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Spatial and Temporal Dynamics of Marine Ecosystem Structures in Tropical Oceans

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Abstract Marine ecosystems in tropical oceans are diverse and dynamic, requiring comprehensive study to understand their spatial and temporal dynamics. The importance of studying these dynamics lies in their crucial role in biodiversity, ecosystem health, and the impacts of climate change. This study aims to explore the spatial and temporal patterns, interactions, ecological implications, human impacts, and management strategies of marine ecosystems in depth. The research discusses the spatial dynamics of marine ecosystems, focusing on the distribution patterns of marine species, habitat heterogeneity, and factors influencing spatial distribution. This study highlights the complex interactions of the spatial and temporal dynamics of tropical marine ecosystems. The findings emphasize the necessity of integrated approaches for effective management and conservation, contributing to the sustainable management and protection of global marine ecosystems.
Keywords Marine ecosystems; Spatial dynamics; Temporal dynamics; Climate change; Sustainable management

1 Introduction

Marine ecosystems in tropical oceans are characterized by their high biodiversity and complex interactions among various species. These ecosystems include coral reefs, mangroves, and seagrass beds, which provide essential services such as coastal protection, carbon sequestration, and support for fisheries. The dynamics of these ecosystems are influenced by a multitude of factors, including climate change, human activities, and natural disturbances. Understanding the spatial and temporal dynamics of these ecosystems is crucial for their conservation and management.

Studying the spatial and temporal dynamics of marine ecosystems is essential for several reasons. Firstly, it helps in understanding how different species and communities respond to environmental changes and anthropogenic pressures. For instance, the spatial aggregation of species can significantly impact the structure and function of ecosystems, as seen in the pelagic community dynamics in Hawaii's near shore ecosystem (Benoit-Bird et al., 2012). Secondly, temporal studies provide insights into the long-term trends and resilience of ecosystems. For example, the temporal turnover in aquatic species assemblages reveals how species composition changes over time in response to ecological, physical, and geographical factors (Korhonen et al., 2010). Additionally, integrating spatial and temporal data can enhance the predictive capabilities of ecosystem models, as demonstrated by the use of a spatial-temporal data framework to drive food web models.

The main objective of this study is to synthesize the current knowledge on the spatial and temporal dynamics of tropical marine ecosystem structure, to study the main environmental and anthropogenic factors that affect the spatial and temporal patterns of tropical marine ecosystems, and to evaluate the different methods used to study these dynamics, including remote sensing, ecological modelling and field observations. Several case studies illustrating the application of these methods and the insights gained from them. Advise on conservation and management practices based on an understanding of spatial and temporal dynamics. By achieving these objectives, this study will contribute to a more comprehensive understanding of how tropical marine ecosystems operate and how they can be effectively managed in the face of ongoing environmental change.

2 Spatial Dynamics of Marine Ecosystems

2.1 Distribution patterns of marine species

The spatial distribution of marine species is influenced by a variety of factors, including habitat type, environmental conditions, and biological interactions. For instance, the spatial distribution of fish species in tropical coastal ecosystems varies significantly across different habitats such as mangroves, seagrass beds, and sandy beaches, with distinct patterns observed between dry and rainy seasons (Silva et al., 2021). Similarly, the distribution of protist communities in the ocean shows clear vertical stratification, with the highest metabolic activity observed in the mesopelagic layer (Giner, 2017). The spatial distribution of marine species is also shaped by historical geological events, such as the breakup of Gondwana, which has influenced the current biodiversity patterns of tropical reefs (Leprieur et al., 2016).

2.2 Habitat heterogeneity and zonation

Habitat heterogeneity plays a crucial role in shaping the spatial structure of marine ecosystems. In tropical macroalgae meadows, the quality and connectivity of local habitats significantly influence the community structure of reef fishes (Lier et al., 2018). The spatial heterogeneity of physical factors, such as salinity and organic matter content, also contributes to the spatial structure of benthic species in coastal lagoons (Morelos-Villegas et al., 2018). Additionally, the spatial structure of pelagic ecosystems is characterized by large-scale horizontal distribution patterns of ecophysiological rate parameters, which are not smoothly continuous but rather piecewise continuous, leading to the formation of distinct ecological provinces.

