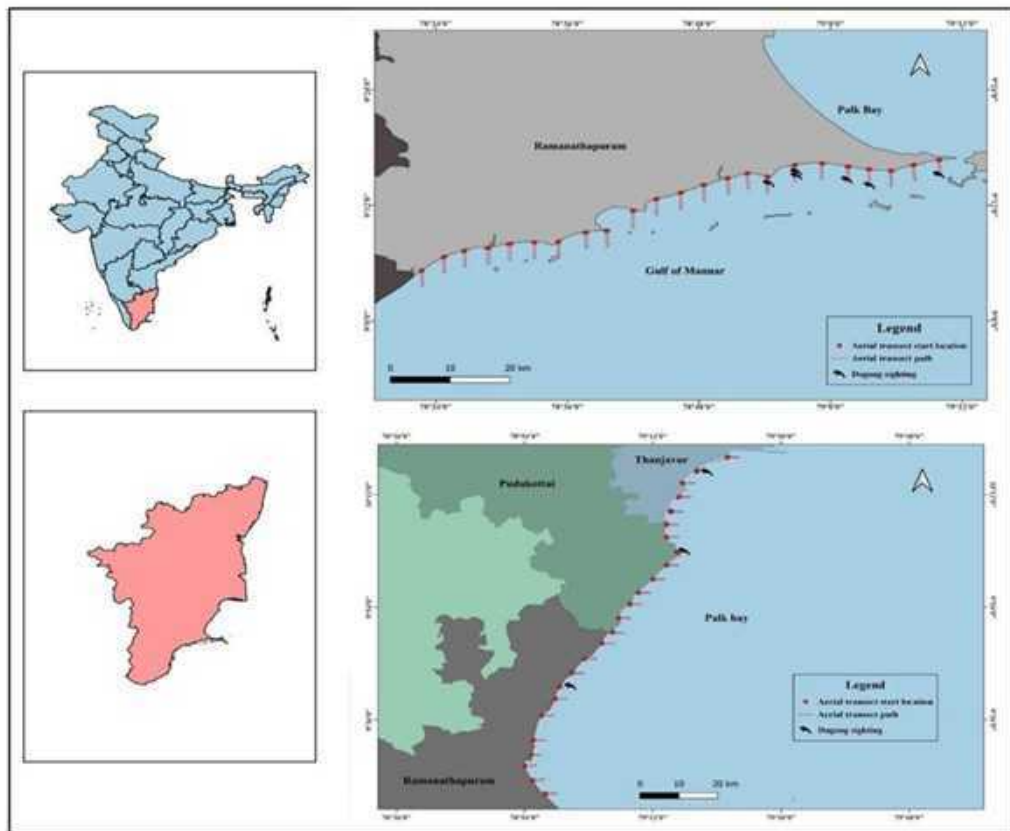


Figure 6.3: Aerial transects for detection of threats in Palk Bay and Gulf of Mannar

6.3 Results

In point counts for potential threats to seagrass, fishing boats including trawl boats and motorized boats, trap nets, gills nets, shore seine nets were recorded. Amongst fishing boats, the greatest number of small fishing boats were found to be operational in the north Palk Bay across seasons in comparison to trawl boats (Figure 6.4). Observed netting activity was prominent in monsoon season (Figure 6.5).

In survey of floating litter, Styrofoam, Plastic bottle, Wrapper, net fragment, Plastic, Balloon, Bottle, Fibre net fragment, Footwear, Oil and Plastic cans were observed. Oil layers over the water surface was observed as the prime threat (49% of total observations; Figure 6.6) were observed, specifically near Setubawachatiram and Mallipattinam jetty. Fibre net fragments were 12% of total observations followed by plastic cans (9% of total observations; Figure 6.6).

According to fisher perception, 78% respondents do not know about seagrass distribution while 16.5% respondents agreed to have observed change in seagrass distribution. The reasons for change in seagrass distribution varied including natural calamities like cyclones, tsunami and water currents as well as anthropogenic factors like trawling, drag netting and mariculture.

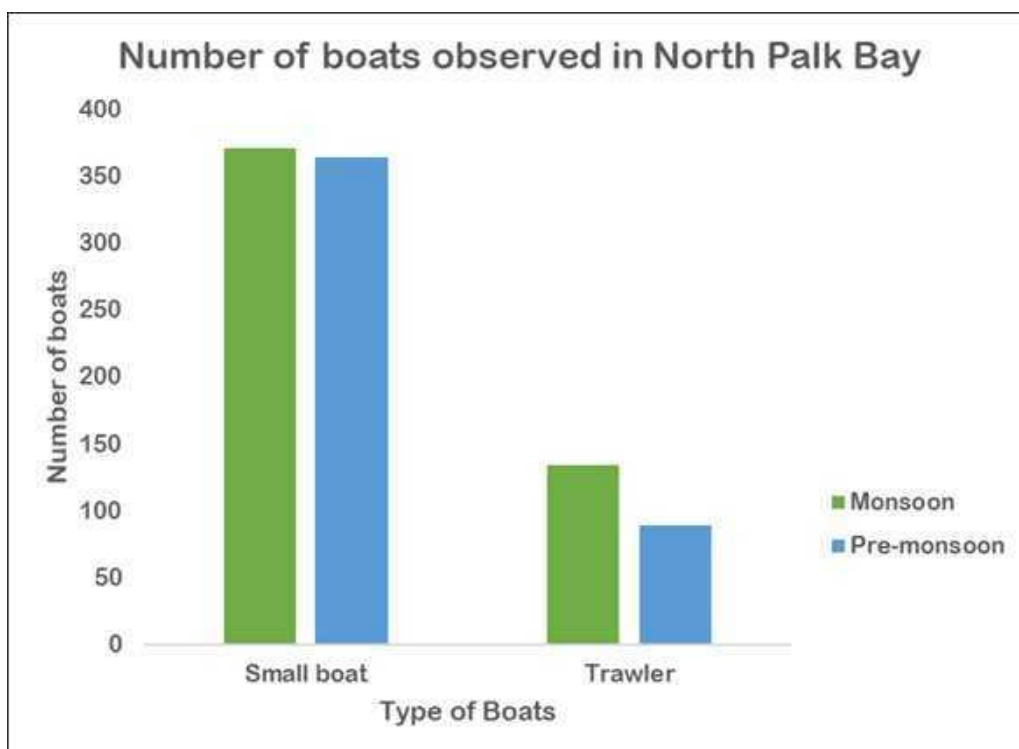


Figure 6.4: Number of fishing boats observed in North Palk Bay

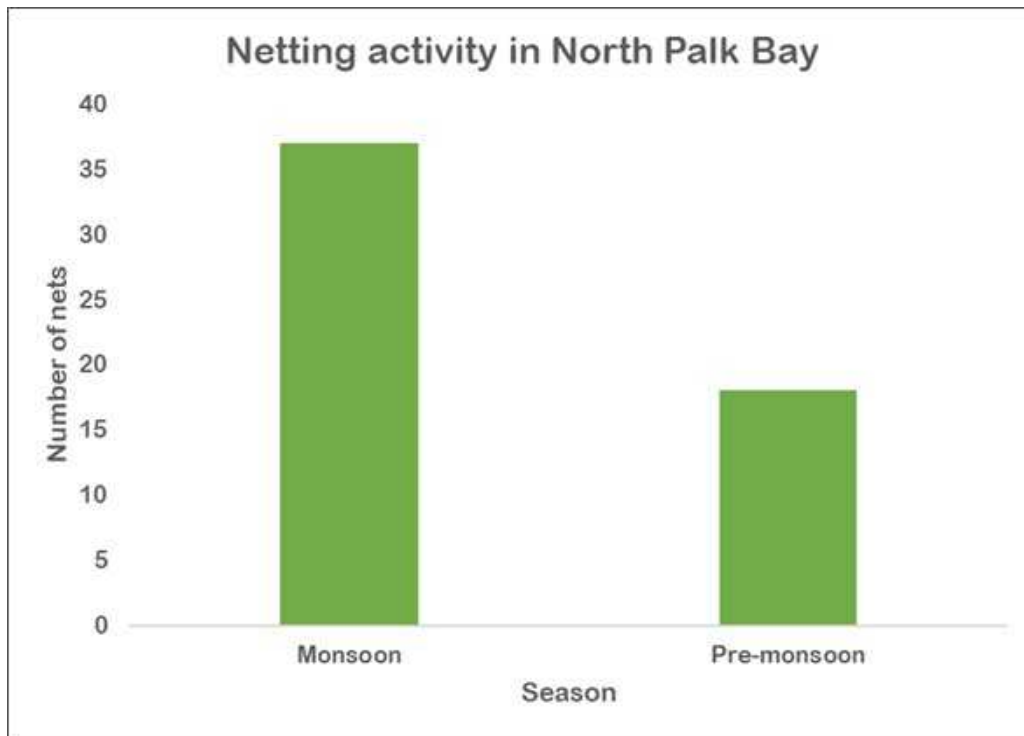


Figure 6.5: Number of fishing net activity observed in North Palk Bay

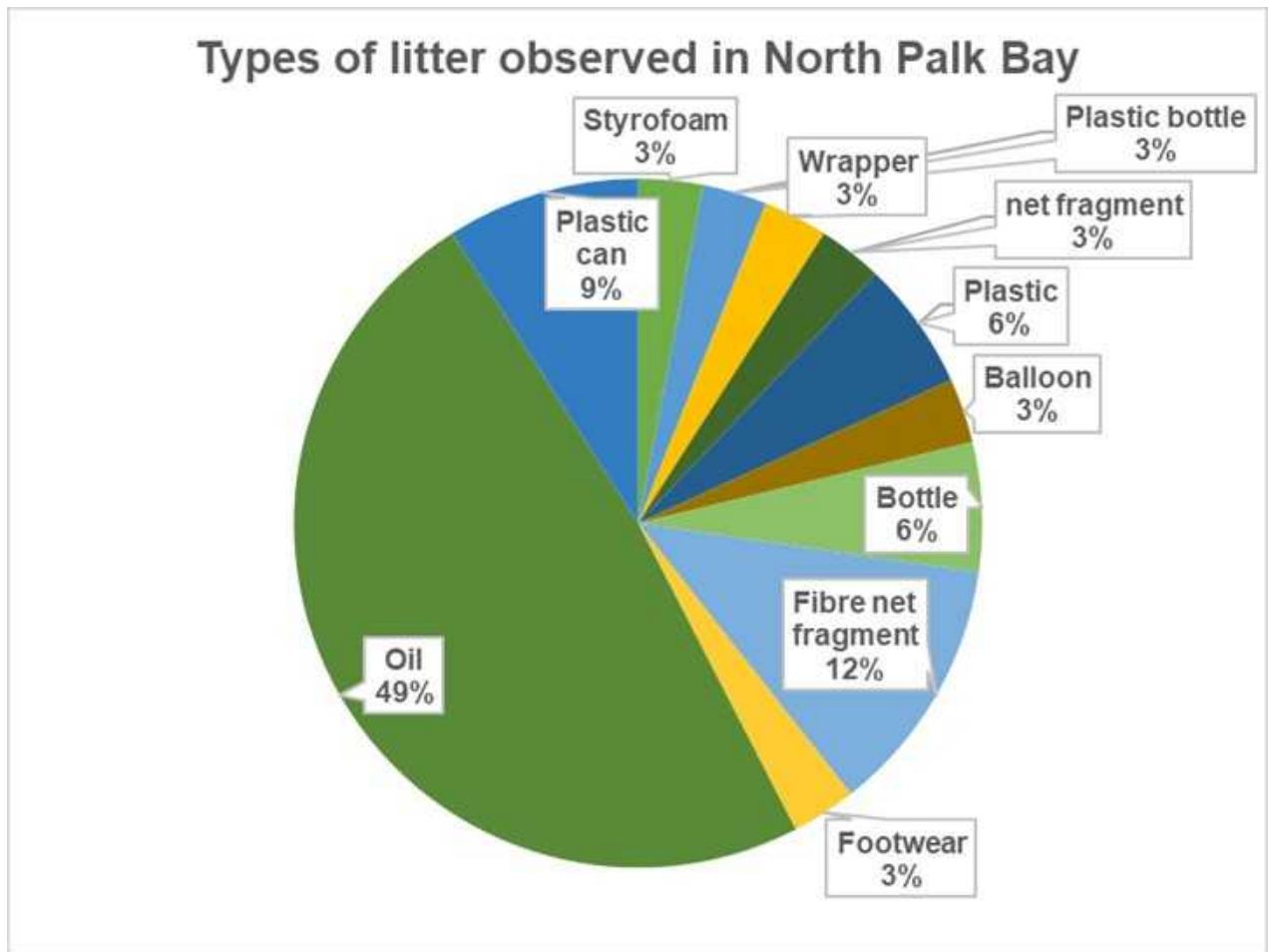


Figure 6.6: Types of floating litter observed in North Palk Bay

6.3.1 Distribution of Fishing Gear and Vessel Types as Threat Indicators

In Dugong Conservation Reserve, 82% of the boats surveyed were mechanized boats while motorized boats were only 18% (Figure 6.7). Set nets also dominated fishing gear, accounting for 82% of recorded fishing, and drag nets for 18%. Indeed, mechanized boats and set nets dominate them, indicating that the pressure upon fishing at the reserve rests on a few highly common fishing practices. These nets are broadly deployed in shallow coastal waters, which is one factor for the increasing interaction of fishing gear with dugongs, particularly in seagrass habitats where dugongs forage. Drag nets were relatively rare but have far-reaching effects on seagrass meadows via repeated contact with the seabed. These disturbances can cause habitat quality to decrease and impact the accessibility of forage resources for dugongs. Using set nets and mechanized fishing vessels predominantly for fishing in Dugong Conservation Reserve are the most common threats to the fishing environment identified.

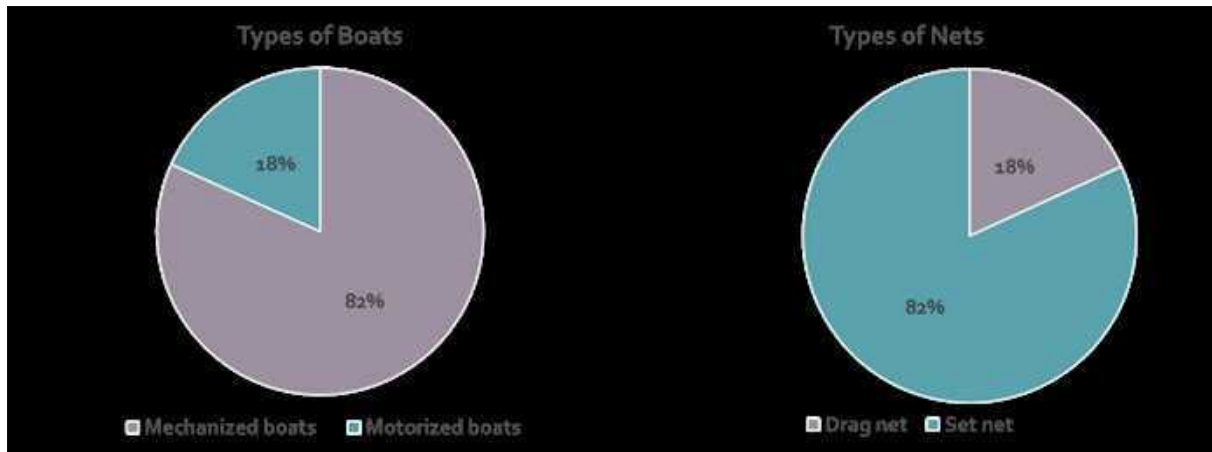


Figure 6.7: Types of fishing crafts and gears in the Dugong Conservation reserve

6.3.2 Fishing gears documented in the Palk Bay and Gulf of Mannar region

A socio-economic survey involving 882 respondents across 40 coastal villages in and around the Dugong Conservation Reserve documented a diverse range of fishing gears and fishing practices used in the region. The recorded gears were divided into drift gillnets, set gillnets, encircling gillnets, hook and line systems, bottom trawls, and beach seines (Table 6.1). Gillnets constituted the most heterogeneous type of gear, with different gear types, mesh size, construction material, deployment depth, target species, and operational properties. The recorded drift gillnets ranged from Seela Valai, Kaala Valai, Vauval Valai, Peesu Valai, Murrall Valai, and Rendakatta Valai. They were also capable of capturing a wide range of pelagic and demersal resources, among which were threadfin, queenfish, pomfret, croakers, mackerel, seerfish, shrimps, and crabs. Another category of set gillnets, namely, Koi/Panna Valai, Nandu Valai, Kundu Valai, Kelaikkan Valai, Kanava Valai, Ooli Seela Valai, Vaalaah Valai, Thirukkai Valai, Thesa Valai, Koduva Valai, Soodai Valai, Kaamili Valai, Senganni Valai, and Sangu Valai was also known. These were functioning on surface, mid-water, and bottom habitats, and were aimed at different fish, crustaceans, and cephalopods. Encircling gillnets such as Murrall Valai, Serraya/Kendai Valai and Eral/Iluppu Valai mainly took schooling fishes and shrimps. Hook-and-line fisheries consisted of Murrall Thoondil, Senganni Thoondil, Koduva Thoondil, and Kanava Thoondil and included species such as barramundi, threadfin, emperor fish, seaperch and squid. Thallumadi bottom trawl operations and beach seine fisheries recorded in several locations within the study area were also recorded. The majority of gears were synthetic in construction: polyamide monofilament, polyethylene multifilament, and polypropylene ropes. Common materials for floats included polyethylene, polyurethane foam, polystyrene and polyvinyl chloride, and ballast materials included lead, concrete and stone.

