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Climate Change Effects on Marine Biodiversity and Ecosystem Services through a Conservation-Oriented Assessment Framework

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Abstract: This study develops a conservation-based evaluation framework to assess the impact of climate change on marine biodiversity and ecosystem services by considering climate exposure, biodiversity state, ecosystem-service importance, vulnerability, and conservation priority. Climate exposure, marine heat waves, acidification, deoxygenation, and sea level rise have been assessed in terms of normalized environmental indicators, whereas biodiversity has been considered in terms of species richness, abundance, Shannon diversity, functional diversity, and habitat quality. Ecosystem services are composed of fisheries, carbon storage, nutrient cycling, coastal protection, and recreation. The combined vulnerability index includes climate exposure, biodiversity sensitivity, and adaptive capacity, followed by a conservation priority index involving biodiversity and ecosystem-service importance. Coral reefs have been observed to show the highest climate exposure (0.82), biodiversity sensitivity (0.88), vulnerability (0.64), and conservation priority (0.66). Pelagic fisheries have been found to be the most important among ecosystem services (0.92), with a vulnerability of 0.50 and a conservation priority of 0.59. The vulnerability and conservation priorities of seagrass were found to be 0.48, while those of mangroves were the lowest at 0.39 and 0.45, respectively. This highlights the fact that conservation priority is determined by the cumulative effect of climate exposure, ecological sensitivity, ecosystem service importance, and adaptive capacity. The results have laid the foundation for the strategic protection and management of marine ecosystems under climate change.

Keywords: Climate Change; Marine Biodiversity; Ecosystem Services; Climate Vulnerability; Conservation Priority; Marine Ecosystems; Adaptive Management.

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I. Introduction

Climate change is becoming increasingly understood as one of the most prominent causes of ecological change, whose impacts span from changes in the environment to disruptions in biodiversity, ecosystem processes, and the delivery of ecosystem services. Ecosystems in the marine environment and on the coastlines are especially vulnerable due to the fact that their biological communities react very quickly to any changes in temperature, ocean chemistry, oxygen levels, etc. Climate-induced stressors may affect the distribution and composition of the biological communities, interactions within the ecosystem, and processes in general, thus impacting both the stability of the ecosystems and the benefits provided by them to humans (Mooney et al., 2009; Cheung et al., 2009). Climate change and its interaction with preexisting human-induced pressures are increasingly important due to their potential risk for biodiversity conservation.

Ocean warming is among the key pressures associated with climate change in the marine environment, and marine heat waves can create an acute and long-lasting disturbance of the ecosystem. New studies highlight that marine heat waves are hotspots for climate change impacts, with consequences for biodiversity and ecosystem services via alterations in the abundance, distribution, habitat conditions, and ecological interactions (Wernberg et al., 2025). Another pressure associated with climate change is ocean acidification, as changes in carbonic acid content in the sea can affect calcification, physiology, species interactions, food webs, and ecosystem functions (Doney et al., 2020). Thus, these impacts associated with the changes in climate conditions can spread through different ecological levels and not only affect individual species independently.

Climate change also has a significant effect on marine and coastal biodiversity. Predicted alterations in environmental conditions can lead to changes in the spatial distribution of marine organisms, changes in community structure, changes in habitats, and changes in the productivity of ecosystems (Cheung et al., 2009). Coastal ecosystems are especially vulnerable to impacts of climate change due to the fact that biodiversity is affected both by environmental change and human actions (Santojanni et al., 2023). These changes are important not only in terms of biodiversity conservation but also due to the fact that biodiversity is responsible for many ecosystem services. The link between biodiversity, ecosystem functioning, and ecosystem services shows how changes in species and functional biodiversity may impact ecosystem functioning and its service provision (Cotter et al., 2017; Mooney et al., 2009).