2.3 Factors influencing spatial distribution

Several factors influence the spatial distribution of marine species, including environmental conditions, biological interactions, and historical events. For example, the spatial distribution of marine food webs is influenced by the energy and material transfer across ecosystem boundaries, as well as local interactions and spatial heterogeneity (Melián et al., 2005). In pelagic ecosystems, the frequency and intensity of spatial aggregations, rather than total biomass, are significant predictors of variation in adjacent trophic levels. Additionally, the spatial distribution of zooplankton is influenced by social interactions, leading to the formation of spatial patterns such as swarms and schools (Verdy, 2008). The spatial distribution of marine species is also affected by habitat-specific factors, such as water salinity and sediment composition, which explain a significant portion of the variance in species abundance

3 Temporal Dynamics of Marine Ecosystems

3.1 Seasonal variations

Seasonal variations in marine ecosystems are driven by changes in environmental conditions such as temperature, light availability, and nutrient concentrations. These variations significantly influence the distribution and abundance of marine species. For instance, phytoplankton and zooplankton populations exhibit periodic oscillations due to seasonal changes in diffusion coefficients and local reactions, leading to patchiness in their spatial distribution (Chakraborty and Manthena, 2015). Additionally, the dynamics of coral communities also show seasonal patterns, where disturbances prevent ecological equilibrium at smaller scales, but larger biogeographic scales reveal more stable community structures (Pandolfi, 2002).

3.2 Long-term changes and trends

Long-term changes in marine ecosystems are often linked to persistent environmental shifts and anthropogenic impacts. Studies have shown that coral community structures have remained relatively stable over tens of thousands of years, but recent massive degradation of coral reef habitats suggests unprecedented changes likely due to human activities (Pandolfi, 2002). Similarly, the spatial dynamics of tuna populations in the Pacific Ocean, modeled over monthly resolutions, reveal significant long-term trends influenced by bio-physical environmental changes and fishing pressures (Lehodey et al., 2008). These long-term trends are crucial for understanding the persistence and resilience of marine ecosystems.

3.3 Impact of climate change

Climate change poses a significant threat to marine ecosystems by altering ocean temperatures, chemistry, and circulation patterns. The integration of spatial-temporal data frameworks with ecosystem models has enhanced our ability to predict the impacts of climate change on marine food webs. For example, changes in primary production due to climate-induced variations cascade through the food web, affecting zooplankton and pelagic fish populations (Steenbeek et al., 2013). Additionally, the spatial and temporal dynamics of biogenic reef habitats, such as those formed by *Sabellaria alveolata*, show that climate change can lead to rapid accretion and erosion patterns, impacting habitat structure and biodiversity (Figure 1) (Jackson-Bué et al., 2021). Understanding these impacts is essential for developing effective management and conservation strategies.

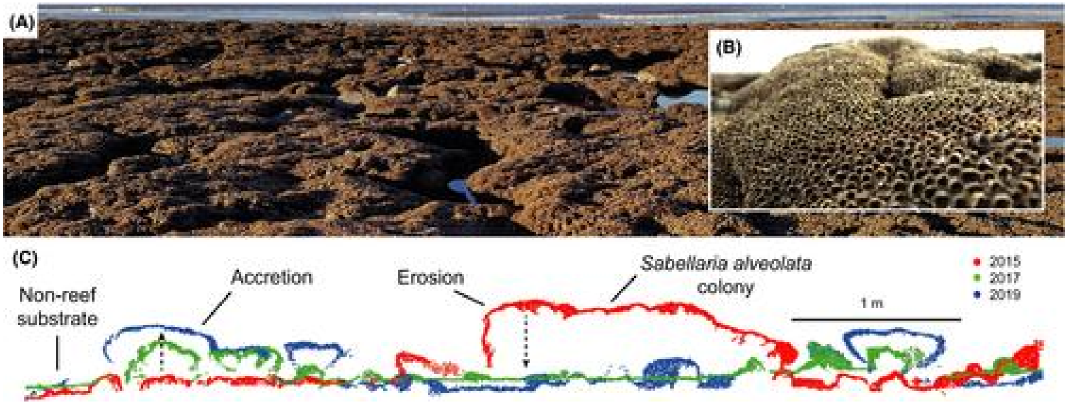

Figure 1 Changes in habitat structure of biological coral reefs (Adopted from Jackson-Bué et al., 2021)

Image caption: (A) The *Sabellaria alveolata* biogenetic coral reef habitat includes aggregates of sediment tubes in the community., B) Close-up image of the gradient colony surface showing a dense tube opening with a diameter of~5 mm, C) Cross-section of 3-year 3D ground laser scanning point cloud data (Adopted from Jackson-Bué et al., 2021)

The study by Jackson-Bué et al. 2021 showed structural changes in coral reef habitats formed by biomass sandworm reefs (*Sabellaria alveolata*), demonstrating the erosion and growth processes of reefs. Using sandworm reefs as an example, the research team showed that rising sea levels and rising sea temperatures have led to changes in habitat structure, such as erosion and physical structure. These changes not only affect the stability and growth of the reef itself, but may also have long-term impacts on marine biodiversity and ecosystem services as a whole.

