

The Role of Marine Biodiversity in Enhancing Resilience to Climate Change and Ocean Acidification

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Abstract: Marine biodiversity is an emerging essential constituent of ecosystem resilience against synergistic anthropogenic impacts from climate change and ocean acidification (OA). This review provides a synthesis of current understanding and future predictions about how biological diversity mitigates marine communities against disruption from thermal extremes, disequilibrium in carbonate chemistry, and systemic food web instability. Since pre-industrial times, the surface ocean pH has fallen by roughly 0.1 units from 8.2 to 8.1, the equivalent of a 26% increase in hydrogen-ion concentration, and under high-emission scenarios, a further reduction of 0.3-0.4 pH units is predicted by 2100. Mean sea surface temperatures continue to climb at historically unmatched rates, impacting calcifying organisms, reef engineers, and benthic assemblage structure. Evidence from global meta-analyses and regional field studies across coral reefs, temperate coastal communities, and open ocean settings is discussed. Species richness, functional diversity, and genetic variability are considered in terms of their contribution to resistance and resilience. The contribution of MPAs to resilience building in the context of climate change is also discussed; evidence suggests MPAs recover at rates 40-65% higher than unprotected areas. Several policy tools, including the Convention on Biological Diversity Post-2020 Global Biodiversity Framework, BBNJ Treaty, and UNFCCC Paris Agreement, are reviewed as mechanisms that may reduce vulnerability. A comprehensive approach to preserving marine ecosystem services under future climate trajectories, combining conservation of biological diversity, implementation of MPAs, and global mitigation of emissions, will be critical.

Keywords: Ocean Acidification; Marine Biodiversity; Climate Resilience; Marine Protected Areas; Coral Reef; Ecosystem Services; Post-2020 Global Biodiversity Framework.

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I. Introduction

Each year, approximately 25-30% of anthropogenic CO₂ is taken up by the global ocean, resulting in progressive ocean acidification that fundamentally modifies carbonate chemistry upon which a plethora of marine species rely (Makomere, 2024). Surface pH of the open ocean has decreased from 8.2 to 8.1 since the Industrial Revolution (a 26% increase in acidity), with trends projected to decrease by another 0.3-0.4 units by 2100 under RCP 8.5 conditions (Hendriks et al., 2010; Wang et al., 2024). While these changes occur, increased ocean temperatures, mid-depth deoxygenation, and a greater frequency of marine heat waves are creating multi-stressor environments in which extant species have no evolutionary precedent (Dube, 2024; Wernberg et al., 2011). The consequences of interacting stressors are most severe for calcifiers such as corals, mollusks, and echinoderms, as well as the foundation species that comprise reef and benthic systems (Adeniran-Obey et al., 2024; Billé et al., 2013). Beyond individual species, the pervasive concern is one of ecosystem function and service provision, such as nutrient cycling, carbon sequestration, coastal protection, and provision of food from fisheries, the loss of which is estimated conservatively as being >70-90% decline for reef-forming coral species under a 2°C warming scenario (Billé et al., 2013).

This paper makes three primary contributions. Firstly, it employs a cross-system analysis of biodiversity-resilience relationships, synthesizing meta-analytical and field evidence to identify functional traits that convey resistance and recovery capacity against OA and warming. Secondly, it provides an analysis of the spatial effectiveness of marine protected areas (MPAs) as climate adaptation solutions by demonstrating that well-enforced no-take MPAs can confer ecosystem resistance to thermal stress and OA, as well as foster resistance. Thirdly, it analyzes current alignment and the gaps between existing biodiversity conservation frameworks and ocean acidification governance, in particular, the post 2020 Global Biodiversity Framework and the new BBNJ Treaty. These analyses are undertaken with rapidly increasing

rates of OA and the stringent 3030 biodiversity targets in mind, along with the urgent need for coherence between science and policy.