Gear, fishing season, depth of deployment and target species also were tailored to the conditions of respective fishing communities and sites within the Dugong Conservation Reserve. The wide range of gears recorded demonstrate the multi-species nature of coastal fisheries that function in the Palk Bay and Gulf of Mannar.

Table 6.1: Summary of fishing gears documented in the Dugong Conservation Reserve and their potential impacts on seagrass ecosystems

Gear Category	Gear Type	Target Species	Fishing Zone	Potential Impact on Seagrass Ecosystem
Drift Gillnet	Seela Valai / Katta Valai	Queenfish, threadfin, trevally, mackerel	Surface–midwater	Lost nets may become ghost gear, causing shading and entanglement in seagrass meadows.
Drift Gillnet	Kaala Valai	Threadfin, seerfish, crabs, shrimps	Near-bottom	Concrete sinkers may drag across the substrate, damaging seagrass shoots and rhizomes.
Drift Gillnet	Vauval Valai	Pomfret, rays, skates, croakers	Midwater–bottom	Repeated deployment may fragment seagrass meadows and reduce habitat complexity.
Drift Gillnet	Peesu Valai	Mackerel, croakers, pomfret, crabs, shrimps	Midwater	Drift and deployment weights may uproot seagrass shoots and disturb sediments.
Drift Gillnet	Murrall Valai	Halfbeak, needlefish	Surface	Lost nets may settle on seagrass beds, causing long-term shading and habitat degradation.

Drift Gillnet	Rendakatta Valai	Mackerel, seerfish, croakers	Near-bottom	Weighted footrope may damage rhizomes and increase sediment resuspension.
Set Gillnet	Koi/Panna Valai	Shad, croaker, mullet	Midwater	Low direct impact; lost gear may contribute to ghost fishing and marine debris.
Set Gillnet	Nandu/Kundu Valai	Blue swimming crab and demersal species	Bottom	Prolonged seabed contact may damage seagrass shoots and associated fauna.
Set Gillnet	Kelaikkan Valai	Whittings, goatfish, grunters	Bottom	Localized disturbance to shallow seagrass habitats.
Set Gillnet	Kanava Valai	Squid	Bottom	Trammel net configuration may entangle seagrass leaves and associated fauna.
Set Gillnet	Ooli Seela Valai	Barracuda	Midwater–bottom	Potential disturbance where deployed in shallow seagrass habitats.
Set Gillnet	Vaalaah Valai	Croakers, shrimp, crabs, snappers	Bottom	Heavy gear may damage benthic vegetation and increase habitat fragmentation.
Set Gillnet	Thirukkai Valai	Rays and skates	Bottom	Long soak periods increase risk of habitat disturbance and bycatch.

Set Gillnet	Thesa Valai	Sardines, anchovies	Surface	Minimal direct impact on seagrass; contributes to marine debris when lost.
Set Gillnet	Koduva Valai	Barramundi, threadfin	Surface	Low direct impact but may contribute to ghost fishing.
Set Gillnet	Soodai Valai	Sardines, shad	Surface	Limited direct impact on benthic habitats.
Set Gillnet	Kaamili Valai	Small shrimps and crabs	Bottom	May disturb shallow seagrass beds through repeated deployment.
Set Gillnet	Senganni Valai	Seaperch, trevally, spinefoot	Midwater–bottom	Often interacts with seagrass, resulting in gear entanglement and vegetation damage.
Set Gillnet	Sangu Valai	Octopus	Sandy bottom	Relatively low impact compared with net-based gears.
Encircling Gillnet	Murrall Valai	Halfbeak, needlefish	Surface	Minimal direct impact on seagrass habitats.
Encircling Gillnet	Serraya/Kendai Valai	Mullet, seerfish, trevally	Shallow coastal waters	May disturb seagrass through repeated encircling operations.
Encircling Gillnet	Eral/Iluppu Valai	Benthic shrimps	Bottom	Direct interaction with seabed can damage seagrass and resuspend sediments.

Hook and Line	Murrall Thoondil	Halfbeak, needlefish	Surface	Negligible impact on seagrass habitats.
Hook and Line	Senganni Thoondil	Seaperch, emperor fish	Bottom	Anchoring stones may locally disturb seagrass substrate.
Hook and Line	Koduva Thoondil	Barramundi, threadfin	Midwater	Minimal habitat disturbance.
Hook and Line	Kanava Thoondil	Squid	Near-bottom	Localized disturbance from placement of artificial spawning structures.
Bottom Trawl	Thallumadi (Ilu Madi)	Shrimps, crabs, demersal fishes	Seabed	High impact; uproots seagrass, disturbs sediments, fragments habitat, and reduces ecosystem resilience.
Beach Seine	Beach Seine Net	Mixed fish and shrimp assemblages	Nearshore shallow waters	High impact; drags across seabed causing shoot removal, sediment disturbance, and habitat degradation.

6.3.3 Anchoring Practices as a Potential Threat to Dugong Habitats in the Dugong Conservation Reserve

Five anchor types were used across the Dugong Conservation Reserve and a couple of anchor categories significantly dominated (Figure 6.8). The 5-spike anchor was the most common, with 517 recorded units, and the 2-spike anchor had 334 reported units. The exception was observed for 4-spike (13 units), 3-spike (8 units), and 1-spike anchors (3 units). The predominance of 5-spike and 2-spike anchors shows that fishing and boating activities within the reserve require major use of anchoring systems with adequate grip of seabed substrates.

Recurrent use of anchor-type systems in shallow coastal waters and at seagrass meadows with high anchorage ratios will lead to continued disturbance of the benthic substrate by anchor penetration, dragging, and retrieval. Such activities may result in physically damaging seagrass beds, which include the uprooting of shoots, rhizome fragmentation and formation of open spaces within continuous meadows. The massive dominance of 5-spike (59.0%) and 2-spike anchors (38.1%) mentions that nearly all the pressure on anchors is placed in either category and the role of other anchor type is almost negligible. Results suggest the possibility to enhance seagrass habitat destruction in Dugong Conservation Reserve by anchoring activity.

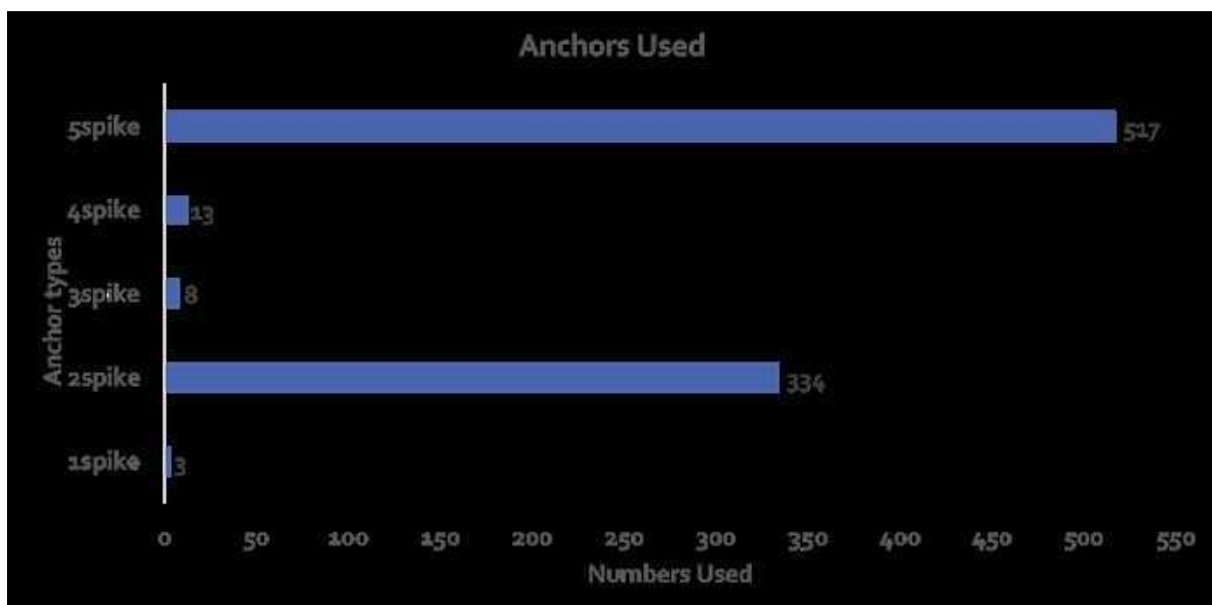


Figure 6.8:Anchor types were used across the Dugong Conservation Reserve

6.3.4 *By-catch Composition and Utilization in the Dugong Conservation Reserve*

In the Dugong Conservation Reserve, the survey reported on a wide variety of by-catch species and debris from fishing in a variety of fishing sites including sea cucumbers, seahorses, small fishes, sea turtles, prawns, crabs, starfish, seagrass, and shells (Figure 6.9). The disposal of these by-catch products often yielded mixed results, some kept and sold, some completely discarded. Sea cucumbers, sea turtles, starfish, and seagrass in all cases were discarded (100%) which suggested that these organisms or the remaining materials had no obvious market value to fishers. This represents the incidental capture of sea turtles in an era when direct contacts between fishing operations and the fauna in the ocean are on the rise. Likewise, seagrass as by-catch reveals that fishing activity could be physically disturbing seagrass meadows — an important feeding environment for dugongs. Among commercially retained by-catch, prawns and crabs retained the highest percentage of catch compared to the catch as a whole

(approximately 50% sold and 50% discarded). Small fishes were commonly caught and preserved; approximately 38% were sold and 62% were discarded. Shells had moderate economic value, with approximately 29% for sale and 71% discarded. Seahorses were kept in occasional cases, around 12% sold, with most of them discarded (88%). As we conclude that fishing in the study, fish activities along the Dugong Conservation Reserve cause the incidental capture of commercially beneficial and ecologically significant species. The acquisition and waste of sea turtles, seahorses and seagrass demonstrate interactions between fisheries and sensitive ecosystem components. Additionally, seagrass removal by fishing may enhance habitat loss, and incidental collection of protected species also suggests a possible ecological impact of fishing in dugong habitats. In its totality, the by-catch profile shows that fishing risks in the reserve go beyond the collection of fish in the vicinity of harvests to those to which it is not a fished animal or seagrass ecosystems on a more directly invasive basis on non-target organisms and seagrass habitats. These results highlight the importance of better fishing skills, bycatch protections and conservation management of by-catch and habitat sensitive management to minimise adverse effects in natural habitats of dugongs on these species and resultant biodiversity.

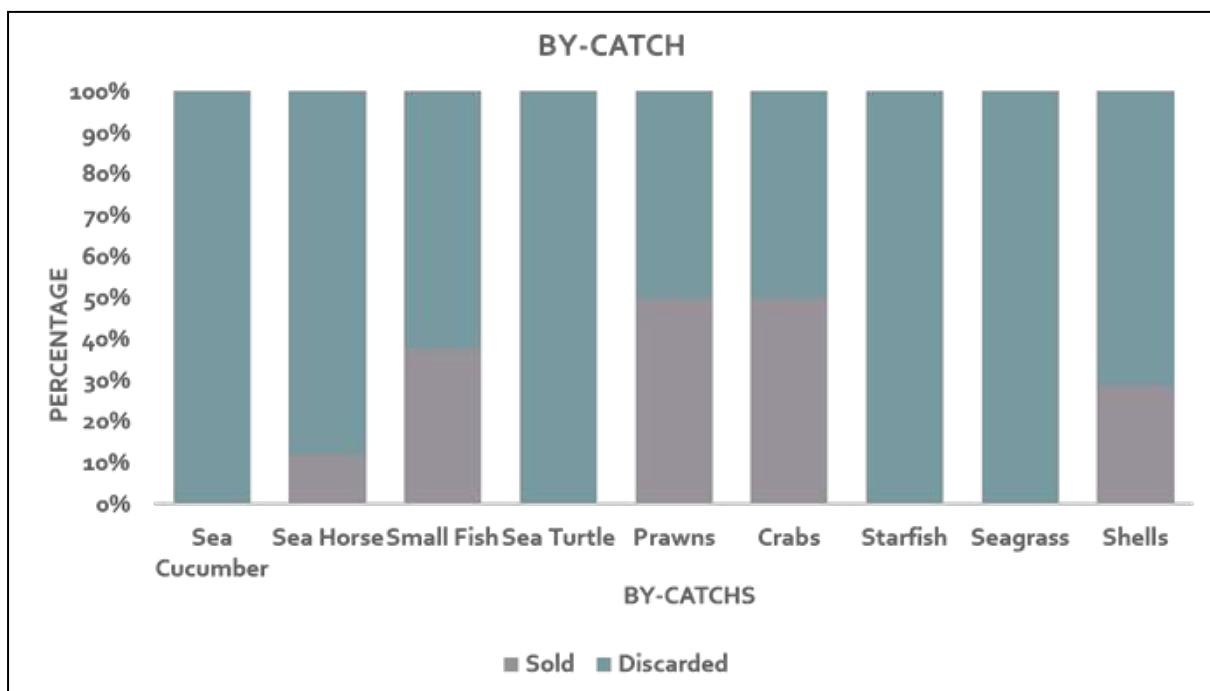


Figure 6.9:By-catch composition in seagrass meadows of Dugong Conservation Reserve

6.3.5 Threat Density observed in aerial surveys

A total survey effort of 288 km consisted of 96 aerial transects measuring about 3 km long. A determination of threat density showed clear regional differences in anthropogenic disturbance occurrence (Figure 6.10). In general, boat-related activities and litter were the most frequent threats found throughout the study area. In Palk Bay, boat-related threats generated the highest encounter rate that reflects the intensive vessel activities within the surveyed area. The second most frequently encountered threat was litter, followed by fishing-related structures: fishing floaters, net lines and seaweed culture installations. In contrast, the Gulf of Mannar was defined by an increased litter occurrence, while boat-related threats had a lower encounter rate. Some threats such as trap nets and seaweed culture structures were heavily limited to Palk Bay, while rafts and fishing floaters were encountered less frequently and were distributed primarily locally. Overall, most category threat densities in Palk Bay were higher, thus indicative of increased anthropogenic pressure in comparison with the Gulf of Mannar.

Overall threat observations per transect differed significantly between Palk Bay and the Gulf of Mannar (Wilcoxon rank-sum test, $W = 835.5$, $p = 0.042$; Figure 6.12). The mean number of threats recorded per transect was higher in Palk Bay (8.49 ± 1.48 SE) than in the Gulf of Mannar (4.59 ± 0.79 SE). On average, threat observations in Palk Bay were nearly twice those recorded in the Gulf of Mannar. The larger error bars observed for Palk Bay indicate greater variability in threat occurrence among transects compared to the Gulf of Mannar. These results suggest that anthropogenic activities and associated threats were more prevalent within the surveyed areas of Palk Bay than in the Gulf of Mannar.

6.3.6 Relative Threat Composition

The categories of threats differed greatly across the two regions (Figure 6.11). Litter was found to be the predominant threat category of Gulf of Mannar, constituting approximately 52% of all observed threat along with boat-related activities giving about 33% of observed threat data. The remaining threat categories (fishing floaters, seaweed culture, fishing nets, rafts, and trap nets) collectively covered a small fraction of overall observations. Boat acts had the greatest number of recorded threats in Palk Bay, constituting nearly 49% of the observations. Litter was the next-most common threat, accounting for about 24% of the threat records. Fishing-related structures, namely fishing floaters and seaweed culture installations, made up a large proportion of the threat picture as they together provided nearly one-fifth of all observations. Net lines, fishing nets, rafts, pump fences, oil spills, and trap nets collectively account for a

relatively small proportion of the total menace and contributed. Distinct composition of threats between the two regions imply the Gulf of Mannar is primarily plagued by solid waste accumulation while Palk Bay has more human-driven factors related to fishing, mariculture, and vessel movement. The results emphasise the importance of targeted regional management actions in addressing dominating threats at the specific scale at which it is being managed.