4 Interactions Between Spatial and Temporal Dynamics

4.1 Synergistic effects

The interplay between spatial and temporal dynamics in marine ecosystems often results in synergistic effects that can significantly influence ecosystem structure and function. For instance, the study on the spatio-temporal dynamics of a phytoplankton-zooplankton system highlights how periodic oscillations and patchiness are fundamental characteristics of marine ecosystems, driven by both local reactions and diffusion processes (Chakraborty and Manthena, 2015). Similarly, the research on coral community dynamics demonstrates that ecological chaos at small scales and order at larger scales are influenced by historical, chance, and regional processes, indicating a complex interaction between spatial and temporal factors (Pandolfi, 2002). Furthermore, the integration of spatial-temporal data into food web models, as shown in the NF-UBC Nereus Program, enhances the predictive capabilities of these models, reflecting observed species population trends and distributions more accurately (Steenbeek et al., 2013).

4.2 Case studies of combined dynamics

Several case studies illustrate the combined effects of spatial and temporal dynamics in marine ecosystems. For example, the study on the spatial ecosystem and population dynamics model (SEAPODYM) for tuna species in the Pacific Ocean shows how spatial dynamics, driven by bio-physical environmental factors, influence the distribution and behavior of tuna populations over time (Lehodey et al., 2008). Another case study on the bottom-up regulation of a pelagic community in Hawaii reveals that spatial aggregations, rather than total biomass, are significant predictors of variation in adjacent trophic levels, demonstrating the importance of patch dynamics in regulating ecosystem structure (Benoit et al., 2012). Additionally, the use of modern 3D mapping technologies to characterize the spatial and temporal variation in biogenic reef habitats provides insights into how dynamic structural changes at the colony scale can result in stable habitat structures over larger scales (Jackson-Bué et al., 2021).

4.3 Modeling approaches

Modeling approaches play a crucial role in understanding the interactions between spatial and temporal dynamics in marine ecosystems. The use of reaction-diffusion equations to model phytoplankton-zooplankton interactions provides a theoretical framework for understanding patchiness in marine environments (Chakraborty and Manthena, 2015). The development of the SEAPODYM model, which incorporates habitat indices, movements, and natural mortality based on empirical evidence, allows for the simulation of spatial dynamics of tuna populations and their responses to environmental changes. Moreover, the integration of spatial-temporal data into food web models, as demonstrated in the NF-UBC Nereus Program, offers a promising step toward interdisciplinary model interoperability, enhancing the ability to include species distribution models and food web dynamics in ecosystem analysis (Giner, 2017). These modeling approaches are essential for predicting ecosystem responses to various environmental and anthropogenic factors, thereby aiding in the effective management and conservation of marine ecosystems.

5 Ecological Implications

5.1 Biodiversity and ecosystem health

The spatial and temporal dynamics of marine ecosystems in tropical oceans have profound implications for biodiversity and ecosystem health. Studies have shown that habitat structure significantly influences ecological interactions and ecosystem functions. For instance, the structural complexity of biogenic reefs, such as those formed by *Sabellaria alveolata*, plays a crucial role in maintaining biodiversity and ecosystem resilience by providing varied microhabitats and influencing species interactions (Jackson-Bué et al., 2021). Additionally, the spatial heterogeneity and structural complexity of habitats can mediate herbivory effects, thereby promoting species diversity and stability in algal metacommunities (Srednick et al., 2023). The temporal turnover of species assemblages, which varies with ecosystem size and geographical gradients, also affects biodiversity. Faster turnover rates in tropical regions suggest a dynamic and resilient ecosystem capable of adapting to environmental changes (Korhonen et al., 2010).

5.2 Productivity and trophic interactions

Marine ecosystems' productivity and trophic interactions are deeply intertwined with their spatial and temporal dynamics. The global connectivity of marine fish food webs highlights the importance of trophic interactions in maintaining ecosystem productivity. Coastal food webs, in particular, exhibit greater interaction redundancy, which enhances their robustness to species extinction and perturbations (Albouy et al., 2019). The spatial structure of marine food webs, including the distribution of trophic interactions, is influenced by sea surface temperature and tends to peak towards the tropics, indicating higher productivity in these regions. Furthermore, the dynamics of fish diversity across different coastal habitats and seasons reveal that taxonomic and phylogenetic diversity are influenced by seasonal changes, which in turn affect ecosystem functioning and productivity (Silva et al., 2021).

5.3 Resilience and adaptation

The resilience and adaptation of marine ecosystems are closely linked to their spatial and temporal dynamics. The ability of ecosystems to maintain stability and function despite environmental changes is partly due to the spatial and temporal variation in habitat structure and species interactions (Figure 2). For example, the dynamic structural changes in biogenic reefs, such as the accretion and erosion patterns observed in *Sabellaria alveolata* colonies, contribute to the overall stability of the reef habitat over larger spatial and temporal scales. Additionally, the spatial structure and dynamics of marine food webs, including the coexistence of interacting species in heterogeneous environments, play a crucial role in the persistence of biodiversity and ecosystem resilience

(Melián et al., 2005). The temporal turnover of species assemblages, driven by ecological, physical, and geographical factors, further underscores the adaptive capacity of marine ecosystems to track and respond to environmental changes (Korhonen et al., 2010).