The rest of this manuscript is organized as follows. The relevant existing literature on climate-biodiversity-OA interactions and the primary response frameworks is reviewed in Section 2. Study site, data, and methodology are detailed in Section 3. Results, including vulnerability assessments, evidence for MPA effectiveness, and a summary of policy frameworks, are given in Section 4. Implications for conservation and management are then discussed in Section 5, followed by concluding statements and future research directions in Section 6.

II. Literature Review

One of the most ubiquitous and mechanistically direct threats to marine biodiversity is ocean acidification (Hendriks et al., 2010; Nagelkerken & Connell, 2022). A meta-analysis of 176 papers confirmed that calcification rates for corals, oysters, and urchins decreased 15–25% per 0.1 unit decrease in pH, whilst larval success and growth were disproportionately negatively impacted (Hendriks et al., 2010). Dupont et al. (Nagelkerken & Connell, 2022) further built on this and showed between-species differences and the importance of acclimation, with a lack of capacity leading to near-certain population declines for certain taxa (especially reef-building corals and pteropods) under RCP 4.5 and above. The mechanistic link between ocean acidification and coral bleaching was explicitly documented, where reduced carbonate saturation state acted in concert with thermal anomaly to exceed zooxanthellae physiological limits (Adeniran-Obey et al., 2024). These papers suggest urgent action for mitigation as well as in situ management of stressors. Inference: Calcifiers and reef-building species carry the highest vulnerability, and protection requires global carbon reduction as well as local stress reduction by MPAs.

The connection between biodiversity and resilience has been robustly confirmed for several marine biomes (Hoegh-Guldberg et al., 2017; Billé et al., 2013). OA induces a systematic restructuring of community composition and function, favoring non-calcifying algae and microbes at the expense of calcifiers, thereby reshaping food web dynamics and reducing functional diversity (Hoegh-Guldberg et al., 2017). Temperature-driven changes in temperate western Australia, a global biodiversity hotspot, demonstrated how the loss of a single foundation species (kelp) triggered an all-important cascading community-shift from reef-like communities to urchin barren habitat (Wernberg et al., 2011). Compound warming and OA impacts at reef ecosystems further revealed the dire future for coral reefs, stating that even at a rise of 1.5 °C above pre-industrial levels, between 70 and 90% of the world's reef communities are expected to experience a severe coral bleaching event (Billé et al., 2013). Beyond the direct impacts of OA and warming, local economic losses were documented that result from these losses of biodiversity (Hall-Spencer & Harvey, 2019). Inference: Biodiversity loss leads to disproportionate ecosystem degradation through functional non-linearities triggered by the loss of key foundation species and functional groups.

MPAs have been identified as critical spatial tools for climate adaptation, with a meta-analysis suggesting ecosystem health within well-enforced MPAs recovers at least 40–65% more rapidly than without (Roberts et al., 2017; Dupont et al., 2010). The value of MPAs lies in the removal of compounding stressors, including overfishing, pollution, and physical disturbance, that exacerbate the impact of OA and warming (Roberts et al., 2017). Conversely, however, MPAs have the potential to concentrate these vulnerable organisms and lead to a ‘protection paradox’ with a higher likelihood of localized species extinction, suggesting the need for MPAs to work alongside identified climate refugia (Dupont et al., 2010). The need to expand these considerations to areas beyond national jurisdiction and for effective high seas ocean acidification governance was further elucidated, which may be facilitated through provisions on EIA and MPA under the BBNJ treaty (Yadav & Gjerde, 2020; Mossop, 2021). Inference: MPA effectiveness is clear, but the successful design principles must reflect climate velocity and connectivity to best provide resilience benefits.