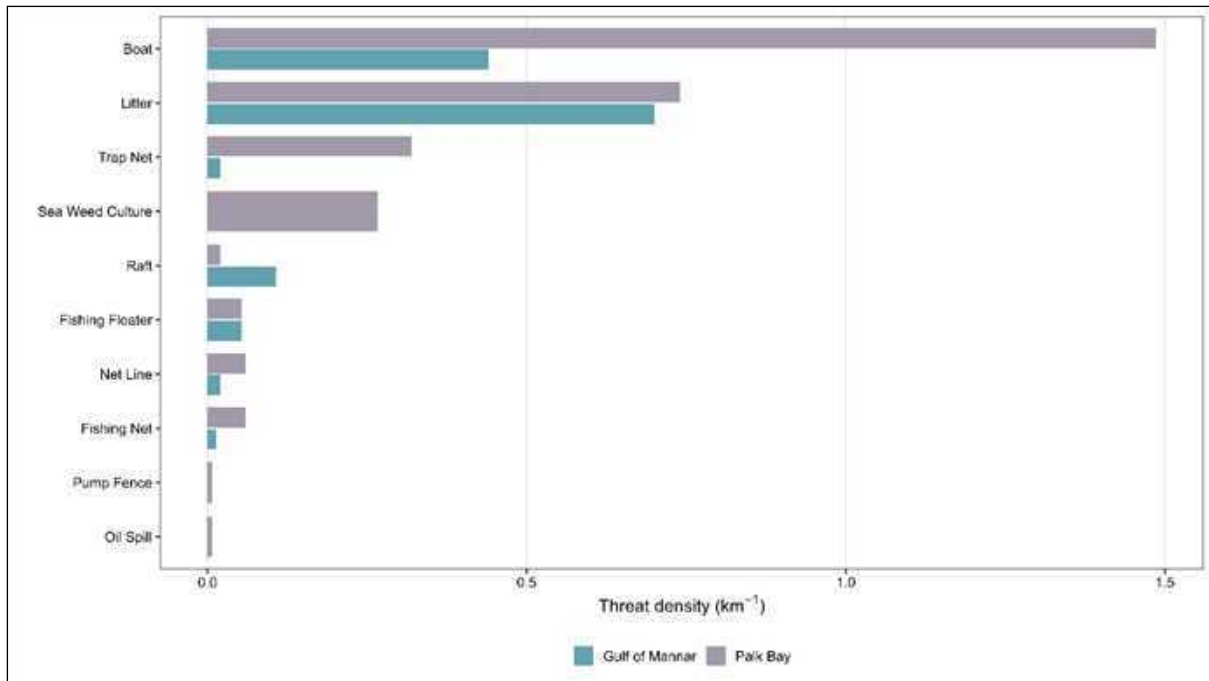


Figure 6.10: Threat density observed by aerial surveys in Palk Bay and Gulf of Mannar

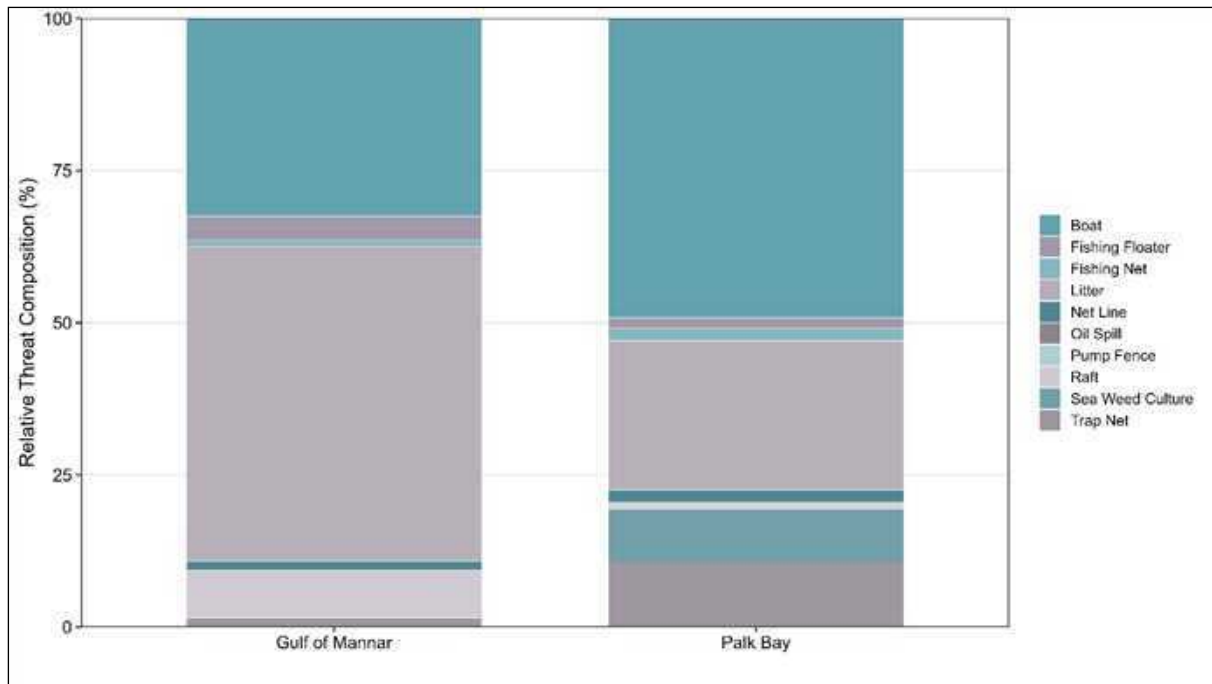


Figure 6.11:Relative threat composition observed by aerial surveys in Palk Bay and Gulf of Mannar

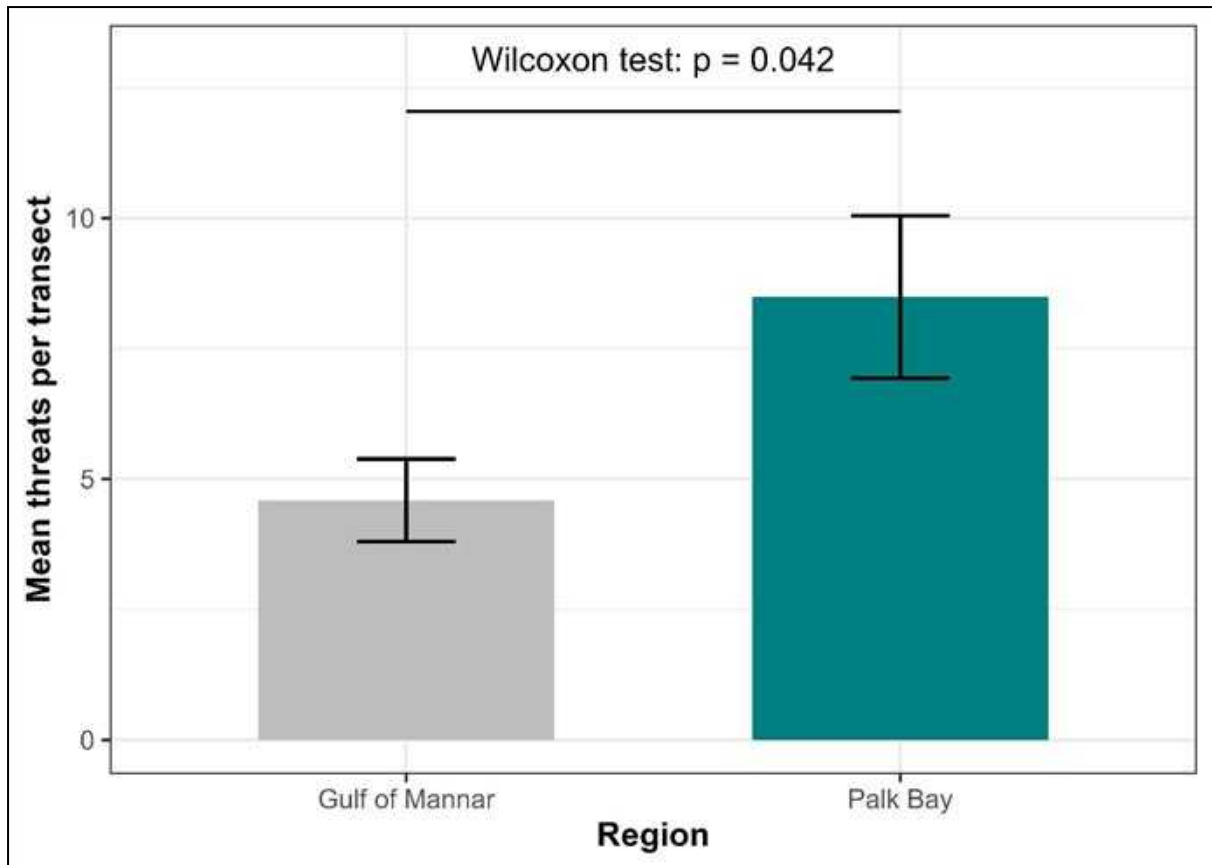


Figure 6.12: Mean (\pm SE) threat observations per transect in Palk Bay and the Gulf of Mannar

6.4 Discussion

Fishing operations, marine litter, anchoring and incidental bycatch were identified in the current study as the greatest challenges to the seagrass biomes of the Palk Bay and Gulf of Mannar areas. Field observation, fisher interviews and aerial surveys revealed that anthropogenic pressure is pervasive across the Dugong Conservation Reserve (DCR), with fishing activities as the major source of disturbance. These results are in agreement with international observations that habitat degradation, fishing stress, pollution, and collective ecological impacts are some of the top drivers of seagrass decline and associated loss of biodiversity (O’Leary et al., 2021; Rees et al., 2023).

6.4.1 *Fishing Activities as a Major Driver of Seagrass Disturbance*

The dominance of mechanized boats, set nets and active fishing in the Dugong Conservation Reserve also indicate strong fishing pressure conditions in seagrass. Fishing boats remained

one of the most commonly reported threats in both point count surveys and aerial surveys, with boat-related activities representing nearly half of all threats identified in Palk Bay. The predominating mechanized fishing vessels and fishing gear indicates the possibility of anthropogenic pressure on marine environments which serve as vital dugong feeding sites and fish nurseries. More specifically, the extensive introduction of set nets is important because shallow seagrass habitats provide habitat for juvenile fish, invertebrates and a variety of threatened marine species. It has been shown in previous research that healthy seagrass meadows harbour higher volume, species composition and recruitment ratios of fishes, in comparison to degraded habitats (Lattanzi et al., 2024; Mwaluma et al., 2022; O’Leary et al., 2021). Thus, intensive fishing in these environments could compromise the quality and functionality of the habitat. The heavier netting season in the monsoon could correspond to seasonal differences in fishing and species availability. Comparable seasonal alterations observed in the abundance and habitat usage of fish larvae have also been carried out for East African seagrass ecosystems where environmental conditions are significant drivers of fish assemblages and recruitment (Ngisiange et al., 2024; Tarimo et al., 2022).

6.4.2 Effects of Fishing Gears on Seagrass Ecosystems

The accurate description of fishing gears was evidence that the most highly utilized gears are capable of physically damaging seagrass meadows. Drift gillnets with sinkers, bottom-set gillnets, trammel nets, beach seines, and bottom trawls each interact in different degrees with the seabed. Frequent contact between the weighted fishing gear and the substrate may have led to shoot removal, rhizome breakage, sediment disturbance, and habitat fragmentation. These effects have been recorded worldwide in seagrass ecosystems subject to chronic anthropogenic disturbances. Rees et al. (2023) reported that accumulated environmental stressors harmed at-risk seagrass populations and the associated fish communities. Similarly, O’Leary et al. (2021) showed that the massive loss of seagrass led to significant shifts in fish populations. Bottom-contact gears such as drag nets and Thallumadi (bottom trawl) can uproot seagrass shoots, disturb the sediments, and reduce habitat stability, which is of grave concern. Worldwide similar impacts of bottom-contact fishing gears on seagrass habitats have been documented with repeated disturbances affecting habitat fragmentation, meadow decline, and reduced ecosystem resilience (Duarte, 2002). Moreover, seagrass meadows have undergone physical damage which contributes to habitat fragmentation and results in decreased complexity, leading to changes in the diversity, abundance, and interactions of fish and the environment (Gomis et al., 2024; Lattanzi et al., 2024).

6.4.3 Marine Litter and Pollution

In field observations and aerial surveys, marine litter presented as one of the most common threats. Oil films accounted for nearly half of all floating litter observations, while plastic containers, fishing gear fragments and other synthetic materials were also common. Oil pollution concentrated all around fishing harbors and landing centres indicates localized pollution related to fishing/vessel operations. Marine debris is fast becoming a significant threat to seagrass ecosystems. Lost & discarded fishing gear adds to ghost fishing entanglement of marine fauna & physical disruption of seagrass meadows. Synthetic fishing chemicals may also degrade to microscopic plastics that build up in coastal environment. Litsi-Mizan et al. (2024) found that, in general, human activities contribute to long-term contamination to seagrass habitats and ecosystem health and related biodiversity. Pollution can also impact fish communities indirectly by reducing water quality and habitat adequacy. Research from Kenya and Zanzibar has demonstrated that abundance and communities, specifically larval fish, are closely related to environmental circumstances and habitat quality (Mwaluma et al., 2022; Tarimo et al., 2022). As such, the high incidence of pollution of litter and oil that appears in this study is likely to lead to extensive ecological impacts other than habitat decline.

6.4.4 Anchoring Disturbance and Habitat Modification

The anchoring disturbances and habitat alteration are another important but mostly overlooked source of seagrass disturbances. Multi-spike anchors dominate in the DCR, which means the seabed has penetration and dragging regularly. Anchors can uproot shoots, fragment rhizomes, et al. (2022) within continuous meadows to lessen habitat integrity and reduce the potential for recovery. The extensive use of multi-spike anchors demonstrates the necessity of enabling seagrass-sensitive mooring practices and regulating anchoring in ecologically sensitive dugong feeding sites to help prevent disturbed habitat and enable consistent, long-term conservation of dugongs and associated ecosystems. Such disturbances are expected to have specific ecological consequences for dugong feeding grounds since dugongs depend on wide and healthy seagrass meadows for its survival. Comparable concerns of physical habitat modification are noted globally as repeated disturbances decrease seagrass cover and change habitat structure (Rees et al., 2023). Habitat complexity is known to affect fish diversity, refuge, and ecology (Bramwell & Hammil, 2023; Gomis et al., 2024). Therefore, anchor-mediated fragmentation could reduce the ecological importance of seagrass habitats for dugongs and also fish communities.

6.4.5 Bycatch and Interactions with Non-Target Species

The assessments of bycatch identified interactions between fisheries and many of the ecologically important species in the catch system, namely sea turtles, seahorses, sea cucumbers and seagrass in general. Seagrass in bycatch is a direct representation of the interactions between the gears of the fishing boats and their benthic habitat. Marine predators, including sea turtles and seahorses, are incidental catches caught in the reserve's ecosystem that show the impact the fisheries can make in the reserve. Such evidence was consistent with more general issues related to fisheries effects on non-target species and the functioning of ecosystems and, hence, the broader impacts on non-target species. Local seagrass habitats are also interrelated, which is helpful to a host of species, fishes and invertebrates (Gilpin, 2023; Ren et al., 2022; Tongnunui et al., 2024). This means disturbances in these habitats as a result of fishing activities can and have cascading effects on coastal biodiversity.

6.4.6 Regional Differences Between Palk Bay and Gulf of Mannar

Aerial surveys revealed significant differences in threat diversity of Palk Bay and Gulf of Mannar. Palk Bay had a significantly higher overall anthropogenic pressure, driven primarily by boat activity, fishing infrastructure and seaweed culture installations. On the other hand, litter dominated the threat category type in the Gulf of Mannar. These regional discrepancies are probably the result of diversity in fishing activity level, coastal development stage and resource use pattern. It has been suggested in the literature that local weather situation, and human activities considerably affected fish assemblages and habitat condition of seagrass ecosystems (Nguyen, 2024; Ren et al., 2022). The greater threat density observed in Palk Bay may therefore account for the continuing concern of seagrass degradation and habitat loss in dugong in the area.

The significantly higher threat observations recorded in Palk Bay reflect increased anthropogenic pressure on coastal and seagrass ecosystems compared to the Gulf of Mannar. This result is consistent with the threat composition analysis, which revealed that boat activity, fishing-related infrastructure, and seaweed culture installations were more common in Palk Bay than in the Gulf of Mannar. The high concentration of fishing activities seen in Palk Bay is possibly attributed to its prevalence as a fishing ground, high levels of vessel traffic, and proliferation of fishing gear installations in shallow coastal waters interspersed with seagrass habitats. The much greater variability in threat observations observed in Palk Bay transects indicates that anthropogenic pressures are not evenly distributed over the region. Some

locations have a focused fishing area, vessel traffic, and infrastructural facilities leading to a spatially isolated hotspot of disturbance. Although threat observations were overall lower and more uniform among transects in the Gulf of Mannar, marine litter was the prevailing threat category across the region. Seagrass ecosystems are particularly vulnerable to cumulative human-induced change, as they live in shallow coastal waters dominated by fisheries and other coastal activities. Vessel traffic, fishing, anchoring, marine litter, and aquaculture can further result in habitat loss and reduced ecosystem functioning. Similar studies have identified fishing pressure and habitat modification as two primary causes for the decline of seagrass and related biodiversity loss across coastal ecosystems worldwide (O'Leary et al., 2021; Rees et al., 2023). Hence, the strikingly elevated threat density in Palk Bay indicates the need for region-specific management strategies to decrease anthropogenic risks to seagrass environments. From an ecological point of view, the findings support the prioritization of Palk Bay with respect to threat mitigation measures that would mean better fisheries management, regulation of destructive fishing activities, better waste management, and the protection of sensitive seagrass habitats. Due to the ecological value associated with seagrass meadows for fish nursery and feeding areas for dugongs, minimizing anthropogenic pressures in Palk Bay will likely greatly contribute to the long-term viability of seagrass ecosystems both spatially and within biodiversity.