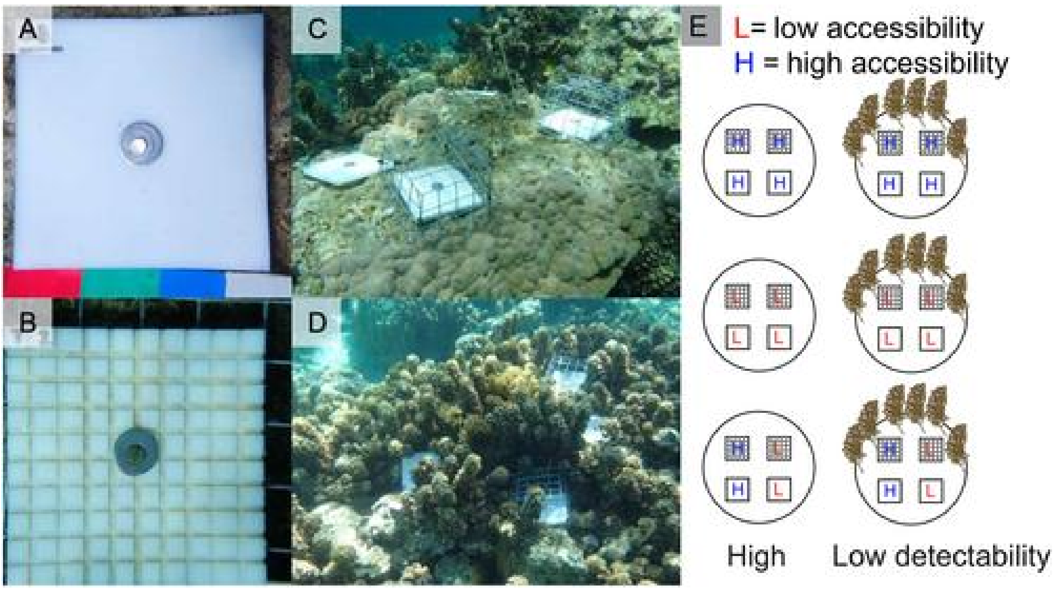

Figure 2 Effects of spatial heterogeneity and habitat complexity on algal community composition and assembly (Adopted from Srednick et al., 2023)

Image caption: (A) high accessibility and (B) low accessibility treatments, and (C) high detectability (no turbinates) and (D) low detectability (presence of turbinates) treatments of algal sedimentation tiles. A visual representation of the experimental design shown in Figure (E) (Adopted from Srednick et al., 2023)

Srednick et al. 2023 investigated the effects of spatial heterogeneity and habitat complexity on algal community composition and structure by using different algal sediment tile treatments. The figure shows the effect of high and low accessibility and high and low detectability processing. This experimental design revealed the resilience and adaptability of algal communities to environmental changes, showing that algae are able to adapt their composition to different characteristics of the habitat to maintain function and diversity under changing environmental conditions. This is of great significance for understanding and predicting the response of marine ecosystems to global change.

6 Human Impacts and Management Strategies

6.1 Overfishing and habitat destruction

Human activities have significantly impacted marine ecosystems, particularly in tropical oceans. Anthropogenic stressors such as land-use change, pollution, and overfishing have led to the degradation of critical habitats like coral reefs, seagrass beds, and mangrove forests. These activities have altered the trophic structure of fish communities, leading to declines in predator populations and changes in benthic structures (Ruppert et al., 2018). Overfishing and habitat destruction are primary drivers of marine ecosystem degradation. The reduction in predator biomass, such as sharks and carnivorous fish, due to overfishing has been observed across the Pacific Ocean, particularly in areas with higher human population densities. This decline in predator populations disrupts the balance of marine food webs, leading to cascading effects on ecosystem health and function. Additionally, habitat destruction from activities like coastal development and pollution further exacerbates these issues by degrading the benthic structures that support diverse marine life.

6.2 Conservation and protected areas

Conservation efforts, including the establishment of marine protected areas (MPAs), are crucial for mitigating the impacts of human activities on marine ecosystems. MPAs can help preserve biodiversity, protect critical habitats, and maintain ecosystem services. However, the effectiveness of MPAs depends on strategic site selection and spatial planning. Incorporating spatial planning principles into conservation efforts can enhance restoration outcomes by ensuring that protected areas are located in regions that maximize ecosystem service benefits and restoration success (Lester et al., 2020). This approach requires a comprehensive understanding of the spatial dynamics of marine ecosystems and the application of advanced analytical tools from marine spatial planning and conservation planning literatures.