Accordingly, climate impact assessment needs to be based on an integrated approach where environmental pressures, biodiversity impacts, and consequences of the degradation of ecosystem services are taken into account. Current conservation planning approaches place a significant amount of emphasis on the relevance of integrating climate change considerations into biodiversity adaptation and conservation approaches (Watson et al., 2012). Likewise, legal and institutional approaches also highlight the relevance of ecosystem services to biodiversity conservation (Prip, 2018). An assessment framework, which takes into account these four factors concurrently, is also essential for proper marine management.

Hence, the current research aims at the development of an assessment framework for evaluating the impacts of climate change on marine biodiversity and ecosystem services.

Consequently, there are three major contributions of this study as follows: first, it proposes a unified approach that integrates the relationships among climate change impacts, marine biodiversity, ecosystem services, and ecological vulnerability; second, it constructs a framework of conservation priority based on biodiversity significance, ecosystem services significance, vulnerability, and conservation capability; and third, it establishes a scientific basis for the prioritization of marine protection, restoration, and adaptive management and monitoring of climate change.

The paper consists of six parts as follows: Section 1: Introduction, Section 2: Climate and Marine Ecosystem Responses, Section 3: Methodology, Section 4: Results, Section 5: Discussion, and Section 6: Conclusion.

II. Climate Change, Marine Biodiversity and Ecosystem-Service Responses

Marine ecosystems are influenced by climate change through complex environmental pressures affecting species, habitats, ecological processes, and ecosystem services. The connection between biodiversity and ecosystem services is crucial in this context since biodiversity helps the functioning of ecosystems in many ways while changes in environmental conditions can influence the ability of ecosystems to perform their functions (Mooney et al., 2009). Therefore, assessment of climate impacts should take into account both ecological changes and ecosystem services related to the functioning of marine ecosystems.

One of the components of this climate pressure is ocean acidification. The increasing CO2 concentrations alter the seawater chemistry and can impact species that use carbonate structures, while ecological and physiological impacts can be observed among various species and in species interactions and food webs (Doney et al., 2020). This can then have an effect on such ecosystem services like fisheries, habitat-forming species, and other services dependent on healthy marine ecosystems. Marine heat waves are another climate stressor that has gained importance recently. The intensity, duration and scale of such phenomena can lead to significant ecological disturbances like changes in species distribution, community structure, habitat status and ecosystem service provision (Wernberg et al., 2025).

Changes in climate can also greatly affect the spatial distribution and make-up of marine biodiversity. The changes caused by climate in the environmental suitability of the areas may result in a change in the range of species, while the variation in sensitivity among the species may cause changes in the community

structure and ecological functions (Cheung et al., 2009). A similar case is the case with coastal ecosystems, as climate influences can interact with the effects of other environmental and anthropogenic influences, causing increased loss of biodiversity and degradation of the ecology (Santojanni et al., 2023). These impacts highlight the requirement of taking an integrated approach to assessing biodiversity rather than using only species indicators.

Biodiversity and ecosystem services assessment should be done keeping in view the issues related to species diversity and functional diversity. An assessment based on biodiversity can offer an understanding of the impacts of change in species and functional characteristics on ecosystem functioning and service delivery (Cotter et al., 2017). Recently, there have been efforts towards improving the methods to assess ecosystem services in marine systems (Socrate et al., 2026).

Conservation planning offers another dimension to climate impact assessments. Biodiversity conservation adaptation to climate impacts should be done through strategies that take into account the changing environment and include climate risk in the conservation planning process (Watson et al., 2012). Assessment procedures for operationalizing marine conservation areas can also serve as systematic tools in evaluating conservation values and the effectiveness of conservation (Petza et al., 2019). Moreover, there is a link between biodiversity conservation and ecosystem services protection within the overall environmental governance system (Prip, 2018).