6.4.7 Conservation Implications

The results underscore the importance of incorporating dual conservation strategies to mitigate both direct and indirect threats to seagrass ecologies. In shallow seagrass habitats at sea, fisheries management should work to mitigate the use of destructive gears, advise gear changes to limit seabed contact, and also apply bycatch-reduction efforts. Also, regulation over anchoring on the vital feeding sites of the dugongs is a necessary action step to reduce physical habitat impact. Marine litter pollution is addressed within such communities by ensuring better waste disposal at fishing harbour facilities, and providing a retrieval program for abandoned fishing gear. Given that fewer fishers were familiar with the availability and ecological importance of seagrass, the implementation of community-based and targeted conservation plans and outreach activities could result in better marine stewardship of the seagrass resources. It also supports ecosystem-based management strategies to retain habitat connectivity and ecological integrity. Healthy and structurally complex seagrass meadows support improved fish diversity, recruitment, and ecosystem functioning; studies conducted in other parts of the globe have confirmed this (Gomis et al., 2024; Lattanzi et al., 2024; Mwaluma et al., 2022).

Thus, seagrass habitat conservation will support dugong conservation and promote fisheries sustainability and biodiversity conservation in the Palk Bay and Gulf of Mannar.

6.4.8 Measures for Conservation of Seagrass Ecosystems in Palk Bay and Gulf of Mannar

From findings in the present study, multiple anthropogenic pressures to seagrass ecosystems in Palk Bay and Gulf of Mannar, such as intensive fishing, damaging fishing gear, anchoring, marine litter, and incidental bycatch of non-target organisms have been identified as impacts. Therefore, they must be managed to enable effective conservation, to control both the direct and indirect threats to coastal fisher communities and safeguard their livelihood. The regulation of fishing activities in seagrass habitats is a critical conservation priority. Fishing gear that are in contact with the seabed may be progressively restricted or controlled within areas where there are dense seagrass meadows, such as drag nets, beach seines, and bottom trawls, that must be restricted or regulated in the seagrass meadows. Low-impact fishing techniques and alterations to gear that minimize seabed disturbance may be promoted in these areas to reduce habitat loss and minimize losses of productive fisheries productivity in order to reduce degradation of habitat. Closures of fishing seasons or locations in ecologically sensitive areas may also help further improve seagrass recovery and decrease disruption at sensitive times for fish recruitment. Pressure from anchoring could also be mitigated by defining anchoring zones and providing seagrass safe mooring facilities. Restriction of anchoring in strategic dugong feeding areas and seagrass hotspots to minimize physical damage caused by anchor penetration and dragging would minimize the amount of anchoring pressure that the animals would have to endure. These actions would be essential for the conservation of habitat stability and ecosystem integrity of habitat continuity and preservation of the integrity of the ecosystem. Marine debris and abandoned fishing gear were found to be significant threats in both regions. By beefing-up waste management infrastructure in fishing harbours and landing facilities, regularly doing some regular pick-ups and responsible disposal of abandoned fishing gear while also promoting the disposal of rubbish from fishing gear. Community-based retrieval plans for abandoned and lost fishing gear would help to mitigate ghost fishing as well as to stop the ongoing effects on seagrass habitats and associated fauna. The occurrence of sea turtles, seahorses, sea cucumbers and seagrass as bycatch emphasises the need for bycatch reduction measures. If fishers are to reduce their interactions with non-target and protected species, by adopting bycatch mitigation strategies, through improved practices or awareness, this should be promoted. Monitoring bycatch composition regularly is also useful for adaptive

fisheries management. The more significant threat density in Palk Bay would also make it an area ripe for attention for conservation. To prevent such an event, management measures need to reduce fishing impacts; seaweed culture expansion, control marine pollution and habitat protection, and enhance habitat protection. Management in the Gulf of Mannar was better geared towards treating litter and conservation of habitat integrity.

Finally, the sustainable conservation of seagrass ecosystems is a result of the positive engagement of local communities. The public awareness programme with respect to the environmental and economic relevance of the seagrass meadows along with community-based monitoring and care can help to increase local commitment to conservation. Integrating the monitoring of scientific, fisheries and habitat, the protection of fauna and fauna systems, and public involvement will be required to promote the sustainable use of seagrass environments, dugong habitats and fisheries resources in Palk Bay and the Gulf of Mannar.

Chapter 7: Discussion and Management Recommendations

7 Discussion and Management Recommendations

Seagrass meadows are one of the most productive and biologically important coastal ecosystems in the world, occupying shallow marine waters that support ecosystem health and stability. They provide shelter, feeding and nursery habitats for a variety of marine creatures including fish, crustaceans, molluscs, sea turtles and marine mammals. In addition to supporting biodiversity, seagrass meadows are also important for the transport of nutrients, sediment stabilization of the ocean floor, shoreline protection and carbon sequestration, making them one of the most valuable components of the coastal seascape. At less than 0.2% of the total ocean floor, their ecological impact is significant, and the productivity and resilience of their neighboring ecosystems such as coral reefs, mangroves and estuaries are significantly affected (Orth et al., 2006; Waycott et al., 2009; Unsworth et al., 2019).

Seagrass meadows are important for fisheries and have been increasingly considered in recent years. These habitats are favorable for juvenile growth and have a large quantity of food sources, thereby enhancing the survival of many economically important species. Seagrass ecosystems in the Indo-Pacific, Mediterranean and Caribbean regions have been found to serve as important nursery areas and play a significant role in local and regional fisheries (Heck et al., 2003; Nagelkerken et al., 2002; Nordlund et al., 2018). However, the ecological and economic significance of seagrass-associated fisheries is still not well understood in most of the world, especially in developing countries where coastal communities are highly dependent on marine resources for their livelihoods.

In India, seagrass ecosystems are mostly restricted to the Gulf of Mannar, Palk Bay, the Andaman and Nicobar Islands, Lakshadweep and a few estuarine systems. Palk Bay and the Gulf of Mannar are among the largest and most diverse seagrass meadows in the country and one of the most significant seascapes in the Northern Indian Ocean. These ecosystems are globally recognized for their biodiversity and support threatened species like the dugong, green turtle and several species of seahorses, as well as sustainable artisanal fisheries that provide employment and food security to thousands of coastal communities. However, these environments are under increasing pressure from intense fishing, coastal development, marine pollution, seaweed farming and climate change. The ecological importance of this area and the growing threats to habitat integrity make Palk Bay and the Gulf of Mannar priority areas for conservation and sustainable management.

Although many studies have documented the distribution and diversity of seagrass species in India, very few have considered the ecological processes that support the functioning of these ecosystems. Most previous research has focused on habitat description and a limited number of flagship species, while the relationships between fish diversity, resource use, ecosystem services and anthropogenic disturbances have received comparatively less attention. There is thus little recognition of the economic impact of seagrass ecosystems on fisheries and coastal livelihoods, and conservation planning as well as resource management has been severely under-invested in these ecosystems. Addressing these knowledge gaps is essential because effective conservation requires an understanding not only of the habitats themselves but also of the ecological interactions and human dependencies that they support.

The study was conducted to develop a comprehensive understanding of the ecological and socio-economic importance of seagrass ecosystems in Palk Bay and the Gulf of Mannar. In contrast to previous studies that focused on individual aspects in isolation, this research explored the interrelationships between commercially important finfish diversity, food and space partitioning, ecosystem services and anthropogenic threats within a common ecological framework. The assessment of fish diversity revealed the species that thrive in seagrass habitats and their dependence on these ecosystems. The evaluation of resource partitioning helped explain the ecological mechanisms that allow numerous species to coexist within the same habitat. The ecosystem service assessment linked ecological functioning with fisheries productivity and local livelihoods, while the analysis of anthropogenic threats identified the major pressures affecting habitat integrity and long-term sustainability.

An important strength of the present study is its interdisciplinary approach. By integrating underwater ecological surveys, fish market assessments, community perception studies and ecosystem service valuation, the investigation bridges the gap between ecological science and resource management. The findings demonstrate that seagrass meadows are not only centers of biodiversity but also productive natural assets that sustain fisheries, support local economies and contribute to the resilience of coastal communities. This integrated perspective is particularly relevant in the context of the Dugong Conservation Reserve, where conservation objectives must be balanced with the livelihood requirements of resource-dependent communities.

This chapter provides a coherent synthesis that brings together the major findings of the study and examines their broader ecological and management implications. Rather than viewing fish

diversity, resource partitioning, ecosystem services and anthropogenic threats as independent themes, the chapter considers them as interconnected processes that collectively determine the functioning and sustainability of seagrass ecosystems. The synthesis also highlights the contribution of the present investigation to Indian seagrass research and discusses its significance for fisheries management, biodiversity conservation and future coastal policy. By integrating ecological and socio-economic perspectives, the study emphasizes that the conservation of seagrass meadows is not merely a habitat protection issue but a fundamental requirement for sustaining coastal ecosystems and the communities that depend upon them.

7.1 Commercially Important Finfish Species Associated with Seagrass Meadows

The first objective of this study was to document the commercially significant finfish species inhabiting the seagrass ecosystems of Palk Bay and the Gulf of Mannar, as well as to elucidate the ecological factors influencing their distribution. While biodiversity inventories are commonplace in ecological research, the findings from this study reveal that fish diversity patterns offer substantial insights into the functioning of tropical seagrass ecosystems and their implications for coastal fisheries. The considerable number of commercially important finfish species found in seagrass habitats underscores the pivotal role these ecosystems play as foundational components of coastal food webs, rather than merely low-vegetation patches of submerged flora.

The presence of economically valuable species—including snappers, emperors, rabbitfishes, mullets, threadfins, groupers, ponyfishes, and goatfishes—in seagrass meadows indicates that these habitats are occupied by species across various trophic levels and ecological niches. Similar findings have been documented in tropical seagrass ecosystems throughout the Indo-Pacific, which serve as critical habitats for feeding and refuge from predators, as well as favorable environments for juvenile fish (Jenkins et al., 2001; Heck et al., 2003; Nordlund et al., 2017). The current study contributes to this understanding within the context of the southeastern coast of India by correlating underwater observations with fish market surveys and linking ecological patterns to fisheries production.

Most prior studies in India have concentrated on the floral diversity and distribution of seagrass habitats, with relatively few addressing the relationship between marine fisheries and fish composition (Jagtap et al., 2003; Thangaradjou et al., 2010). As a result, the ecological role of

seagrass habitats in supporting coastal fisheries has been inadequately understood. The findings of our study indicate that a significant proportion of commercially collected fishes are associated with seagrass meadows, thus highlighting the ecological value of these habitats. Protecting seagrass ecosystems is essential for biodiversity conservation and marine ecosystem management, extending beyond mere fisheries and coastal livelihoods.

The comparative analysis between Palk Bay and the Gulf of Mannar further supports these conclusions, suggesting that fish diversity in seagrass ecosystems is highly contingent upon habitat heterogeneity and seascape structure. The Gulf of Mannar exhibits greater fish diversity and richness compared to Palk Bay, where fewer species are represented despite a higher abundance of individuals. Similar trends have been observed in tropical coastal habitats, where diverse environments—such as coral reefs, seagrass meadows, rocky substrates, and sandy bottoms—yield greater fish diversity than more homogeneous habitats (Nagelkerken et al., 2002; Dorenbosch et al., 2005). The increased habitat complexity and connectivity in the Gulf of Mannar may provide more diverse environments for fish species with varying habitat requirements, presenting an important insight into tropical marine ecology.

Seagrass meadows should not be regarded as isolated ecosystems but rather as integral components of an interconnected coastal ecosystem. Fish utilize seagrass beds, coral reefs, estuaries, and sandy habitats throughout different stages of their life cycles. Consequently, the ecological significance of seagrass ecosystems is influenced not only by local habitat conditions but also by the health and accessibility of neighboring habitats. This concept of habitat connectivity has gained prominence in seascape ecology, as the degradation of one habitat can have cascading biological effects on adjacent ecosystems (Unsworth et al., 2008; Olds et al., 2016). Fish assemblages serve as effective indicators of habitat connectivity, with factors such as seagrass height, cover, depth, coral cover, and substrate composition shaping community structure. This indicates that a diversity of ecological niches is generated across varying ecological contexts. Hori et al. (2009) demonstrated a similar relationship between canopy complexity and fish diversity in subtropical seagrass ecosystems, suggesting that taller and denser seagrass meadows offer superior shelter and foraging opportunities for fish. The association of certain species with dense seagrass habitats or coral-dominated areas indicates that many fish do not consistently utilize the same habitats. The relatively small number of species contributing to the differences between the fish assemblages of Palk Bay and the Gulf of Mannar provides additional ecological insights. Species such as *Terapon puta* and *Siganus*

spp. account for a significant portion of the differences observed, potentially serving as key indicators of community structure, wherein fluctuations in the abundance of these species may impact the overall ecological framework. Similar patterns have been recognized in other tropical marine ecosystems, where dominant species play a crucial role in community composition and ecosystem functionality. Thus, these species may serve as ecological signals for monitoring habitat health and long-term environmental changes. A major finding from the analysis of fish diversity in seagrass meadows is the compelling evidence of their nursery function. Juvenile and sub-adult fishes were found to be more concentrated in seagrass habitats than in non-seagrass areas, with feeding and habitat guilds dominated by younger life stages. These observations align with the nursery-value hypothesis posited by Beck et al. (2001), which asserts that certain habitats contribute disproportionately to adult populations by enhancing juvenile survival and growth.

The high density of juvenile fishes in seagrass meadows suggests that these habitats are less susceptible to predation, possess abundant food resources, and provide suitable conditions for young fish during their most vulnerable developmental stages. Some species residing in seagrass habitats as juveniles ultimately transition to offshore fisheries or neighboring reef ecosystems. The productivity of coastal fisheries likely hinges on the health and sustainability of seagrass meadows. Habitat destruction or fragmentation could diminish recruitment success, adversely affecting fishery yields. Global concerns have been raised regarding the loss of seagrass, which has been linked to declines in fish populations and shifts in ecological organization (Waycott et al., 2009; Unsworth et al., 2015).

The distribution of feeding and habitat guilds further indicates that seagrass ecosystems support fish with diverse ecological strategies. Carnivores, herbivores, omnivores, benthivores, and planktivores utilize these habitats, each contributing to the deep ecological functions sustained by seagrass meadows. The trophic diversity within these ecosystems suggests their capacity to support complex food webs and facilitate energy transfer across coastal environments. Such diversity of trophic environments enhances ecosystem resilience, as various ecological functions are performed by numerous individuals rather than a select few species.

The predominance of estuarine and reef-associated guilds further illustrates that seagrass meadows serve as transitional habitats within coastal ecosystems. The interplay between coral reefs, seagrasses, and estuaries forms a complex ecological network that sustains fish populations throughout their life cycles. Comparable ontogenetic habitat shifts have been

observed in the Caribbean and Indo-Pacific regions, where juvenile fishes find refuge in seagrass meadows before migrating to coral reefs as adults (Nagelkerken et al., 2002; Kimirei et al., 2011). Findings from southeastern India bolster the growing consensus that effective marine conservation must prioritize the protection of entire seascapes rather than isolated habitats. Conservation strategies for seagrass ecosystems have frequently focused on the welfare of threatened species, such as dugongs and sea turtles. While these species remain critical to conservation efforts, this study underscores that seagrass meadows also support economically valuable fish species essential for local livelihoods. Consequently, conservation plans should account for the ecological and economic benefits provided by these habitats. Protecting seagrass meadows can yield numerous benefits in terms of biodiversity and the sustainability of fisheries and coastal communities.

However, certain limitations must be acknowledged. Fish market surveys were conducted exclusively in Palk Bay due to differences in fishing practices between the two regions, and data collection was restricted to specific sampling periods. Seasonal migration patterns, interannual environmental variability, and long-term climatic influences may have affected fish populations in ways that could not be captured during the study period. Furthermore, while clear associations between fish and their habitats were identified, the scope of this study did not encompass fish movement among seagrass meadows, coral reefs, and adjacent habitats.

In conclusion, the analysis of commercially important finfish biodiversity indicates that the seagrass meadows of Palk Bay and the Gulf of Mannar constitute critical ecological habitats for fish production, biodiversity, and coastal fisheries. Fish diversity is influenced by habitat complexity, environmental gradients, and landscape connectivity, with a substantial number of juvenile fishes suggesting that these ecosystems serve a crucial nursery function. This study has demonstrated that seagrass habitats are not merely biodiversity concerns; they are vital for fisheries management and the security of coastal livelihoods. The findings also provide a foundational ecological basis for the subsequent aim of this research: to investigate the potential diversity of fish species inhabiting these habitats through the partitioning of food and spatial resources.