6.3 Sustainable management practices

Sustainable management practices are essential for the long-term health of marine ecosystems. These practices include regulating fishing activities, reducing pollution, and implementing habitat restoration projects. Restoration techniques for marine and coastal ecosystems, such as seagrass beds, salt marshes, and mangrove forests, are generally more expensive than terrestrial ecosystems, making careful site selection critical for maximizing return on investment. By focusing on locations that offer the highest probability of restoration success and ecosystem service outcomes, sustainable management practices can support more effective and efficient restoration efforts (Lester et al., 2020).

In conclusion, addressing the spatial and temporal dynamics of marine ecosystem structures in tropical oceans requires a multifaceted approach that includes understanding human impacts, mitigating overfishing and habitat destruction, establishing conservation and protected areas, and implementing sustainable management practices (Lorenzo et al., 2020). By integrating these strategies, we can better protect and restore the rich biodiversity and ecosystem services provided by tropical marine ecosystems.

7 Technological Advances in Monitoring and Research

7.1 Remote sensing and GIS

Remote sensing and Geographic Information Systems (GIS) have revolutionized the monitoring and mapping of marine ecosystems. Satellite imagery and aerial surveys provide large-scale, high-resolution data on oceanographic parameters, such as sea surface temperature, chlorophyll concentration, and ocean color. These technologies enable the continuous observation of marine environments, allowing for the detection of changes over time and the assessment of spatial patterns in ecosystem structures. For instance, remote sensing has been instrumental in mapping coral reefs and detecting bleaching events. Studies have shown that satellite-derived data can accurately monitor coral health and predict bleaching events by analyzing sea surface temperatures and other stress indicators (Guo et al., 2019). Additionally, GIS tools facilitate the integration and analysis of spatial data, supporting the development of habitat maps and the identification of critical areas for conservation.

7.2 Autonomous underwater vehicles (AUVs)

Autonomous Underwater Vehicles (AUVs) have emerged as powerful tools for exploring and monitoring marine ecosystems. AUVs can operate independently, collecting high-resolution data on physical, chemical, and biological parameters at various depths and locations (Mason et al., 2020). These vehicles are equipped with advanced sensors and imaging systems, enabling detailed surveys of the seafloor and water column. AUVs have been particularly valuable in studying hard-to-reach areas, such as deep-sea habitats and remote coral reefs. Research utilizing AUVs has provided insights into the distribution and health of benthic communities, revealing the impacts of environmental changes and human activities on these ecosystems. Furthermore, the continuous advancements in AUV technology, including improved battery life and navigation systems, are enhancing their capabilities for long-duration and large-scale missions.

7.3 Data integration and modeling

The integration of diverse data sources and advanced modeling techniques has greatly enhanced our ability to understand and predict the dynamics of marine ecosystems. Combining data from remote sensing, in-situ observations, and AUVs allows for comprehensive analyses of marine environments, facilitating a more holistic understanding of ecosystem processes. Advanced modeling techniques, such as ecological niche modeling and predictive habitat modeling, leverage integrated datasets to simulate and forecast changes in ecosystem structures. These models can predict the impacts of climate change, habitat degradation, and other stressors on marine biodiversity and ecosystem services (Ma et al., 2023). The development of sophisticated algorithms and computational tools is further enhancing the accuracy and reliability of these models, supporting informed decision-making for marine conservation and management. In conclusion, technological advances in remote sensing and GIS, AUVs, and data integration and modeling are significantly contributing to our understanding of the spatial and temporal dynamics of marine ecosystem structures in tropical oceans. These innovations are providing valuable insights and tools for the effective monitoring, conservation, and management of marine resources.

8 Challenges and Future Directions

8.1 Methodological challenges

The study of spatial and temporal dynamics in marine ecosystems faces several methodological challenges. One significant issue is the integration of diverse data types and scales into cohesive models. For instance, the development of a spatial-temporal data framework to drive food web models with external data highlights the complexity of achieving model interoperability. This approach, part of the NF-UBC Nereus Program, aims to bridge the gap between ecosystem modeling tools and geographic information systems (GIS) technology, but it requires a flexible and modular software approach to separate technical and scientific challenges (Steenbeek et al., 2013). Additionally, the use of reaction-diffusion equations to model phytoplankton-zooplankton interactions demonstrates the difficulty in capturing the inherent patchiness and self-organized spatial patterns in marine environments (Chakraborty and Manthena, 2015). These challenges underscore the need for advanced modeling techniques and computational tools to accurately represent the dynamic nature of marine ecosystems.

8.2 Knowledge gaps and research needs

Despite advancements in modeling and data collection, significant knowledge gaps remain in our understanding of marine ecosystem dynamics. One critical area is the impact of human activities and climate change on coral reef communities. Studies have shown that the degradation of coral reef habitats and changes in species composition may be linked to human-induced environmental modifications, but the extent and predictability of these changes are still uncertain (Pandolfi, 2002). Furthermore, the need for detailed information about habitat properties and their variation across spatial and temporal scales is crucial for effective ecosystem management. Modern 3D mapping technologies, such as drone-derived photogrammetry and terrestrial laser scanning, have begun to address this need by providing high-resolution data on biogenic reef structures, but more research is required to fully understand the implications of these findings (Jackson-Bué et al., 2021).