From the experience with climate change assessments in other ecosystems, it has been shown that environmental scenarios can make a great difference in terms of biodiversity and ecosystem-service values. It confirms the need for using an integrated scenario-based approach for the evaluation (Kattel, 2022; Baskent, 2019). Additionally, it was also found that changes in land use conditions affect the ecosystem services related to water (Aghsaei et al., 2025). In total, all these studies confirm the use of a framework based on climate exposure, biodiversity sensitivity, ecosystem service significance, and conservation potential assessment.

III. Conservation-Oriented Marine Biodiversity and Ecosystem-Service Assessment Methodology

Research Design and Assessment Strategy

This research uses an integrated assessment design with a conservation orientation to explore how the environmental stresses arising from climate change affect marine biodiversity and ecosystem services. This approach links climate stresses with ecological responses, which are in turn translated into implications for ecosystem services and conservation issues. The four major components of the assessment are climate exposure, biodiversity state, ecosystem service state, and conservation vulnerability. These components are linked together to create linkages between environmental changes, ecological states, ecosystem functioning, and conservation needs. The entire sequence of analysis includes data collection, indicator creation, normalization, climate exposure assessment, biodiversity assessment, ecosystem services assessment, vulnerability integration, and conservation priority determination.

Climate Stressor Assessment

The climate-based pressures are identified with the help of indicators depicting the major environmental factors influencing marine systems. Sea surface temperature and temperature anomalies are considered to depict the ocean warming pressure. Marine heatwaves are considered in order to account for short-term thermal disturbances. Ocean acidification is depicted through carbonate chemistry indicators such as seawater pH when information on the same is available. Oxygen is considered in order to depict the climate-related deoxygenation factor, whereas sea level variation is also taken into consideration where possible.

Marine Biodiversity Condition Assessment

Marine biodiversity is measured by complementary indices, which cover taxonomic composition, abundance, diversity, and condition of habitat. The number of species and their abundance are used as measures of biological communities' composition and magnitude, whereas the Shannon diversity index is applied for diversity. When appropriate data are available, indices of functional diversity and habitat extent are also included in order to include ecological features that could not be reflected only by the number of species. Special indices reflecting conditions of coral or seagrass coverage are included when relevant for a particular ecosystem. Thus, marine biodiversity assessment reflects the state of biological condition under various exposures to climate change.

The Shannon diversity index is calculated as:

$$H' = -\sum_{i=1}^{S} p_i \ln(p_i) \quad (1)$$

Equation (1), where H'represents the Shannon diversity index, Srepresents the total number of species, and $p_i$represents the proportional abundance of species i.

Ecosystem-Service Assessment

The ecosystem service indicator component assesses the potential impact that shifts in the condition of the marine ecological system may have on the services offered by the marine ecosystem. The provisioning services are indicated through indicators related to fisheries, whereas regulating services could be indicated using indicators for carbon storage or sequestration. Supporting services are indicated through indicators related to productivity and nutrient cycles, whereas cultural services could be indicated through indicators related to tourism or other types of human usage.

Indicator Normalization and Weighting

Since the chosen indicators have different units of measure and scales of measurement, all the indicators are converted to normalized data before integrating them. This is because the indicators have different units and scales of measurement. Normalization of the positive indicator is performed using Equation (2):

$$X'_{ij} = \frac{X_{ij} - X_j^{min}}{X_j^{max} - X_j^{min}} \quad (2)$$

For a negative indicator, where a higher value represents greater environmental pressure or ecological degradation, the normalized value is calculated as:

$$X'_{ij} = \frac{X_j^{max} - X_{ij}}{X_j^{max} - X_j^{min}} \quad (3)$$

Equation (3), where X_{ij} is the observed value of indicator j for assessment unit i, while X_j^{max} and X_j^{min} represent the maximum and minimum values of the corresponding indicator.

Weights of the indicators are allocated based on their ecological importance and sensitivity analysis.