7.2 Resource (Food and Space) Partitioning among Seagrass-associated Commercial Finfishes

My second objective was to identify how commercially relevant finfish species coexist with each other in the seagrass ecosystems of Palk Bay and the Gulf of Mannar despite sharing a

habitat. Behaviour patterns, habitat use, microhabitat associations, niche overlap and food resources on environmental basis illustrate that coexistence of species is not the result of unlimited resources but ecological segregation in multiple domains. The findings show that seagrass meadows support fish diversity because different species use different parts of the habitat and use food resources differently, and this reduces competition.

One of the most important findings of this study is that seagrass meadows are heterogeneous ecosystems. Rather than being common habitats, they can have a variety of ecological niches constructed by different canopy heights, seagrass density, substrate types, water depth and proximity to coral reefs and other coastal habitats. Fish responses to this habitat complexity were different with some species favoured very dense seagrass meadows and others were more likely to be associated with sparse habitats, sandy bottoms and reef edges. This diversity of habitats in seagrass ecosystems suggests that the ecological value of seagrass ecosystems is not just the size of their areal floor but also the diversity of microhabitats that they provide. This interpretation is supported by the behaviour of seagrass meadows, where movement, feeding and hiding are predominant as well as feeding sites, shelter habitats and movement routes. The difference in behaviour between Palk Bay and the Gulf of Mannar, which has the same habitat in both areas, could also indicate the fishes respond to regional differences in habitat and the availability of food. The larger feeding activity in the Gulf of Mannar could be due to the presence of neighbouring coral reefs that have the same habitat as the ones in Palk Bay and therefore the presence of high pass and refuge activity in these meadows (a sign that these meadows are transitional habitats).

Vertical segregation in the seagrass canopy is another mechanism that reduces competition between coexisting species. Most fishes used the lower canopy, whereas others used the upper canopy, bottom substrate, or adjacent habitats. Even within the same meadow, species used different components of the structure. Bottom-dwelling gobiids, fishes on the seagrass blades and species in the water column all occupied different parts of the habitat, so there was a lack of direct overlap. This means that the three-dimensional structure of seagrass ecosystems offers fish a great deal of ecological possibilities.

The habitat associations and indicator species also showed that the commercially important finfishes clearly have good habitat preferences. *Terapon puta*, *Lutjanus fulviflamma* and *Oplopomus oplopomus* were associated strongly with certain seagrass density classes and some were more adaptable. The coexistence of habitat specialists and habitat generalists appears to

be an important feature of these ecosystems. I found that when habitat niche overlaps are high, they do not mean intense competition. Some closely related species have large habitat sharing with each other and others have almost complete habitat segregation. In Palk Bay, gobiid fishes have similar bottom habitats, and gerreid species have big overlap in the shallow seagrass area. In the Gulf of Mannar, lutjanids, lethrinids and mullids have large habitat sharing while benthic gobiids are very much separated from larger mobile predators. These patterns suggest that species coexist through a combination of habitat sharing and habitat differentiation; competition is reduced by dividing up other ecological areas.

Those species with broad niche breadths such as rabbitfishes, goatfishes and several lutjanids utilize different habitat types and are considered ecological generalists. Gobiid fishes and various benthic species, however, have narrow niche breadths and thus are particularly well suited to the habitat. The coexistence of generalists and specialists in an ecosystem helps to maintain the ecosystem as different ecological roles are shared by species with different adaptive strategies. Generalists can help to buffer the fluctuating environment and specialists help to promote biodiversity as they play special ecological roles.

Although only a few of species were able to provide dietary information, the gut content analyses could provide very important evidence for trophic segregation. *Gerres erythrouros* appeared to feed on fish scales, algae, invertebrates and other benthic food resources, which is an opportunistic feeding strategy. On the other hand, *Psammoperca waigiensis* was found to be more dependent on crustaceans, especially shrimps, so there seems to be more specialization in the diet. These different eating strategies reduce trophic overlap and therefore in the seagrass ecosystem species that use the same habitat can better exploit different resources.

Analyzing spatial and trophic information shows that resource partitioning happens at different levels on many ecological scales. Species that have similar habitats are generally in different food habitats and the same prey are in different microhabitats. Such a multi-dimensional partitioning avoids direct competition and allows a large number of commercially important finfish species to live in relatively small areas. This is in line with classical niche theory, which assumes that species coexist by diverging from the same habitat, rather than full habitat segregation.

The patterns observed in the present study also offer insights into the ecology of tropical seascapes. The vast habitat use of many commercially important species, especially in the Gulf

of Mannar, demonstrates the close ecological connection between seagrass meadows, coral reefs and coastal habitats. At the same time, the persistence of very specialized benthic species shows that small-scale habitat features are also critical to maintain biodiversity. Consequently, the conservation value of seagrass ecosystems is beyond habitat area only but also includes habitat complexity and landscape connectivity.

The findings have direct implications for fisheries management and conservation planning. Habitat degradation via destructive fishing practices, sedimentation, coastal development or seagrass loss may simplify habitat structure and reduce the opportunities for resource partitioning. Such changes are likely to affect habitat specialists more severely than ecological generalists, potentially resulting in reductions in biodiversity and changes in community structure. The loss of microhabitat diversity may also diminish the capacity of seagrass ecosystems to support commercially important fish populations. The food and space partitioning analysis thus indicates that the persistence of more than one fish population depends on the existence of a complex and diverse seagrass habitat. Dense, medium, and sparse seagrass meadows and sandy bottoms and reef edges provide for different ecological functions and fish communities. Conservation should therefore take place not only for the protection of seagrass extent but also for the diversity of habitats and ecological processes that ensure fisheries productivity.

Some limitations can also be noted. Dietary analysis was limited because fish samples were opportunistically available and so we could not directly compare with other species. Similarly, timing of partitioning and seasonal variation in resource usage were not investigated. Stable isotope analysis, fatty acid profiles, acoustic telemetry, and environmental DNA analysis are some of the ways to better understand the relationships between the trophic ecology and habitat in seagrass. The food and space partitioning results demonstrate the high diversity in commercially important finfishes in seagrass ecosystems, which is achieved by habitat specialization, ecological flexibility, and trophic differentiation. Resource partitioning is a key ecological mechanism in which different species with the same habitat requirements can coexist but can allocate the most resources possible. The findings add to the background that the ecological integrity of seagrass meadows is not only conditioned by a diversity of habitats but also by the ecosystem services and fisheries benefits derived from these habitats in the next part of this study.

7.3 Ecosystem Services Provided by Seagrass Meadows with reference to Fisheries

For the third objective of the present research, we assessed the ecosystem services provided by seagrass meadows and concentrated on their importance for commercial fisheries and coastal livelihoods. Seagrass ecosystems are widely recognized to be ecological assets but are rarely considered as productive natural assets that are economically beneficial for humans. Our ecological observations and the fish market survey and community-based analysis of seagrass meadows in this study reveal that seagrass meadows are more than biodiversity conservation in the end and are essential in ecosystem functioning and economic well-being of coastal communities. The most important contribution of this study is to understand that seagrass meadows are social as well as ecological systems and that there is an interconnection between the ecological processes and human livelihood. The fishing communities themselves overwhelmingly identified seagrass meadows as core fishing habitats, and they were therefore directly engaged in the management of local fisheries. But a large proportion of them also recognized the role of seagrass meadows as breeding grounds, nursery grounds, feeding areas and shelter for commercially vital species. Finding these things is an indication of the fact that local communities are not only financially aware of seagrass ecology but also some other ecological functions and also the potential for them to be involved in the maintenance of the ecosystem of biodiversity in the seagrass meadows.

The economic analyses show that seagrass meadows also contribute to fisheries not only in the form of fish biomass production but also in the process of maintaining the entire market chain for coastal fisheries. Fish market studies showed that seagrass-based fisheries serve as a source of locally integrated value chain for fishers, market intermediaries, retailers and consumers. The relatively short supply chain in Palk Bay indicates that local economies depend on fishing grounds closer to them. With the close spatial relationship between habitat, harvest and consumption, the loss of seagrass ecosystems would have immediate effects on fisher incomes and regional food security. The variability in fish prices between markets and among fish families is also an indicator of the ecological and economic function of seagrass fisheries. The presence of a few high-value species and a larger number of moderately priced species is typical of multi-species fisheries in tropical areas. Such a pattern implies that the economic impact of seagrass ecosystems does not lie equally in all species, but rather in the survival of

economically valuable species that live in them during some part of their life cycle. The degradation of seagrass meadows may disproportionately affect those with higher earnings and thus the fishing communities. The assessment also indicates that habitat quality impacts economic value. The earlier objectives were to demonstrate that seagrass meadows provide nursery habitats and that different species of fish can be successfully formed in them through habitat diversity and resource partitioning. The objective now is to show that these ecological functions translate into economic value. Fish diversity, habitat heterogeneity and ecological connectivity are not just ecological characteristics in themselves but are necessary to the productivity and stability of fisheries.

One of the key results of this study is the estimate of the fishery production value of seagrass-based ecosystems in the Dugong Conservation Reserve. Although based on conservative assumptions, the estimated annual fishery production value for seagrass-based fisheries indicates that such ecosystems are very profitable natural capital assets. The significant monetary returns associated with each square kilometre of seagrass habitat highlight the hidden economic support those ecosystems provide to coastal communities. These kinds of estimates are particularly important because ecosystem services that are not directly market-valued are often overlooked in coastal development and management activities.

It also highlights that seagrass ecosystem services are not limited to direct provisioning benefits. These meadows support nursery habitat development, fish population maintenance and food web dynamics and enhance habitat connectivity and thus indirectly support long-term fisheries productivity. Sustained sediment stabilization, nutrient cycling and favourable environmental conditions also contribute to the sustainability of coastal ecosystems, and these supporting and regulating functions are rarely considered in economic studies. The total value of seagrass ecosystems is probably much larger than the fishery value estimated in this thesis. The integration of ecological and economic information highlights the importance of an ecosystem-based approach to fisheries management. In traditional fisheries management, we have focused on catch and fishing; we have not paid much attention to the habitats that sustain fish populations. Our findings indicate that habitat conservation is a basic part of fishery management because the long-term productivity of fisheries is in large part based on the healthy seagrass ecosystem. Therefore, protecting seagrass meadows is an investment in biodiversity conservation and economic sustainability.

The valuation of ecosystem services also provides a practical framework for policy development. Translating ecological functions into measurable economic values is how seagrass ecosystems are integrated into blue economy programmes, natural capital accounting and marine spatial planning. In many coastal areas, habitat degradation continues because the economic benefits of ecosystem conservation are still not recognized. By demonstrating the great role seagrass meadows play in fisheries production and local livelihoods, our study shows that conservation and economic development should not be considered as competing objectives but as complementary strategies.

At the same time, the study acknowledges several methodological shortcomings related to ecosystem service valuation. The valuation of fisheries production exclusively on seagrass habitats may make the direct impact of fisheries production less clear because many species are in many habitats throughout their lifecycle. Fishing effort, catch rates and market prices are also not fully captured in the valuation of ecosystem service prices and a number of indirect and non-market benefits are not taken into account. In future studies, habitat residency indices, production function models and ecosystem accounting can be used to improve economic estimates and to provide a better understanding of ecosystem services for seagrass. We find that the findings demonstrate the need to consider habitat connectivity while considering ecosystem services, as many commercially significant species that are found in the study are found in coral reefs, sandy habitats and seagrass meadows throughout their life cycle. Consequently, the fisheries value of seagrass ecosystems is in part a function of the seascape of the ecosystem, and these habitats will be less important if conservation approaches are based on ecological connectivity than on protecting individual habitats.

Considering together, the assessment of ecosystem services indicates that seagrass meadows are productive ecological infrastructure that maintain biodiversity, fisheries and coastal livelihoods at once. They are not only important for fisheries because they contribute to the production of commercially valuable species and nursery functions and habitat connectivity and ecological resilience that sustain long term fish production. Integration of ecological and economic assessment supports the notion that seagrass conservation should be a key element of coastal management and blue economy planning. The findings also serve as a natural follow-up to the research that is to investigate the anthropogenic pressures that are affecting these ecosystems and the impact of habitat degradation on the sustainability of fisheries and ecosystem services.

7.4 Anthropogenic Threats to Seagrass Ecosystems and Conservation Measures

The fourth objective of this study was to identify and describe the primary anthropogenic threats to seagrass ecosystems in Palk Bay and the Gulf of Mannar, with a view to proposing long-term conservation measures. The survey employed a combination of field observations, aerial surveys, and community-based information to ascertain both the nature of the threats to seagrass habitats and the extent to which human activities impact these ecosystems. Our findings indicate that habitat degradation in these areas is rarely attributable to a single factor. Rather, the cumulative effects of fishing activities, marine litter, anchoring, bycatch, and other human-related activities can lead to the long-term deterioration of seagrass habitats. This study further establishes a critical connection between fisheries and seagrass ecosystems. As previously noted by other researchers, seagrass meadows provide essential nursery functions for economically significant fish species, enhance habitat complexity, and facilitate resource partitioning. It is vital to strengthen this understanding, as the fishing activities reliant on healthy seagrass habitats can simultaneously drive habitat degradation if not managed sustainably. This challenge is particularly pertinent in many tropical coastal ecosystems, where livelihoods and conservation are interdependent, and sustainable fisheries rely on healthy habitats to support fish populations.

In the Dugong Conservation Reserve, mechanized boats and set nets are the predominant fishing methods. Their extensive use in shallow coastal waters increases interactions between fishing gear and seagrass habitats. While not all fishing gear exerts the same ecological impact, repeated use of bottom-contact gears, weighted nets, and drag nets can physically damage seagrass shoots, disrupt sediments, and fragment meadows. Our observations of various fishing gear types and their ecological impacts highlight the need for a nuanced understanding of the ecological risks associated with fishing practices.

Moreover, physical disturbances to seagrass habitats extend beyond fishing gear. Anchoring has been identified as a significant yet frequently overlooked source of seagrass degradation. The prevalent use of multi-spike anchors in the Dugong Conservation Reserve suggests that the seabed is frequently disturbed, leading to the uprooting of shoots, breaking of rhizomes, and fragmentation of otherwise continuous meadows. Although the absolute number of anchoring events may appear minimal, their cumulative effects can compromise habitat stability, resulting in prolonged recovery times and potentially widespread ecosystem implications.

Marine litter and pollution represent additional major anthropogenic threats. Our observations of various litter categories, including oil films, plastic debris, and discarded fishing gear, indicate persistent contamination of seagrass ecosystems from fishing and coastal activities. Synthetic materials and lost fishing gear can cause direct physical damage to seagrass habitats and contribute to ghost fishing and entanglement of marine animals. Furthermore, pollution can indirectly impair ecosystem functioning by degrading water quality and affecting the organisms residing within these habitats. Hence, habitat degradation encompasses not only physical damage but also the chronic environmental stressors associated with coastal development and waste disposal.

A key finding of this study is the identification of bycatch interactions with ecologically important non-target species. The incidental capture of sea turtles, seahorses, sea cucumbers, and seagrass itself demonstrates that fishing impacts a broader array of organisms than the intended target catches. The presence of seagrass in bycatch is clear evidence of detrimental effects on benthic life, while the capture of protected and vulnerable species underscores the ecological costs of intensive fishing practices. This evidence emphasizes the necessity for fisheries management to consider ecosystem-level impacts rather than focusing solely on harvested species.

The comparative analysis between Palk Bay and the Gulf of Mannar reveals notable ecological differences. In Palk Bay, threats were significantly higher, primarily due to increased fishing activity, vessel movement, and fishing infrastructure. Conversely, litter emerged as the most frequent threat in the Gulf of Mannar. These regional disparities suggest that anthropogenic pressures vary based on resource utilization, fishing intensity, and coastal development practices, thus necessitating tailored conservation strategies that reflect local conditions. One of the major findings is the limited awareness among local fishing communities regarding seagrass ecosystems. Many individuals were unfamiliar with the distribution and ecological roles of seagrass, although they recognized its importance as a fishing site. This disconnect between ecological dependence and awareness presents both a challenge and an opportunity for conservation efforts. Enhancing community engagement through awareness programs and local stewardship can strengthen the link between habitat conservation, fishery sustainability, and long-term livelihood security.

The results of this study underscore the importance of ecosystem-based management strategies to enhance environmental sustainability. Previous objectives have demonstrated that seagrass

meadows play a vital role in maintaining fish diversity, resource partitioning, and ecosystem services. The current objectives highlight that habitat degradation poses a threat to these ecological functions. Fragmentation can diminish nursery value, habitat structure, species interactions, and ultimately fishery productivity. Thus, conservation efforts must protect ecological processes rather than focusing solely on habitat preservation. The conservation measures identified in this study provide a framework for achieving sustainable management. These measures include regulating destructive fishing gear, promoting sustainable fishing practices, establishing seagrass-sensitive anchoring zones, removing marine litter, and developing bycatch mitigation strategies. Involving local communities in awareness programs, participatory monitoring, and habitat conservation initiatives is essential. An integrated approach that combines fisheries management, habitat protection, and community participation can yield more effective conservation outcomes than isolated efforts.