8.3 Emerging trends and innovations

Emerging trends and innovations in the study of marine ecosystems are promising steps toward overcoming existing challenges and filling knowledge gaps. The integration of remote sensing data with food web models, as demonstrated in the NF-UBC Nereus Program, enhances the predictive capabilities of these models and provides a more accurate reflection of species population trends and distributions. Additionally, the application of modern 3D mapping technologies to characterize spatial and temporal dynamics in biogenic reef habitats offers new insights into ecosystem biodiversity (Figure 3), function, and resilience. These technologies have revealed previously undocumented patterns in reef accretion and erosion, highlighting the potential for advanced tools to enhance our understanding of ecosystem dynamics across scales (Gissi et al., 2019). Continued innovation in data collection, modeling, and analysis will be essential for addressing the complex and interconnected challenges facing marine ecosystems in the future.

The figure illustrates the changes in species composition of different intertidal coral reefs and benthic communities over the course of a year. Capturing and analyzing these communities through 3D imaging technology provides an emerging research trend that allows scientists to observe and monitor biodiversity with unprecedented detail and precision. This innovative approach not only improves the efficiency and accuracy of data collection, but also provides valuable insights into the response of biological communities to environmental changes, thereby advancing the development of marine ecology research.

9 Concluding Remarks

The research on the spatial and temporal dynamics of marine ecosystem structures in tropical oceans has revealed several critical insights. Firstly, the study of phytoplankton-zooplankton interactions using reaction-diffusion equations has shown that patchiness is a fundamental characteristic of marine ecosystems, with self-organized spatial patterns emerging due to local reactions and diffusion processes. Additionally, investigations into coral community dynamics have highlighted the significant impact of spatial and temporal scales on ecological observations, with large-scale studies revealing persistent community structures over millennia, while smaller scales show ecological chaos due to disturbances. The integration of spatial-temporal data frameworks with ecosystem models has enhanced the predictive capabilities of food web models, allowing for more accurate reflections of species population trends and distributions. Furthermore, the importance of spatial aggregations in regulating pelagic communities has been underscored, with patch dynamics playing a crucial role in resource limitation and trophic interactions. The SEAPODYM model has provided valuable insights into the spatial dynamics of tuna populations, emphasizing the influence of bio-physical environments on species distribution and interactions. Lastly, modern 3D mapping technologies have enabled detailed characterization of habitat structures, revealing scale-dependent dynamics in biogenic reef habitats.