Integrated Climate Vulnerability Assessment

These normalized climate, biodiversity, and adaptive capacity indices are then combined to measure ecological vulnerability. The evaluation is based on the assumption that vulnerability rises with climate exposure and ecological sensitivity, while it reduces with adaptive or conservation capacity. Vulnerability is thus formulated as:

$$V_i = w_E E_i + w_S S_i - w_{AC} AC_i \quad (4)$$

Equation (4), where V_i represents the vulnerability of assessment unit i, E_i represents climate exposure, S_i represents ecological sensitivity, AC_i represents adaptive or conservation capacity, and w_E, w_S, and w_{AC} represent their respective weights.

High vulnerability scores denote assessment units under higher levels of combined climate stress and ecological sensitivity when compared with the ability of such units to respond.

Biodiversity and Ecosystem-Service Linkage

The connection between the state of biodiversity and the state of ecosystem services is further assessed to see if there is a link between ecological degradation and the decreased supply of services. Methods of correlation and regression analysis could be employed based on the nature of the dataset that has been collected. The indicators of biodiversity are used as explanatory ecological variables, while the ecosystem service indicators are used as the outcomes of services.

Conservation Priority Assessment

Conservation priorities from ecological vulnerability and ecosystem service importance are generated at the last stage of analysis. The conservation priority index is derived by combining climate vulnerability, biodiversity importance, ecosystem service importance, and conservation potential:

$$CPI_i = w_V V_i + w_B B_i + w_{ES} ES_i - w_C C_i \quad (5)$$

Equation (5), where CPI_i represents the conservation priority of assessment unit i, V_i represents climate vulnerability, B_i represents biodiversity importance, ES_i represents ecosystem-service importance, and C_i represents conservation capacity.

Greater numbers reflect higher levels of conservation priority taking into account the combination of ecological and service attributes of the assessment unit.

Validation and Uncertainty Assessment

The robustness of the assessment approach is assessed through sensitivity and uncertainty analysis. Various weights and aggregations of indicators are investigated to see whether variations in methodological assumptions have a significant impact on vulnerability and conservation priority scores calculated. Where independent measurements and established ecological indicators exist, the outcomes of the assessment are compared with these measurements.

Conservation-Oriented Assessment Framework

Methodology of this kind encompasses the integration of individual analytical parts in a conservation-oriented sequence. Climate stressors act as the exposure element, while biodiversity indicators act as the indicator of ecological sensitivity, ecosystem-service indicators as an indicator of the impact, and conservation capacity as the response element. The obtained vulnerability analysis is followed by conversion into conservation priorities and possible management responses. This approach helps in linking the processes of environmental change with observable ecological impacts and further with the decision-making related to the conservation of ecosystems.

Figure 1 represents the suggested scheme of assessment, which incorporates the connection between climate stressors, like ocean warming, marine heat waves, acidification, and deoxygenation, biodiversity impacts, changes in ecosystem services, ecological vulnerability, and conservation priorities.