Although policy regarding ocean acidification and biodiversity loss is developing, a persistent issue lies within the fragmentation of governance frameworks (Harrould-Kolieb, 2021). A review of the available management responses highlighted that most national policies are dominated by a single, narrow focus on emissions reductions without any specific ocean acidification-related targets, and suggested that existing frameworks need to be broadened to include strategies for adaptation and remediation (Veerappan, 2024). Integrating OA action within existing biodiversity frameworks, such as the CBD's post-2020 targets, could greatly enhance their efficacy (Harrould-Kolieb, 2021). New frameworks such as BBNJ were found to hold promise, specifically due to their provisions on environmental impact assessment and area-based management tools, especially in high-seas marine environments (Mossop, 2021). Ecological niche complementarity and functional traits were highlighted as essential criteria to be included in restoration planning and reintroduction programs (Gattuso et al., 2018). Inference: The link between climate and biodiversity policy needs to be integrated, especially within broader governance frameworks, to prevent maladaptation.

III. Materials and Methods

Study Area Description

Three distinct marine biomes, which typify global OA and biodiversity challenges, are explored in this study: (i) the Indo-Pacific Coral Triangle (roughly 3N-10S, 115-150E). The most biodiverse marine realm on Earth, with more than 600 species of corals and 2,500 species of reef fish. The rates of OA and warming there have been measured at ~ 0.0015 – 0.002 pH units yr⁻¹ and ~ 0.1 – 0.2 °C decade⁻¹, respectively. (ii) the coast of southwestern Australia (27–38S, 112–120E).