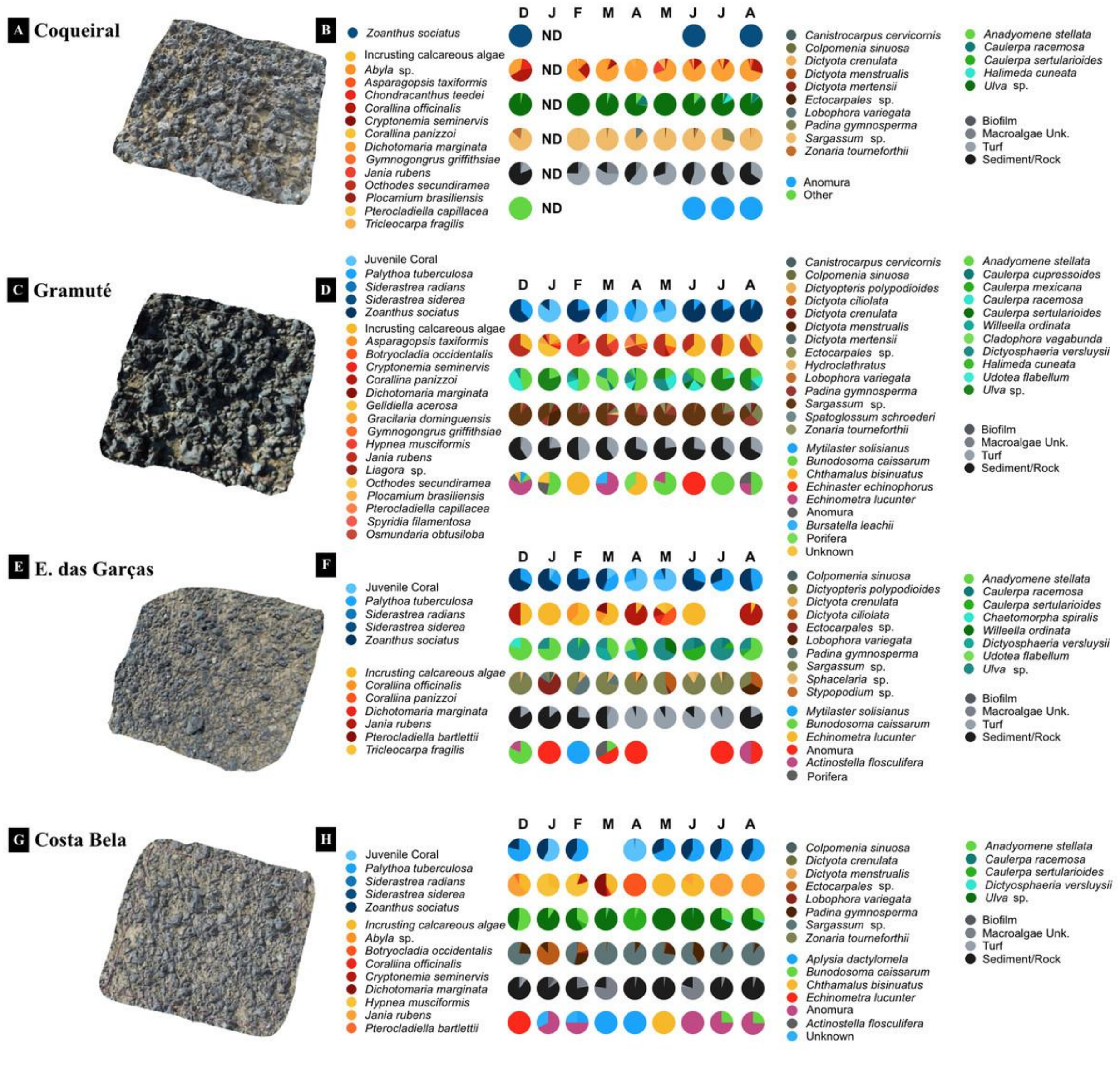

Figure 3 3D imaging of intertidal coral reefs and benthic communities (Adopted from Mazzuco et al., 2020)

The findings from these studies underscore the importance of integrated approaches in understanding marine ecosystem dynamics. By combining various modeling tools, geographic information systems (GIS), and advanced mapping technologies, researchers can achieve a more comprehensive understanding of the complex interactions within marine ecosystems. The integration of spatial and temporal data frameworks with ecosystem models, as demonstrated in the NF-UBC Nereus Program, allows for better interoperability and enhances the predictive capabilities of these models. Additionally, the use of modern 3D mapping technologies has proven essential in capturing the fine-scale structural variations in habitats, which are critical for understanding ecosystem functions and biodiversity. These integrated approaches facilitate a more holistic view of marine ecosystems, enabling researchers to address the multifaceted challenges posed by climate change, human activities, and natural variability.

Future research should continue to focus on the development and application of integrated modeling frameworks that incorporate spatial and temporal dynamics. There is a need for more studies that utilize advanced technologies, such as 3D mapping and remote sensing, to capture detailed habitat structures and their variations over time. Additionally, research should aim to improve the resolution and accuracy of ecosystem models by incorporating more comprehensive data on species interactions, environmental variables, and human impacts. Long-term monitoring programs are essential to track changes in marine ecosystems and to validate model predictions. Furthermore, interdisciplinary collaborations that bring together ecologists, oceanographers, and data scientists will be crucial in advancing our understanding of marine ecosystem dynamics and in developing effective conservation and management strategies. Finally, there is a need to explore the implications of spatial and temporal scales in greater detail, particularly in relation to the persistence and resilience of marine communities under varying environmental conditions.

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Conflict of Interest Disclosure

The authors affirm that this research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest.

References

Albouy C., Archambault P., Appeltans W., Araújo M., Beauchesne D., Cazelles K., Cirtwill A., Fortin M., Galiana N., Leroux S., Pellissier L., Poisot T., Stouffer D., Wood S., and Gravel D., 2019, The marine fish food web is globally connected, Nature Ecology and Evolution, 3(8): 1153-1161. https://doi.org/10.1038/s41559-019-0950-y

Benoit-Bird K.J., and McManus M.A., 2012, Bottom-up regulation of a pelagic community through spatial aggregations, Biology Letters, 8: 813-816. https://doi.org/10.1098/rsbl.2012.0232

Chakraborty K., and Manthena V., 2015, Modelling and analysis of spatio-temporal dynamics of a marine ecosystem, Nonlinear Dynamics, 81: 1895-1906. https://doi.org/10.1007/S11071-015-2114-1

Giner C., 2017, Spatial, temporal and behavioral patterns of marine protists, Universitat Politècnica de Catalunya (UPC), 7. https://doi.org/10.13039/501100004837

Gissi E., Fraschetti S., and Micheli F., 2019, Incorporating change in marine spatial planning: a review, Environmental Science and Policy, 92: 191-200. https://doi.org/10.1016/J.ENVSCI.2018.12.002