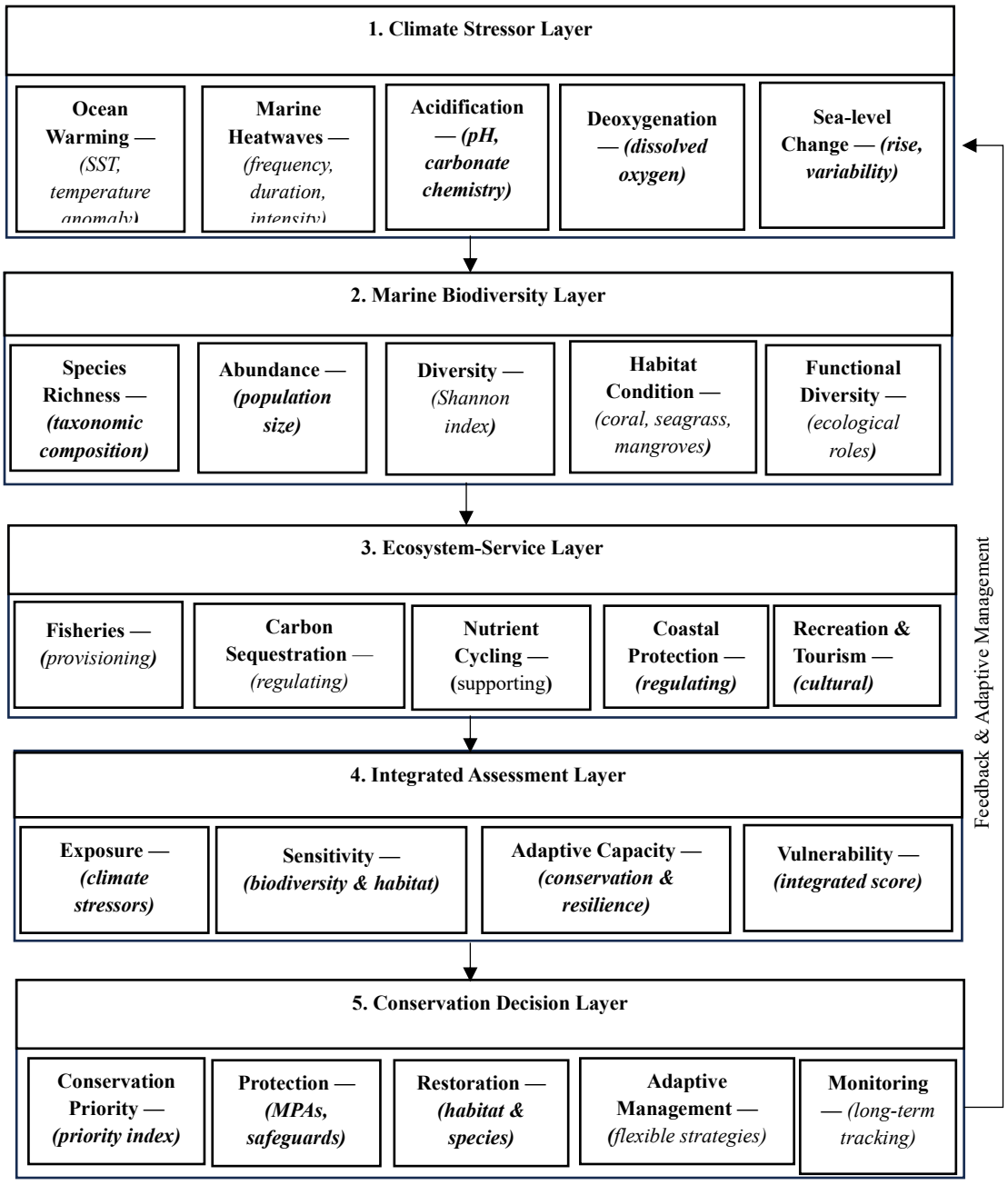


Figure 1: Integrated Conservation-Oriented Framework for Assessing Climate Change Effects on Marine Biodiversity and Ecosystem Services

IV. Results

Climate Stressor Assessment

Ocean warming, marine heatwaves, acidification, deoxygenation, and changes in sea level have been determined to be the major climate stressors. The standardized stressor assessment allows for comparison among the various components of an ecosystem by standardizing the environmental indicator to one scale. This combination of assessments will provide the foundation for assessing biodiversity vulnerability.

Marine Biodiversity Condition

The assessment of marine biodiversity status was based on parameters such as species richness, abundance, Shannon diversity, functional diversity, and habitat condition. Each of these measures adds complementary insights into changes in both taxonomic and ecological aspects. It is possible for the assessment system to incorporate differential sensitivities of biodiversity within the calculation of integrated vulnerability.

Ecosystem-Service Assessment

The evaluation included fisheries, carbon storage, nutrient cycling, coastal protection, and recreation as key services provided by ecosystems. The link between ecosystem services and the indicators of biodiversity helps to provide a more complete picture of the impacts of climate change on the ecology. Those ecosystems that contain high biodiversity and important ecosystem services become more significant in the following analysis.