It is important to acknowledge certain limitations of this assessment. The focus has primarily been on large-scale, measurable threats and does not account for the long-term impacts of climate change, coastal pollution, and cumulative environmental stressors. Additionally, the recovery of seagrass following disturbances could not be effectively assessed. Long-term ecological monitoring, remote sensing, and habitat resilience assessments are critical for informing future management approaches and evaluating cumulative effects, as well as developing adaptive management strategies. In conclusion, the assessment of anthropogenic threats indicates that the conservation of seagrass ecosystems must be integrated with ecological protection and the livelihoods of coastal communities. The interlinked pressures from fishing, anchoring, and marine litter/bycatch significantly impact both habitat and ecosystem health. Healthy seagrass meadows are essential not only for the conservation of dugongs but also for fisheries, biodiversity, and the ecosystem services that coastal societies depend on. This research advocates for the development of integrated, region-based management approaches that safeguard seagrass ecosystems and promote the sustainable use of marine resources.

7.5 Management Recommendations

This research underscores that the long-term conservation of seagrass ecosystems in Palk Bay and the Gulf of Mannar cannot be achieved solely through the protection of individual species. Ecological assessments indicate that seagrass meadows support commercially significant finfish species, provide nursery habitats, facilitate resource partitioning, and deliver essential

ecosystem services that sustain coastal fisheries and local livelihoods. These ecosystems, however, are subject to numerous anthropogenic pressures. Consequently, future management strategies must adopt an ecosystem-based approach, recognizing that habitat conservation is integral to fishery sustainability and community well-being.

The significant presence of juvenile fish in seagrass ecosystems highlights the necessity of designating these ecological conditions as essential fish habitats for effective coastal fisheries management. To ensure the success of fisheries management, it is imperative to protect nursery grounds, as many economically important species rely on suitable juvenile habitats for their survival. Therefore, attention should be directed toward areas with high juvenile abundance and favorable ecological conditions that promote recruitment, growth, and survival. This strategy will not only benefit biodiversity conservation but also contribute to the long-term stability of coastal fisheries.

Furthermore, the present study reveals that fish diversity within seagrass ecosystems is supported by habitat diversity and ecological connectivity. Seagrass meadows, sandy bottoms, and coral reef habitats, while varying in richness and sparsity, each support distinct fish communities and fulfill different ecological functions. Management strategies should not treat seagrass ecosystems as isolated patches; rather, they should consider these habitats within the broader marine context. Marine spatial planning initiatives must incorporate ecological corridors between seagrass meadows, coral reefs, and other habitats to facilitate natural fish movement and life-cycle migration. Fragmentation and overdevelopment of these habitats can compromise biodiversity.

The assessment of resource partitioning further underscores the importance of maintaining structural complexity within seagrass ecosystems. These meadows provide habitats for both specialist and generalist species. Habitat disturbances that reduce structural complexity may diminish the availability of niches for various ecological species and adversely affect specialized species. Consequently, management programs should prioritize the protection of structurally diverse seagrass habitats and focus on restoring them to a more complex structure, rather than solely expanding seagrass areas.

Fishing activities represent a primary driver of changes in seagrass habitats, necessitating the promotion of sustainable fishing practices in sensitive areas. Management strategies should not emphasize a singular fishing method but should instead encourage the adoption of low-impact

fishing systems and regulate gear that frequently disturbs the seabed. Fishing equipment that uproots seagrass shoots, disrupts sediments, or damages habitats should be critically assessed. Involving fishers in the decision-making process is vital, as conservation efforts are most likely to succeed when local communities understand the ecological and economic benefits.

Additionally, anchoring activities warrant greater management attention, as repeated anchoring in shallow seagrass meadows can lead to cumulative habitat degradation. Designated anchoring sites and environmentally friendly mooring systems can mitigate physical disturbances and allow fishing communities to continue utilizing coastal waters. Such measures are particularly crucial in the Dugong Conservation Reserve, where heightened vessel activity coincides with ecologically sensitive seagrass habitats.

The prevalence of marine litter and discarded fishing materials highlights the need for enhanced coastal waste management practices. Effective disposal of plastic waste, recovery of fishing gear, and proper management of fishing-related materials should be integral to habitat conservation efforts. Establishing waste collection facilities at fish landing centers and harbors, along with community-led cleanup initiatives, can significantly reduce debris accumulation in seagrass meadows and improve habitat quality.

The incidental capture of non-target organisms such as sea turtles, seahorses, and sea cucumbers underscores the importance of adopting an ecosystem-oriented perspective in fisheries management, rather than focusing exclusively on target species. Modifications to fishing gear and improved handling practices for protected fauna can minimize bycatch, thereby preserving biodiversity and mitigating the impact of fishing on seagrass ecosystems.

A significant finding of this study is that, despite local communities' reliance on seagrass ecosystems for fisheries, a considerable portion of their ecological knowledge remains underutilized. Therefore, community involvement should be a core component of conservation research. Awareness programs that link seagrass conservation to fisheries productivity and livelihood security can foster local stewardship. Engaging fishers and local stakeholders in community-based conservation monitoring schemes will enhance conservation outcomes and integrate traditional ecological knowledge into management practices.

The assessment of ecosystem services in seagrass meadows reveals that these habitats provide substantial economic benefits, which should inform coastal development planning and natural resource policies. Conservation decisions must acknowledge that habitat degradation can lead

to long-term economic losses, manifested through decreased fish production and reduced fisheries income. The integration of seagrass ecosystem services into blue economy projects, natural capital accounting, and environmental impact assessments will reinforce the economic rationale for habitat protection and restoration.

Long-term ecological monitoring is essential for evaluating seagrass conditions and the effectiveness of management strategies. The baseline data collected in this study can inform the design of monitoring programs that assess seagrass distribution, fish diversity, juvenile recruitment, fishing pressures, marine litter, and other anthropogenic disturbances. In addition to underwater visual surveys, remote sensing technologies and community-based observations will be necessary to detect ecological changes and facilitate adaptive management.

Future conservation strategies must also consider climate change and cumulative environmental stressors affecting coastal ecosystems. While local disturbances such as fishing and habitat destruction can be managed at the local level, their impacts may be exacerbated by shifting environmental conditions. Restoration programs should therefore prioritize the recovery of ecosystem resilience by protecting healthy seagrass meadows, restoring degraded habitats, and enhancing ecological connectivity across the coastal landscape. Overall, the findings of this study indicate that seagrass management should encompass habitat conservation, sustainable fisheries management, community involvement, and long-term ecological monitoring processes. The protection of seagrass meadows should be viewed not only as an investment in biodiversity and fisheries production but also as a vital component of future coastal community livelihoods. The sustainability of Palk Bay and the Gulf of Mannar will ultimately be determined by management strategies that acknowledge the ecological and economic interconnections between healthy seagrass ecosystems and the human societies dependent upon them.

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Annexure 1: Peer-reviewed Publications

1. **Ghanekar, C., Rajpurkar, S., Gokhale, T., Aggarwal, A., Sivakumar, K., & Johnson, J. A. (2026).** *Assessing anthropogenic pressures on seagrass ecosystems in India's first dugong conservation reserve. Journal of Wildlife Science (Accepted for publication)*

Journal of Wildlife Science Jeyaraj Antony Johnson | Logout


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← Submissions with an Editorial Office Decision for Author

Page: 1 of 1 (2 total completed submissions) Results per page 10

Action	Manuscript Number	Title	Initial Date Submitted	Status Date	Current Status	Date Final Disposition Set	Final Disposition
View Submission View Decision Letter Similarity Check Results (6%) View Attachments Correspondence Send E-mail	JWLS-26-0090	Assessing Anthropogenic Pressures on Seagrass Ecosystems in India's First Dugong Conservation Reserve	06 Jun 2026	23 Jun 2026	Accept		

6/23/26, 11:48 AM Gmail - Fwd: Your submission JWLS-26-0090R1, Journal of Wildlife Science

 Chinmaya Ghanekar <chinmayaghanekar@gmail.com>

Fwd: Your submission JWLS-26-0090R1, Journal of Wildlife Science
2 messages

Dr J Antony Johnson - Scientist <jaj@wii.gov.in> Tue, Jun 23, 2026 at 11:01 AM
To: Chinmaya Ghanekar <chinmayaghanekar@gmail.com>

----- Original Message -----

Subject:Your submission JWLS-26-0090R1, Journal of Wildlife Science
Date:2026-06-23 10:57
From:Journal of Wildlife Science <em@editorialmanager.com>
To:Jeyaraj Antony Johnson <jaj@wii.gov.in>
Reply-To:Journal of Wildlife Science <info@jwls.in>

Ref.: Ms. No. JWLS-26-0090R1
Assessing Anthropogenic Pressures on Seagrass Ecosystems in India's First Dugong Conservation Reserve
 Journal of Wildlife Science

Dear Dr Johnson,

I am delighted to inform you that your manuscript has been accepted for publication in Journal of Wildlife Science, following the recommendations from academic editor and the reviewers.

It was first submitted on 06 Jun 2026 and accepted on 23 June 2026 after a thorough peer review process.

The production team will contact you shortly to address any final queries and coordinate the publication process.

Thank you for choosing Journal of Wildlife Science as the platform for sharing your research. We appreciate your contribution and look forward to featuring your work.

With kind regards

MEWA SINGH, Ph.D.
 Editor-in-Chief
 Journal of Wildlife Science

Journal of Wildlife Science

Assessing Anthropogenic Pressures on Seagrass Ecosystems in India's First Dugong Conservation Reserve

--Manuscript Draft--

Manuscript Number:	JWLS-26-0090R1
Full Title:	Assessing Anthropogenic Pressures on Seagrass Ecosystems in India's First Dugong Conservation Reserve
Short Title:	
Article Type:	Research Article
Keywords:	Fishing practices; socioecological survey; aerial surveys; Dugong conservation
Corresponding Author:	Jeyaraj Antony Johnson INDIA
Corresponding Author Secondary Information:	
Corresponding Author's Institution:	
Corresponding Author's Secondary Institution:	
First Author:	Chinmaya Ghanekar
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Order of Authors:	Chinmaya Ghanekar Sagar Rajpurkar Tanmay Gokhale Akarsh Aggarwal Sivakumar Kuppusamy Jeyaraj Antony Johnson
Order of Authors Secondary Information:	
Abstract:	<p>Despite being among the most productive ecosystems worldwide, seagrasses have been increasingly threatened by rapid degradation and loss across the world. The Dugong Conservation Reserve (DCR) contains about 122.5 km² of seagrass meadows which overlaps with intensive fishing grounds and faces multiple anthropogenic pressures. This study therefore provides an integrated understanding of anthropogenic pressures posed onto the seagrass ecosystems in the DCR through fisherfolk questionnaire survey and aerial surveys. We find that fishing activities, vessel anchoring, marine litter, and bycatch of seagrass and associated species are principal anthropogenic pressures that affect the seagrass habitats in the DCR. The prevalence and scale of mechanized fishing vessels, the widespread use of set nets, and a 28% increase in anthropogenic pressure from 2021 to 2023 show increased human use of those critical dugong habitats. The frequent occurrence of fishing nets, anchored boats, seagrass bycatch, and interactions with protected species reveals that these processes can affect the dugong directly and indirectly through the destruction of habitat. To enhance protection of this area, the findings highlight the necessity for specific management interventions including sustainable fishing, bycatch reduction techniques, regulation of anchoring activities, and ongoing monitoring of seagrass habitat.</p>
Manuscript Classifications:	Human Dimensions; Marine and Freshwater Ecosystems
Additional Information:	
Question	Response

**CONFLICT OF INTEREST
DECLARATION**

Yes

Please read through each statement carefully and declare any disagreement with a statement in this declaration.

Do you confirm that:

All authors agree with the content of this submission. The corresponding author has approval from all Co-authors to submit this manuscript.

The submitted work is original research carried out by the authors. No part of this research (including results, data and figures) has been published elsewhere, unless acknowledged in the manuscript.

The manuscript is not submitted elsewhere for publication while under consideration for publication in this journal.

All funding sources are fully acknowledged and the authors declare that there are no direct financial benefits to the author that could result from this publication.

The authors do not have any conflict of interest with any person listed on the editorial board of the journal.

Date:06 June 2026

To,
The Editor-in-chief,
Journal of Coastal Conservation,
Springer Nature

Subject: Submission of manuscript titled ***Assessing anthropogenic Pressures on Seagrass Ecosystems in India's First Dugong Conservation Reserve***

Sir,

We are pleased to submit our manuscript entitled "***Assessing anthropogenic Pressures on Seagrass Ecosystems in India's First Dugong Conservation Reserve***" for consideration for publication in the *Journal Wildlife sciences*.

Globally, principal fishery species depend on seagrass habitats, in turn facing immense anthropogenic pressure. In India, The Dugong Conservation Reserve (DCR) contains about 122.5 km² of seagrass meadows which also overlaps with intensive fishing grounds. As a recently declared protected area, it is imperative to understand the anthropogenic pressures and potential threats to seagrasses in the DCR region.

Recognizing this need, the present work provides an integrated understanding of anthropogenic pressures posed onto the seagrass ecosystems in through fisherfolk questionnaire survey and aerial surveys in Dugong Conservation Reserve, Palk Bay, India. Our study documents that that fishing-related activities, vessel anchoring, marine litter, and incidental bycatch are principal anthropogenic pressures that affect the seagrass habitats. Notably, the prevalence and scale of mechanized fishing vessels, the widespread use of set nets, and a 28% increase in anthropogenic pressure from 2021 to 2023 show increased human use of those critical dugong habitats.

We believe this manuscript is well aligned with the scope of the *Journal of Wildlife Sciences*, as it deepens understanding of the anthropogenic pressures on the recently declared Dugong conservation Reserve and offers insights directly relevant to conservation planning.

This work is original, has not been published previously, and is not under consideration elsewhere. All authors have reviewed and approved the manuscript and its submission. Field sampling was conducted in full compliance with required permits and ethical guidelines. We appreciate your consideration and look forward to the opportunity to contribute to the journal's mission of advancing coastal conservation science.

Thanking you



Dr. J.A. Johnson
Scientist F & Head Department of Habitat Ecology
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Assessing anthropogenic Pressures on Seagrass Ecosystems in India's First Dugong Conservation Reserve

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Conflict of Interest

All the authors declare no conflict of interest and have agreed with its submission to the journal.

Funding Statement

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Author contribution

CG: Conceptualization, Methodology, Formal analysis, Investigation, Writing - Original Draft, Visualization

SR: Conceptualization, Methodology, Formal analysis, Investigation, Writing - Review & Editing

TG: Methodology, Formal analysis, Investigation, Writing - Review & Editing, Visualization

AA: Methodology, Formal analysis, Investigation, Writing - Review & Editing, Visualization

KS: Writing-Review & Editing, Supervision, Project administration

JAJ: Writing-Review & Editing, Supervision, Project administration, Funding acquisition

1 **Title: Assessing anthropogenic Pressures on Seagrass Ecosystems in India's First Dugong**
2 **Conservation Reserve**

3 **Summary**

4 Despite being among the most productive ecosystems worldwide, seagrasses have been
5 increasingly threatened by rapid degradation and loss across the world'. The Dugong
6 Conservation Reserve (DCR) contains about 122.5 km² of seagrass meadows which overlaps
7 with intensive fishing grounds and faces multiple anthropogenic pressures. This study therefore
8 provides an integrated understanding of anthropogenic pressures posed onto the seagrass
9 ecosystems in the DCR through fisherfolk questionnaire survey and aerial surveys. We find
10 that fishing activities, vessel anchoring, marine litter, and bycatch of seagrass and associated
11 species are principal anthropogenic pressures that affect the seagrass habitats in the DCR. The
12 prevalence and scale of mechanized fishing vessels, the widespread use of set nets, and a 28%
13 increase in anthropogenic pressure from 2021 to 2023 show increased human use of those
14 critical dugong habitats. The frequent occurrence of fishing nets, anchored boats, seagrass
15 bycatch, and interactions with protected species reveals that these processes can affect the
16 dugong directly and indirectly through the destruction of habitat. To enhance protection of this
17 area, the findings highlight the necessity for specific management interventions including
18 sustainable fishing, bycatch reduction techniques, regulation of anchoring activities, and
19 ongoing monitoring of seagrass habitat.