Jackson-Bué T., Williams G., Walker-Springett G., Rowlands S., Davies A., and Lecours V., 2021, Three-dimensional mapping reveals scale-dependent dynamics in biogenic reef habitat structure, Remote Sensing in Ecology and Conservation, 7(4): 621-637. https://doi.org/10.1002/rse2.213

Dou J.P., Li H., Pang X.L., Zhang C.N., Yang T.H., and Jin X.M., 2019, Research progress of quantum memory, Acta Phys. Sin., 68(3): 030307. https://doi.org/10.7498/APS.68.20190039

Korhonen J., Soininen J., and Hillebrand H., 2010, A quantitative analysis of temporal turnover in aquatic species assemblages across ecosystems, Ecology, 91(2): 508-517. https://doi.org/10.1890/09-0392.1

Lehodey P., Senina I., and Murtugudde R., 2008, A spatial ecosystem and populations dynamics model (SEAPODYM)-Modeling of tuna and tuna-like populations, Progress in Oceanography, 78: 304-318. https://doi.org/10.1016/J.POCEAN.2008.06.004

Leprieur F., Descombes P., Gaboriau T., Cowman P., Parravicini V., Kulbicki M., Melián C., Santana C., Heine C., Mouillot D., Bellwood D., and Pellissier L., 2016, Plate tectonics drive tropical reef biodiversity dynamics, Nature Communications, 7(1): 11461. https://doi.org/10.1038/ncomms11461

Lester S.E., Dubel A.K., Hernán G., McHenry J., and Rassweiler A., 2020, Spatial planning principles for marine ecosystem restoration, Frontiers in Marine Science, 7: 328.
https://doi.org/10.3389/fmars.2020.00328

Lier J., Wilson S., Depczynski M., Wenger L., and Fulton C., 2018, Habitat connectivity and complexity underpin fish community structure across a seascape of tropical macroalgae meadows, Landscape Ecology, 33: 1287-1300.
https://doi.org/10.1007/s10980-018-0682-4

Lorenzo M., Guidetti P., Franco A., Calò A., and Claudet J., 2020, Assessing spillover from marine protected areas and its drivers: a meta‐analytical approach, Fish and Fisheries, 21(5): 906-915.
https://doi.org/10.1111/faf.12469

Ma Y.H., Zhang H.G., Cao W.T., and Wang J., 2023, Detection of coral bleaching in oceanic islands using normalized bottom reflectance change index from multispectral satellite imagery, IEEE Geoscience and Remote Sensing Letters, 20: 1-5.

Mason W., Skirving and S., Dove., 2020, Integrating physiology with remote sensing to advance the prediction of coral bleaching events, Remote Sensing of Environment, 246: 111794.

Mazzuco A., Stelzer P., and Bernardino Â., 2020, Substrate rugosity and temperature matters: patterns of benthic diversity at tropical intertidal reefs in the SW Atlantic, PeerJ, 8: e8289.
https://doi.org/10.7717/peerj.8289

Melián C.J., Bascompte J., and Jordano P., 2005, Spatial structure and dynamics in a marine food web, Aquatic Food Webs, 19-24.
https://doi.org/10.1093/acprof:oso/9780198564836.003.0003

Morelos-Villegas A., Condal A., and Ardisson P., 2018, Spatial heterogeneity and seasonal structure of physical factors and benthic species in a tropical coastal lagoon Celestun Yucatan Peninsula, Regional Studies in Marine Science, 22: 136-146.
https://doi.org/10.1016/J.RSMA.2018.06.008

Pandolfi J. 2002, Coral community dynamics at multiple scales, Coral Reefs, 21: 13-23.
https://doi.org/10.1007/s00338-001-0204-7

Ruppert J., Vigliola L., Kulbicki M., Labrosse P., Fortin M., and Meekan M., 2018, Human activities as a driver of spatial variation in the trophic structure of fish communities on Pacific coral reefs, Global Change Biology, 24: e67-e79.
https://doi.org/10.1111/gcb.13882

Silva V., Dolbeth M., and Fabré N., 2021, Assessing tropical coastal dynamics across habitats and seasons through different dimensions of fish diversity, Marine Environmental Research, 171: 105458.
https://doi.org/10.1016/j.marenvres.2021.105458

Srednick G., Cohen A., Diehl O., Tyler K., and Swearer S., 2023, Habitat attributes mediate herbivory and influence community development in algal metacommunities, Ecology, 104(4): e3976.
https://doi.org/10.1002/ecy.3976

Steenbeek J., Coll M., Gurney L., Mélin F., Hoepffner N., Buszowski J., and Christensen V., 2013, Bridging the gap between ecosystem modeling tools and geographic information systems: driving a food web model with external spatial-temporal data, Ecological Modelling, 263: 139-151.
https://doi.org/10.1016/J.ECOLMODEL.2013.04.027