Table 1: Integrated Climate, Biodiversity and Ecosystem-Service Assessment

Ecosystem component	Climate exposure	Biodiversity sensitivity	Ecosystem-service importance	Adaptive capacity	Vulnerability
Coral reef	0.82	0.88	0.85	0.42	0.64
Seagrass	0.74	0.76	0.72	0.55	0.48
Mangrove	0.68	0.72	0.80	0.63	0.39
Pelagic fisheries	0.79	0.70	0.92	0.50	0.50

As can be seen from table 1, coral reefs have the maximum climatic exposure (0.82) and biodiversity sensitivity (0.88), which is the reason for maximum vulnerability (0.64). The pelagic fisheries exhibit maximum ecosystem service importance (0.92) but with moderate vulnerability (0.50). The mangrove forests are least vulnerable due to their adaptive capacity (0.63).

Integrated Vulnerability Assessment

The integrated vulnerability analysis uses exposure, sensitivity, and adaptive capacity in order to determine the distinctions between the risks to ecology due to climate change. As can be seen from the results, vulnerability is affected not only by environmental factors, but also by ecosystem properties. This type of analysis gives a much more complete understanding than that of climate exposure and allows the interpretation of the conservation needs for specific ecosystems.

Conservation Priority Assessment

Priority for conservation was calculated using the combination of vulnerability, biodiversity importance, ecosystem services importance, and conservation capacity. The priority index identifies ecosystem components where there is an intersection between vulnerability and significant ecological or service values. The priority index generated from this is used as a basis for protection, restoration, adaptive management, and long-term monitoring.

Table 2: Conservation Priority Assessment of Marine Ecosystem Components

Ecosystem component	Vulnerability	Biodiversity importance	Ecosystem-service importance	Conservation capacity	Conservation priority
Coral reef	0.64	0.90	0.85	0.40	0.66
Seagrass	0.48	0.78	0.72	0.55	0.48
Mangrove	0.39	0.75	0.80	0.60	0.45
Pelagic fisheries	0.50	0.84	0.92	0.48	0.59

Coral reefs have a very high priority (0.66), characterized by vulnerability (0.64), biodiversity significance (0.90), and ecosystem service significance (0.85). Pelagic fisheries show a priority of 0.59 while seagrass and mangrove habitats have priorities of 0.48 and 0.45, respectively. The numbers above highlight differences in conservation needs in table 2.