20 **Keywords:** Fishing practices, socioecological survey, aerial surveys, Dugong conservation

21 **1. Introduction**

22 Seagrass ecosystems are among the most productive and biologically diverse habitats in coastal
23 and marine environments (Hori et al., 2009). Seagrass ecosystems are distributed globally
24 except for continent of Antarctica and serve as fishing grounds across their distribution
25 (Nordlund et al., 2018; Short et al., 2007). Seagrass ecosystems support large-scale fishery
26 production by acting as a refuge, foraging and nursery grounds (Nordlund et al., 2018).
27 Considering this fishery production, many coastal fisherman communities worldwide depend
28 on these seagrasses for both subsistence and commercial fishery (Cullen & Unsworth, 2013).
29 As the fish production largely depends on seagrass ecosystems, it is essential to document the
30 fishing practices and threats posed by them on seagrasses (Nordlund et al., 2018).
31 In the past studies it is observed that seagrass degradation has amplified rapidly across the
32 world (Short et al., 2007; Cullen-Unsworth & Unsworth, 2013; Nordlund et al., 2017;

33 Gullström et al., 2002). Seagrass loss can reduce fish abundance, alter associated faunal
34 community structure, and impair nursery functions (O’Leary et al., 2021; Rees et al., 2023).
35 Pollution from fishing, aquaculture, and land-based activities can further affect seagrass health
36 and associated biodiversity (Litsi-Mizan et al., 2024; Smulders et al., 2022). Anthropogenic
37 activities such as anchoring and moving boats and ships, dredging and discharging sediments,
38 landfilling, and untreated sewage disposal negatively impact seagrass ecosystems (Jagtap et
39 al., 2003, Short et al., 2007). Along with these threats having destructive impacts on seagrass
40 ecosystems, a lack of awareness of the importance of seagrass is an essential aspect of future
41 conservation management (Orth et al., 2006).

42 In the regions of Southeast Asia and the Indo-Pacific, seagrass meadows play a crucial role in
43 sustaining artisanal fisheries that are essential for food security and income for countless
44 coastal communities (Fortes, 2018; Ambo-Rappe, 2020). The degradation of these systems,
45 attributed to coastal development, unsustainable fishing practices, and seaweed cultivation, has
46 raised significant concerns about long-term economic viability (Unsworth et al., 2018). In
47 India, Palk Bay is one of the most vital seagrass ecosystems (Thangaradjou et al., 2007; Jagtap
48 et al., 2003). Harboring abundant diversity, many villages near these seagrass ecosystems in
49 Palk Bay region mainly depend upon fishery practices as a source of income (Thangaradjou et
50 al., 2007). The DCR which is located in northern region of Palk Bay, Tamil Nadu, was created
51 to conserve dugongs and their seagrass meadows. However, it overlaps with intensive fishing
52 grounds and faces multiple anthropogenic pressures (Seal et al., 2024).

53 This study therefore provides an integrated understanding of anthropogenic pressures posed
54 onto the seagrass ecosystems in the DCR, Palk Bay, Tamil Nadu using fisher surveys, and
55 aerial surveys. We also aim to propose management interventions to support the long-term
56 conservation of seagrass ecosystems, dugong habitats, and seagrass-associated fisheries.

57 **2. Study Area**

58 We conducted the study in the DCR, Palk Bay, which is situated along India's southeast coast.
59 Palk Bay is a shallow marine region with depths typically between 1 and 10 meters that is
60 located between the coasts of Sri Lanka and India. These habitats provide nursery and feeding
61 grounds for many fish, prawns, crabs, and other marine organisms that support coastal fisheries
62 (Kaladharan et al., 2018; Nordlund et al., 2018). Numerous fishing communities are supported
63 by the area. Traditional fishermen mostly use small boats and basic fishing gears such as non-
64 mechanized, manually operated gear including small gill nets or hand operated hooks and
65 fishing lines to fish in this area. Palk Bay is a key area for comprehending the function of
66 seagrass ecosystems in sustaining fisheries and coastal livelihoods because many commercially

67 significant species are closely associated with seagrass habitats (Unsworth et al., 2018). The
68 DCR extends along the coast of Thanjavur District and Pudukkottai District and was
69 established in 2022 by the Government of Tamil Nadu to protect seagrass habitats and conserve
70 the vulnerable marine mammal *Dugong dugon*, which feeds mainly on seagrass. The reserve
71 contains about 122.5 km² of seagrass meadows, making it one of the most important seagrass
72 and associated fishing zone in Palk Bay (Johnson et al., 2026).

73 **3. Methods**

74 A semi-structured questionnaire survey was conducted in 37 villages in North Palk Bay from
75 2019-20 (Figure 1) for understanding their fishing practices. A total of 844 interviews were
76 conducted to understand the perception of local communities towards seagrass ecosystems,
77 their importance, community dependence on seagrass and threats to the seagrass meadows. The
78 questionnaire entailed details about fishing methods, gears and vessels used to understand the
79 anthropogenic pressures on seagrass meadows of DCR. This paper focusses on part of the
80 questionnaire focussing on anthropogenic pressures on seagrass meadows of DCR.

81 To complement the community-based information with field-based observations of
82 anthropogenic pressures across the seagrass habitats, aerial surveys were undertaken with
83 unmanned aerial vehicles DJI Mavic 2. A survey effort of 168 km consisting of two replicates
84 of 28 aerial transects measuring about 3 km long was deployed (Figure 1) between 2021 and
85 2023. Each transect measured approximately 3 km in length with an effective observation width
86 of 0.130 km. The width of the transect was calculated based on the fixed elevation of the drone
87 of 100 meters and the swath (width) covered. Further it was calculated using a measuring tape,
88 while on video mode. The surveys were carried out using 100 m altitude aerial reconnaissance,
89 during which all visible anthropogenic and environmental threats were recorded along the
90 transects. Observations included fishing activities, marine debris, vessel movements, and other
91 potential anthropogenic pressures. To quantify the relative occurrence of anthropogenic
92 pressures, encounter rates were calculated for each pressure category using the number of
93 observations per km.

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100 **4. Results**

101 The respondents of the questionnaire survey were aged 14 to 84 and engaged in fishing as their
102 occupation.

103 ***Fishing Gear and Vessel Types in operating in DCR***

104 In DCR, 82% (n=691) of respondents worked on mechanized boats while only 18% (n=154)
105 respondents worked on motorized boats (Figure 2.1). Set nets are recorded as the predominant
106 fishing gear with 76% (n= 644) using them while drag nets are used by 24% of respondents
107 (n=200)(Figure 2.2). Indeed, mechanized boats and set nets dominate them, indicating that the
108 pressure upon fishing at the reserve rests on a few highly common fishing practices.

109 ***Anchoring Practices as a Potential Threat to seagrass habitats***

110 Five anchor types were used across the DCR and a couple of anchor categories significantly
111 dominated (Figure 2.3). The 5-spike anchor was the most common, with 517 recorded units,
112 and the 2-spike anchor had 334 reported units. The exception was observed for 4-spike (13
113 units), 3-spike (8 units), and 1-spike anchors (3 units). The predominance of 5-spike and 2-
114 spike anchors shows that fishing and boating activities within the reserve require major use of
115 anchoring systems with adequate grip of seabed substrates. The massive dominance of 5-spike
116 (59.0%) and 2-spike anchors (38.1%) mentions that nearly all the pressure on anchors is placed
117 in either category and the role of other anchor type is almost negligible.

118 ***Bycatch Composition and Utilization***

119 In the DCR, the survey reported on a wide variety of by-catch species and debris from fishing
120 in a variety of fishing sites including sea cucumbers, seahorses, small fishes, sea turtles,
121 prawns, crabs, starfish, seagrass, and shells (Figure 2.4, figure 5). The disposal of these by-
122 catch products often yielded mixed results, some kept and sold, some completely discarded.
123 Sea cucumbers, sea turtles, starfish, and seagrass in all cases were discarded (100%) which
124 suggested that these organisms or the remaining materials had no obvious market value to
125 fishers. This represents the incidental capture of sea turtles in an era when direct contacts
126 between fishing operations and the fauna in the ocean are on the rise. Among commercially
127 retained by-catch, prawns and crabs retained the highest percentage of catch compared to the
128 catch as a whole (approximately 50% sold and 50% discarded). Small fishes were commonly
129 caught and preserved; approximately 38% were sold and 62% were discarded. Shells had

130 moderate economic value, with approximately 29% for sale and 71% discarded. Seahorses
131 were kept in occasional cases, around 12% sold, with most of them discarded (88%).

132 *Anthropogenic pressures observed in aerial surveys*

133 The composition of anthropogenic pressures recorded in this study ranged from 2021 to 2023
134 (Figure 3). Fishing nets represented the main anthropogenic pressure observed in both years,
135 making up some 45% of all recorded pressures in 2021 and significantly increasing to
136 approximately 65% in 2023. Anchored boats were the next most common pressure, providing
137 close to 20% in both years but with a slight increase in 2023 relative proportions. In 2021,
138 moving boats, litter and fishing cages together collectively represented a significant part of the
139 pressures that were recorded around 10%, 8% and 2% respectively. In 2023, however, their
140 relative contributions decreased considerably: litter and moving boats accounted only for a
141 small fraction of the total pressures. In 2023, we did not observe any fishing cages in our survey
142 effort. Low frequency pressures included anchor lines, oil spills, and pipe inlets. Anchor lines
143 were seen only in 2023, and accounted for a small proportion (less than 5%) of the total
144 pressures. Both oil spills and pipe inlets were recorded at very low levels in both years, which
145 were less than 5% of the overall data from each year.

146 The 2021 survey observed anthropogenic pressures at 85 sighting instances that consisted of
147 162 units. Fishing nets were the most common pressure category detected (45 detections,
148 Figure 4), while anchored boats comprised the highest percentage of total units (86 units;
149 53.1%). The average detection rate of anthropogenic pressure encounters is reported as 1.01
150 detections km^{-1} , one unit detection per kilometre of survey effort. Among individually
151 identified anthropogenic pressures, fishing nets had the highest encounter rate at 0.536
152 detections km^{-1} , followed by anchored boats (0.179 detections km^{-1}). Litter and moving boats
153 each recorded encounter rates of 0.107 detections km^{-1} (Table 1).

154 The 2023 survey recorded 109 detections comprising 200 individual units. Fishing nets
155 remained the most frequently encountered anthropogenic pressure category, accounting for 65
156 detections and yielding an encounter rate of 0.774 detections km^{-1} . Anchored boats contributed
157 the greatest proportion recorded (109 units; 54.5%). Additional pressures recorded during 2023
158 included anchor lines and pipe inlets, which were absent from the 2021 dataset. The overall
159 anthropogenic pressure encounter rate increased to 1.30 detections km^{-1} , representing
160 approximately one threat detection every 770 metres of survey effort (Table 1).

161 An overall increase of 28% anthropogenic pressures was observed in the DCR from 2021 to
162 2023.

163 **Discussion**

164 The most important finding of this study is that fishing-related activities represent the dominant
165 anthropogenic pressure on seagrass habitats within the Dugong Conservation Reserve (DCR).
166 Fishing pressures accounted for the majority of recorded threat encounters and increased
167 substantially between 2021 and 2023, reflecting growing human use of seagrass habitats
168 despite the protected status of the reserve. Overall anthropogenic pressure increased by
169 approximately 28%, with threat encounter rates rising from 1.01 to 1.30 detections km⁻¹.
170 Fishing nets, particularly set nets and other bottom-contact gears, were the most frequently
171 encountered threats throughout the study period, highlighting the extensive spatial overlap
172 between fishing grounds and critical seagrass habitats. Similar patterns have been documented
173 globally, where fishing activities are recognized as major drivers of seagrass degradation
174 through direct physical disturbance, sediment resuspension, habitat fragmentation, and
175 reductions in ecosystem resilience (Waycott et al., 2009; Nordlund et al., 2018; Turschwell et
176 al., 2021).

177 The ecological implications of increasing fishing pressure are particularly concerning in Palk
178 Bay because seagrass meadows serve as the primary feeding habitat of dugongs and sea turtles.
179 Bottom-contact gears such as drag nets, trawl-derived operations, and weighted gillnets can
180 remove shoots and rhizomes, alter sediment characteristics, and reduce forage availability
181 (Duarte, 2002; Herrera et al., 2023). The occurrence of seagrass in bycatch samples provides
182 direct evidence of habitat disturbance associated with fishing activities within the reserve.
183 Furthermore, incidental captures of sea turtles and other protected fauna indicate that fishing
184 activities are affecting both habitat structure and broader ecosystem functioning. Fishing gear
185 also poses a direct threat to dugongs through entanglement and bycatch, which remain among
186 the leading causes of dugong mortality throughout their range (Marsh et al., 2011). Collectively,
187 these findings identify fishing operations as the most damaging activity currently affecting the
188 ecological integrity of the DCR.

189 The second major finding is the widespread occurrence of vessel anchoring within seagrass
190 habitats. Anchored boats were the second most frequently recorded threat and represented a
191 substantial proportion of all anthropogenic pressures observed during aerial surveys. Repeated
192 anchoring and anchor dragging can uproot seagrass shoots, fragment rhizome networks, disturb

193 sediments, and create persistent scars that reduce meadow connectivity and recovery potential
194 (Montefalcone et al., 2008; Pergent-Martini et al., 2022). Given the shallow bathymetry of Palk
195 Bay and the concentration of fishing vessels operating within seagrass habitats, chronic
196 anchoring disturbance is likely to contribute significantly to long-term habitat degradation.

197 Other threats, including marine litter, moving vessels, anchor lines, and pipe inlets, were
198 recorded less frequently but may exert cumulative impacts on seagrass ecosystem health.
199 Marine litter can alter habitat quality and sediment characteristics, while vessel movement and
200 coastal infrastructure may increase physical disturbance, introduce contaminants, and
201 contribute to localized habitat degradation (Erftemeijer & Lewis, 2006). Although these
202 pressures were comparatively lower than fishing and anchoring, their continued occurrence
203 may further reduce the resilience of seagrass meadows already subjected to intense
204 anthropogenic disturbance.

205 The findings highlight the need for management interventions that prioritize reductions in
206 fishing-related impacts and anchoring pressure. Successful conservation initiatives elsewhere
207 provide useful examples. In the Mediterranean Sea, the installation of eco-mooring systems
208 substantially reduced anchor damage to *Posidonia oceanica* meadows while maintaining access
209 for local users (Pergent-Martini et al., 2022). Similarly, community-based fisheries
210 management and spatial zoning in northern Australia have reduced interactions between fishing
211 activities and dugong habitats while improving stakeholder participation and compliance with
212 conservation measures (Marsh et al., 2012). Comparable approaches within the DCR could
213 include the establishment of no-anchoring zones, deployment of eco-mooring systems,
214 promotion of dugong-safe fishing practices, seasonal restrictions in important dugong feeding
215 grounds, strengthened bycatch mitigation measures, and community-led monitoring
216 programmes involving local fishers.

217 Protecting the seagrass ecosystems of Palk Bay is of exceptional conservation importance. Palk
218 Bay supports one of the largest remaining seagrass landscapes in India and represents the only
219 transboundary seagrass ecosystem in South Asia, shared between India and Sri Lanka. Most
220 importantly, the region supports the largest remaining population of dugongs in Indian waters
221 and is widely regarded as the last stronghold for the species in South Asia (Sivakumar & Nair,
222 2010). The persistence of dugongs in the region is therefore intrinsically linked to the health
223 and extent of these seagrass meadows. Beyond supporting dugongs, these habitats provide
224 nursery grounds for commercially important fisheries, enhance coastal productivity, stabilize

225 sediments, sequester blue carbon, and sustain marine biodiversity. Safeguarding the ecological
226 integrity of Palk Bay's seagrass meadows is consequently essential not only for dugong
227 conservation but also for maintaining one of the most significant coastal ecosystems in South
228 Asia.

229 Overall, this study demonstrates that fishing activities and vessel anchoring are the principal
230 threats affecting seagrass habitats within the Dugong Conservation Reserve. The increasing
231 occurrence of fishing nets, anchored vessels, seagrass bycatch, and interactions with protected
232 species underscores the close relationship between human activities and critical dugong
233 habitats. Addressing these pressures through targeted management interventions, long-term
234 ecological monitoring, and active community participation will be essential for maintaining
235 ecosystem resilience and ensuring that South Asia's last extensive dugong-supporting seagrass
236 stronghold remains healthy and protected into the future.

237

238

239

240 **Declaration of Generative AI and AI-Assisted Technologies:**

241 The author(s) used ChatGPT and Microsoft copilot for paraphrasing and reference checking in
242 preparation of this manuscript. The author(s) thoroughly reviewed and edited the content
243 generated and take(s) full responsibility for the content of the publication.

244

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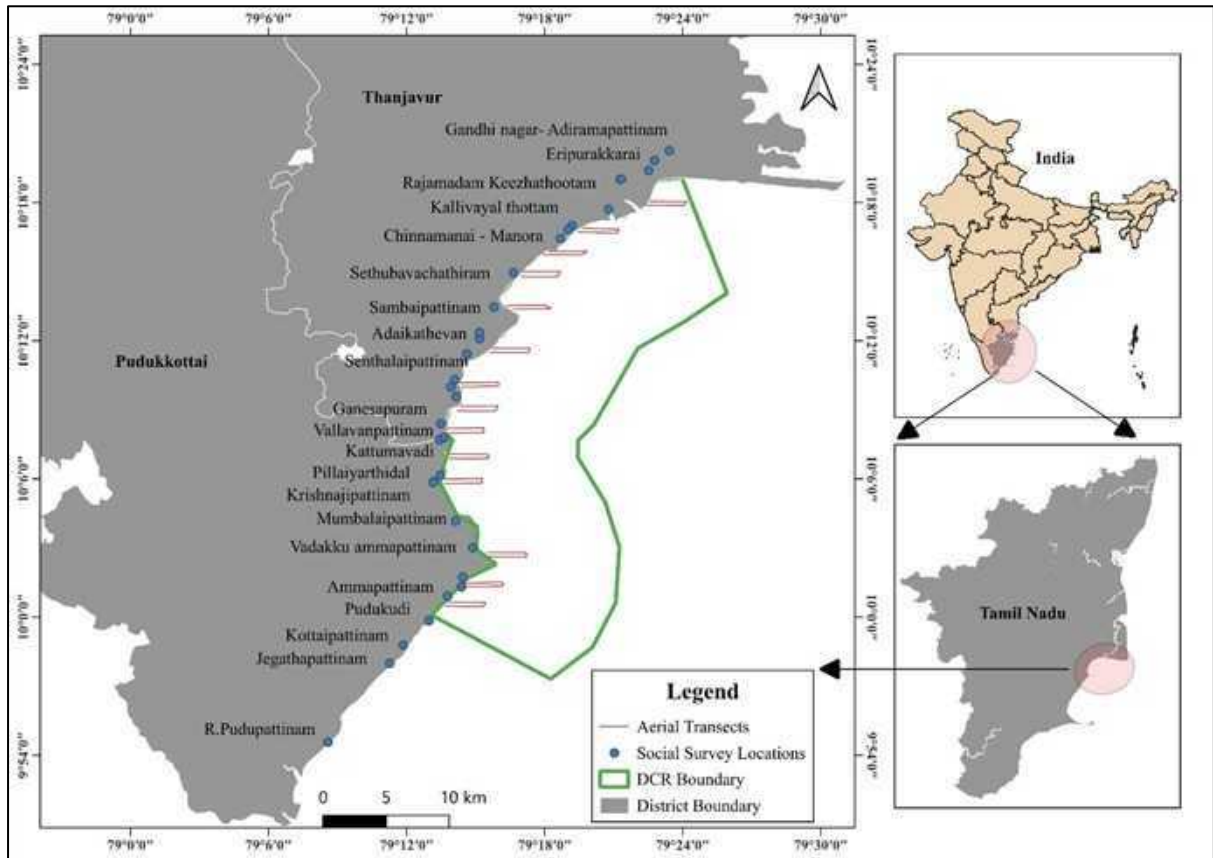
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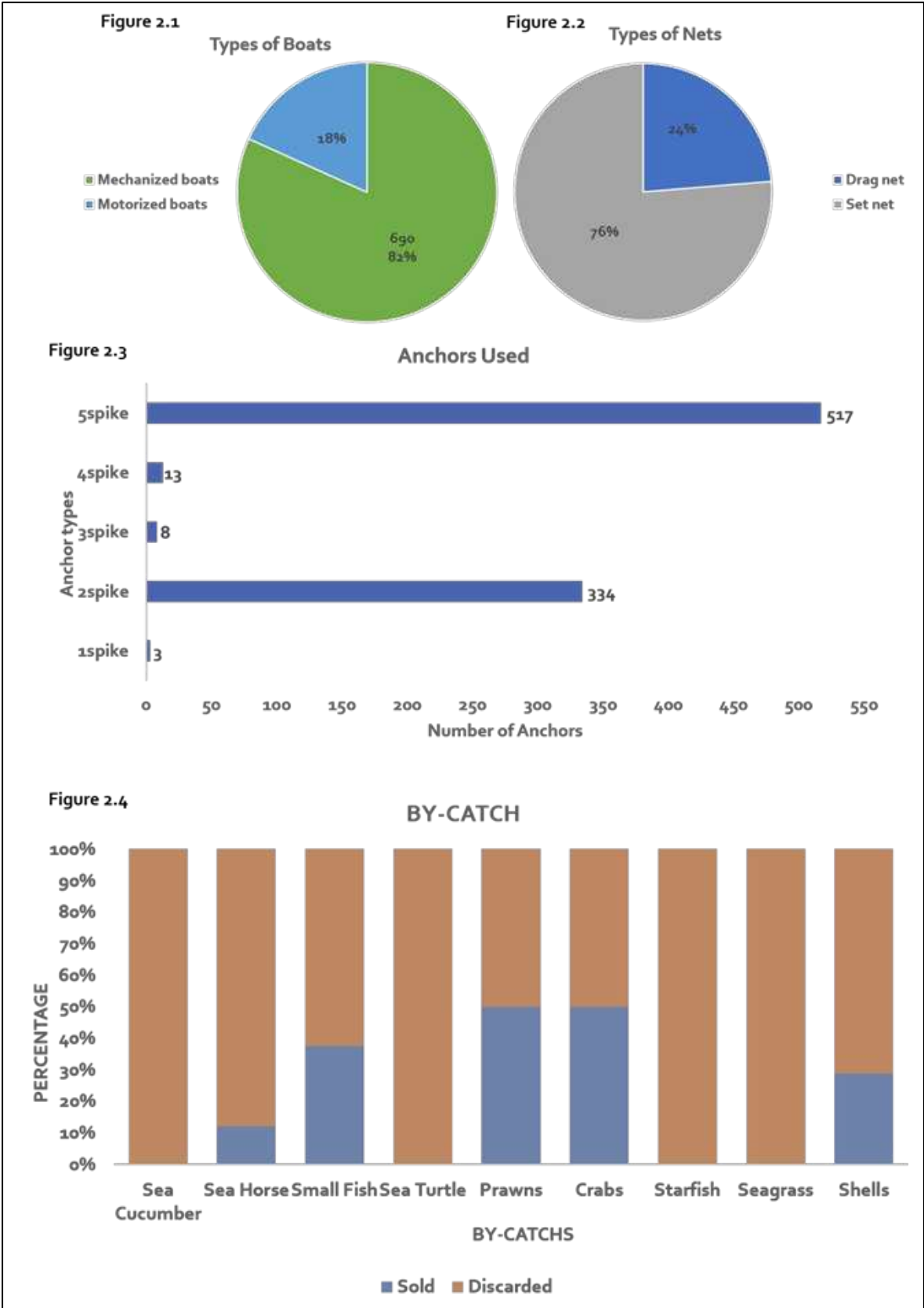
332 **Figures**



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334

335 **Figure 1: Study area map for anthropogenic pressure assessment in Dugong Conservation**
336 **Reserve**



337

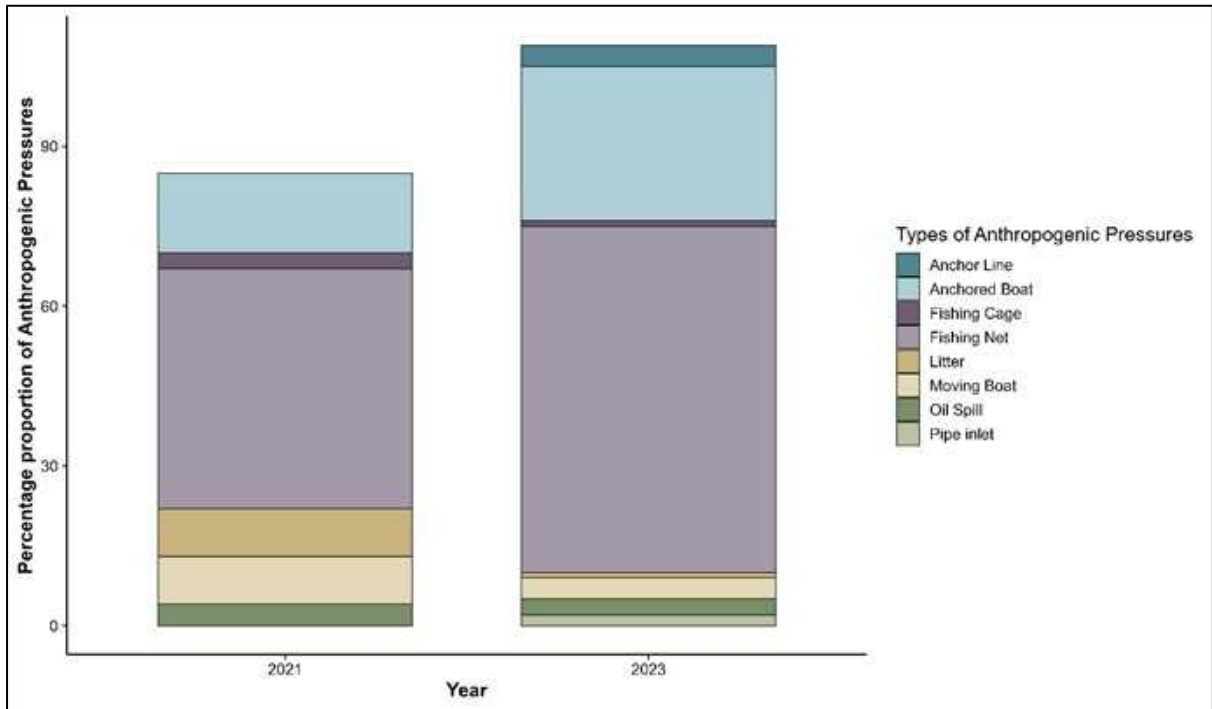
338 **Figure 2.1: Types of fishing crafts and gears in the Dugong Conservation Reserve**

339 **Figure 2.2: Types of fishing nets in the Dugong Conservation Reserve**

340 **Figure 2.3: Anchor types were used across the Dugong Conservation Reserve**

341 **Figure 2.4: By-catch composition in seagrass meadows of Dugong Conservation Reserve**

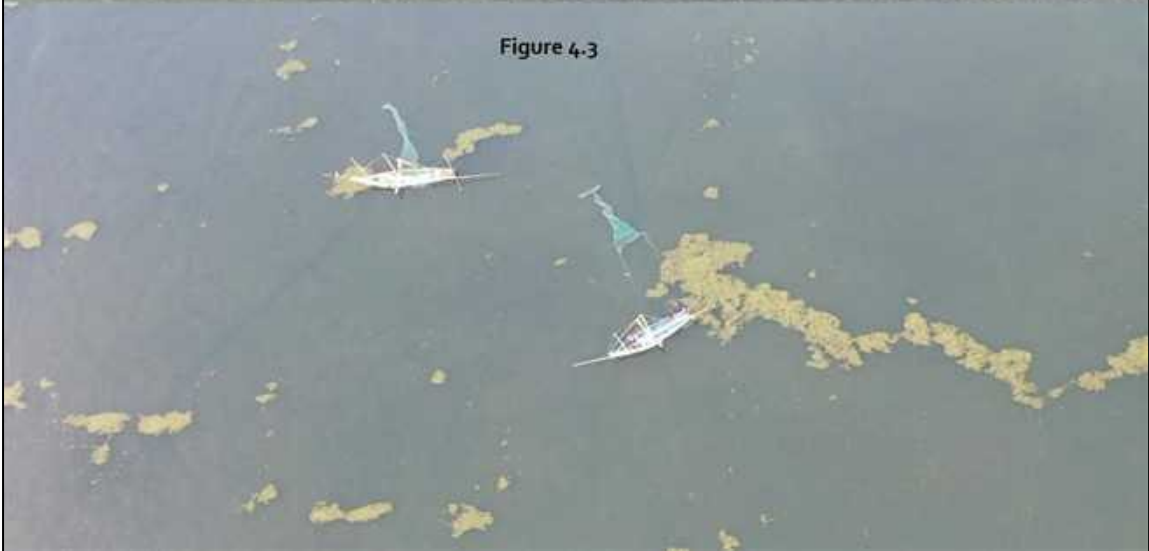
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343

344 **Figure 3: Percentage composition of Anthropogenic pressures in Dugong Conservation**

345 **Reserve**



346

347 **Figure 4.1 and 4.2: Fishing nets recorded during aerial survey in DCR**

348 **Figure 4.3: Fishing boats recorded during aerial survey in DCR**

349



350 **Figure 5.1: Total catch of fishing effort depicting targeted and bycatch together in DCR**

351 **Figure 5.2: Seagrass as bycatch in on a fishing boat in DCR**

352 **Figure 5.3: Small fish bycaught in net in DCR**

353

354

355 **Tables**

356 **Table 1: Encounter rate of anthropogenic pressures in Dugong conservation reserve**

357

Type of Anthropogenic pressure	No. of Detections in 2021	Encounter Rate (km⁻¹) in 2021	No. of Detections in 2023	Encounter Rate (km⁻¹) in 2023	% Change in Encounter Rate
Fishing Net	45	0.536	65	0.774	+44.4
Anchored Boat	15	0.179	29	0.345	+92.7
Moving Boat	9	0.107	4	0.048	-55.1
Litter	9	0.107	1	0.012	-88.8
Oil Spill	4	0.048	2	0.024	-50.0
Fishing Cage	3	0.036	1	0.012	-66.7
Anchor Line	–	–	3	0.036	New observation
Pipe Inlet	–	–	2	0.024	New observation
Combined	85	1.012	109	1.298	+28.3

358

2. **Ghanekar, C., Sivakumar, K., & Johnson, J. A. (2026).** *Seagrass-dependent fisheries: Evaluating finfish productivity in Palk Bay, India* (Manuscript submitted for publication to *Journal of Coastal Conservation*).

The screenshot shows a user dashboard for Antony Johnson on the Springer Nature platform. At the top, the Springer Nature logo is on the left, and 'Notifications' and 'Account' links are on the right. A dark blue banner contains the text 'Welcome back, Antony Johnson' and 'Celebrating and supporting your past, present and future contributions.' Below this, three circular statistics are displayed: '9 Articles', '181 Citations', and '10.5k Accesses'. The main section is titled 'Your research' and features two tabs: 'Submitted' (active) and 'Published'. Under the 'Submitted' tab, there is one submission card for the article 'Seagrass dependent Fisheries: Evaluating Finfish Productivity in Palk Bay, India', which was updated on 23 Apr 2026 and is currently in 'Peer review' status. To the right of the submission list is a sidebar titled 'Explore your benefits' with a right-pointing arrow. This sidebar contains three options: 'Promote your latest article' with a share icon, 'Watch your research impact grow' with a rocket icon, and 'Increase the' with a partially visible icon.

3. **Ghanekar, C.,** Dudhat, S., Pande, A., Sivakumar, K., & Johnson, J. A. (2026). *Comparative assessment of fish populations in seagrass habitats of the Andaman Islands* (Manuscript submitted for publication to *Journal of Applied Ichthyology*).



Comparative Assessment of Fish Populations in Seagrass Habitats of the Andaman Islands

Journal:	<i>Journal of Applied Ichthyology</i>
Manuscript ID	JAI-S2026-0030
Manuscript Type:	Research Articles
Date Submitted by the Author:	14-May-2026
Complete List of Authors:	Ghanekar, Chinmaya; Wildlife Institute of India Dudhat, Sohini; University of St Andrews Scottish Oceans Institute Pande, Anant; WWF-India, Oceans & Coasts Conservation, WWF- India Gole, Swapnali; Wildlife Institute of India Sivakumar, Kuppusamy; Pondicherry University, Department of Ecology, School of Life Sciences Johnson, Jeyaraj; Wildlife Institute of India
Keywords:	Seagrass associated, fish, marine protected areas, underwater visual census, habitat complexity

Annexure 2: Conferences – National and International

1. **Ghanekar, C., Johnson, J. A., Sivakumar, K., Anant, P., Prem, J., Rukmini, S., & Madhu, M. (2018, October 4–6).** *Ecology of seagrass associated fin fish and provisioning services of seagrass ecosystems in Palk Bay and Gulf of Mannar, Tamil Nadu* [Poster presentation]. International Biodiversity Congress 2018, Forest Research Institute.



2. Ghanekar, C. (2020, August 17–28). *A study of seagrass habitat utilization by fishes in Palk Bay and Gulf of Mannar, India* [Poster presentation]. 6th International Marine Conservation Congress. Kiel, Germany.

IMCC6 Abstract Decision & Registration



From IMCC6 <info@imcc6.com>
To <chinmaya@wii.gov.in>
Date 2020-06-25 00:10

Dear Chinmaya,

Thank you for submitting an abstract to present at IMCC6. We apologise for the delay in notifying you of the outcome of the review process. We are delighted to inform you that your abstract has been accepted as Poster presentation.

Abstract ID: 41115

Title: A study of seagrass habitat utilization by fishes in Palk Bay and Gulf of Mannar, India

Presenting author: Chinmaya Ghanekar

Please check the above details of your presentation carefully, as all conference material will be made available online. If there are any corrections please inform us as soon as possible by email to: info@imcc6.com

As a condition of abstract acceptance, you as the presenting author need to register for the conference by 10 July 2020. The abstracts of all unregistered presenters will be removed from the programme after this date.

Registration is open now. Please follow the registration link here (<https://xinyuqi.com/okff9v2c>).

As you are likely aware, IMCC6 is unexpectedly moving online due to the COVID19 pandemic. The conference will take place from August 17-28 2020. We have extended the conference by a week to distribute the programme over multiple time zones. A rough outline schedule is available here (<https://xinyuqi.com/ybi7choa>) and a more detailed schedule will be made available later in July.

3. Ghanekar, C. (2023, April 9–11). *Protecting the mermaids: Insights from the first Dugong Conservation Reserve of India* [Conference presentation]. Indian Conservation Conference 2023, Mysuru.