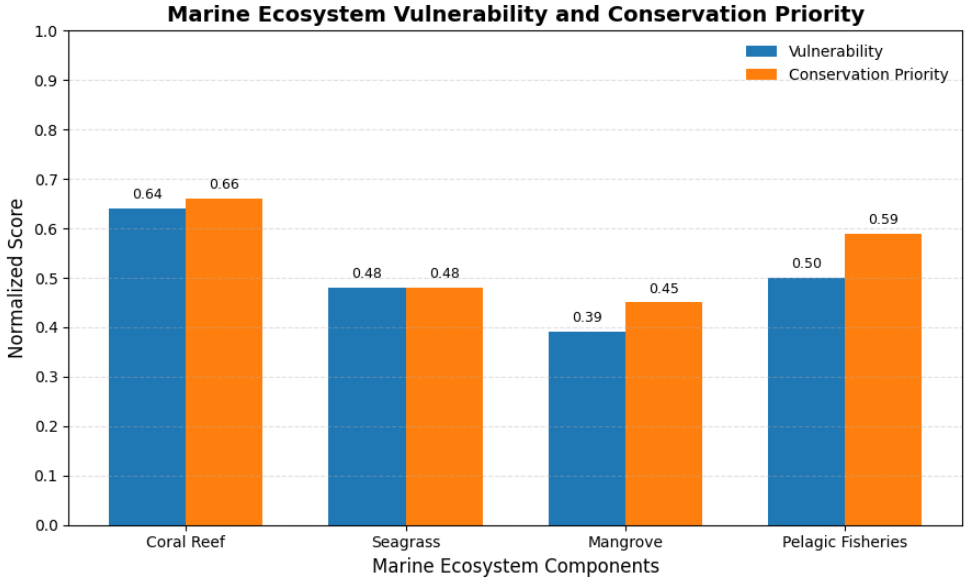


Figure 2: Marine Ecosystem Vulnerability and Conservation Priority

Figure 2 illustrates the vulnerability and conservation priority for different marine ecosystem components. Coral reefs have the highest vulnerability (0.64) and conservation priority (0.66) scores, followed by pelagic fisheries (0.50 and 0.59). Seagrass scored equally at 0.48, while mangroves have the lowest vulnerability (0.39) and priority (0.45) scores.

V. Discussion

Summary of Key Results

Climate vulnerability and conservation priority among marine ecosystem components were clearly illustrated through the assessment. Coral reefs had the highest climate exposure (0.82), biodiversity sensitivity (0.88), vulnerability (0.64), and conservation priority (0.66) scores. The pelagic fisheries had the highest ecosystem service importance (0.92) and vulnerability score (0.50), making their conservation priority score 0.59. The seagrass had vulnerability and priority scores of 0.48, whereas mangroves had the least vulnerability (0.39) and priority (0.45) scores.

This study shows that climate exposure does not dictate conservation priority on its own. Factors such as environmental stress, sensitivity of biodiversity, importance of the ecosystem services provided by a specific system, and the capacity for adaptation all play into the final analysis. Higher scores for corals show that they are highly sensitive to the combined climatic impacts, and the higher conservation priority for pelagic fisheries is attributed to their importance in terms of providing ecosystem services.

Implications

The results highlight the importance of adopting a conservation-focused approach to marine management. The combination of biodiversity, ecosystem services, and climate vulnerability may help target efforts aimed at protection, restoration, adaptive management, and monitoring. It can help stakeholders recognize those parts of the ecosystem that are vulnerable to climate change.

Limitations

The assessment can neither determine causality between climate drivers and changes in biodiversity without time series observations. The normalization of the scores and the weighting can also impact the resulting vulnerability and priority rankings. Hence, the sample outputs should not be seen as indicators of individual marine ecosystems.

Recommendations

Further research can use the same framework on data sets of site-specific monitoring for an extended period and various geographic locations. Another type of further research would be to use different weighting systems and analyze the influence of species-specific climate response functions. Future studies could also combine remote sensing, ecological modeling, and socioeconomic factors.

VI. Conclusion

The study responded to the requirement for an integrative method to determine the influence of climate change on marine biodiversity, ecosystem function, ecosystem services, and conservation needs. The conservation framework suggested in this research relates climate exposure, biodiversity sensitivity, ecosystem service significance, adaptability, vulnerability, and conservation priority into one assessment system. The findings showed the evident distinctions between the ecosystem elements. The coral reefs had the maximum climate exposure (0.82), biodiversity sensitivity (0.88), vulnerability (0.64), and conservation priority (0.66). Pelagic fishery exhibited the highest priority of ecosystem services (0.92), vulnerability (0.50), and conservation priority (0.59). The vulnerability and conservation priorities of seagrass were observed to be 0.48, whereas mangroves had the lowest vulnerability (0.39) and priority (0.45). The main lesson learned from this study is that climate exposure does not automatically imply conservation priority. Biodiversity sensitivity, ecosystem service value, adaptive capacity, and conservation capacity are equally important parameters to consider. Thus, the proposed approach can be used as a scientific basis for future marine conservation actions, adaptive management, and monitoring programs. Further studies need to use the presented framework in combination with remote sensing, modeling, and socioeconomic analysis of specific sites.

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