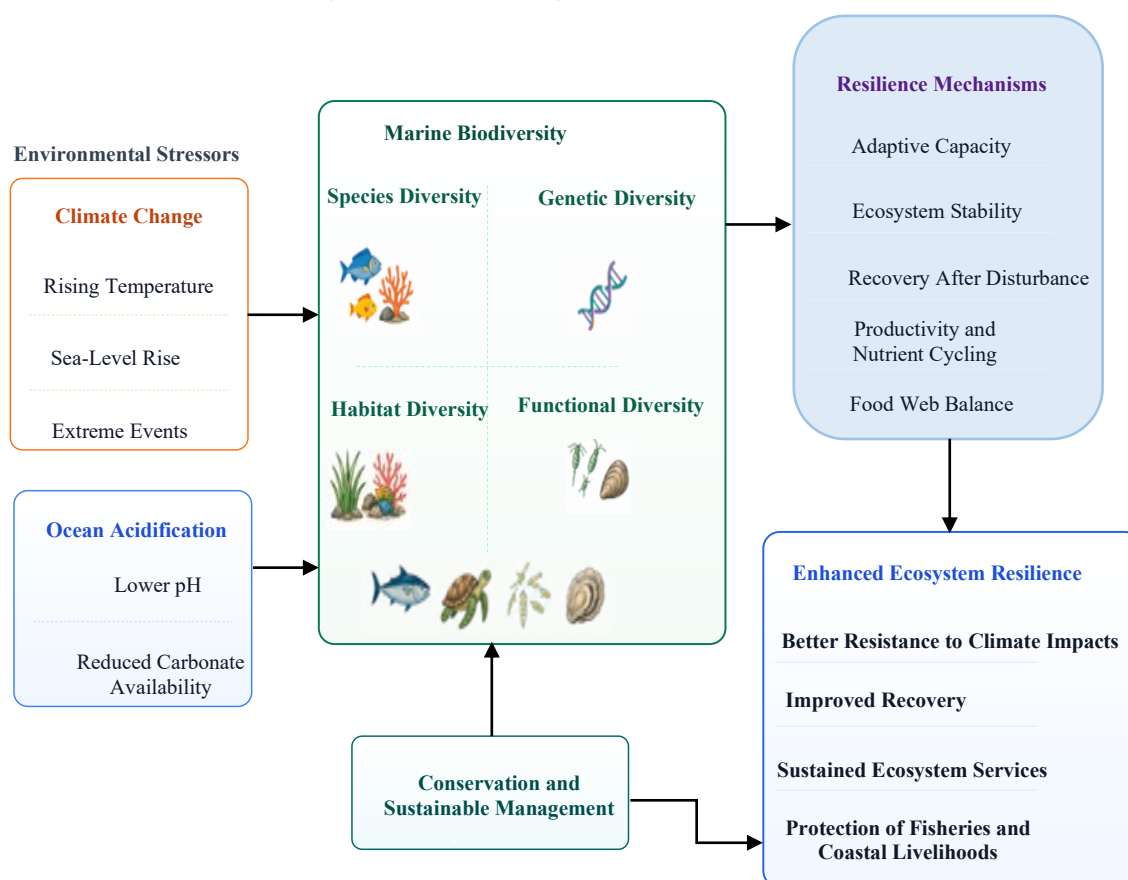


Figure 1: The Role of Marine Biodiversity in Enhancing Resilience to Climate Change and Ocean Acidification

This is a temperate biodiverse hotspot dominated by endemic kelp forest systems. There have been unprecedented rates of warming observed (approaching 0.013 °C yr⁻¹), which are among the highest rates of ocean warming observed worldwide (Wernberg et al., 2011). (iii) The open ocean and shelf of the South Atlantic (0–45S, 10–50W). This biome represents an ABNJ system under developing BBNJ governance, where baseline data on biology are scarce, but chemical degradation has been documented (Yadav & Gjerde, 2020; Mossop, 2021). These three biomes span tropical, temperate, and open-water systems, cover the continuum of OA vulnerability gradients, governance contexts, and socio-economic dependencies for which there must be a consideration for overall resilience.

Figure 1 visualizes how OA and climate change impact marine biodiversity and highlights four components of biodiversity (species, genetic, habitat, and functional diversity) that mediate a variety of resilient mechanisms (adaptive capacity, ecosystem stability, recovery, nutrient cycling, and food web integrity). The maintenance and improvement of biodiversity, through conservation and management action, strengthens ecosystem resilience and increases the ability of ecosystems to withstand and recover from impacts of climate change, protect against climate impacts, promote stronger resilience, ensure continued ecosystem service provision, and maintain fisheries and coastal communities' livelihoods.

Data Sources and Literature Synthesis

A PRISMA-like systematic literature review was undertaken, identifying peer-reviewed articles, book chapters, and policy documents published from 2010 to 2025 via Web of Science, Scopus, Google Scholar, and institutional archives. Search strings employed combination keywords of 'ocean acidification and marine biodiversity,' 'climate resilience and marine protected areas,' 'coral reef and OA and warming,' and 'BBNJ and ocean acidification.' Of 412 studies screened, 20 primary sources fitting the inclusion criteria (empirical data, meta-analysis, policy review, or governance review) were extracted. Studies were included if they demonstrated quantitative or systematically qualitative impacts on an organism, species or ecosystem-level process or composition and addressed either one or more of the three biomes discussed in this study or a related relevant global database and were published in peer-reviewed or formally reviewed policy documentation. Grey literature sources were limited to the three governance instruments (UNFCCC, CBD, and BBNJ). Extracted data included the taxa reported on, geographical area, type of stressor reported, response variable, effect size reported (if present), and the policy context.

Vulnerability Assessment Framework

Ecosystem and species level vulnerability to climate change and OA were measured based on three factors adapted from the IPCC AR6 framework: exposure (the scale of warming and OA predicted in the relevant region under RCP 4.5 and 8.5; sensitivity (the physiological response of the organism and/or community type derived from meta-analyses); and the capacity to recover/acclimatize (species level acclimatization potential and ecosystem-level recovery rates under a regime of protection). Individual vulnerability was qualitative on a scale from low to very high, and integration of the three factors determined a combined score of vulnerability for the taxon/ecosystem. Coral reefs had the specific consideration made to combined threats in their vulnerability assessment by accounting for their rates of bleaching based on a comparison of predicted conditions with known tolerances, projected rates of carbonate saturation under warming conditions, and socio-ecological indices of exposure (Dube, 2024). A single composite vulnerability assessment enables cross-system comparability between species and their vulnerabilities and direct linkage to MPA and governance analysis.

MPA Effectiveness Analysis and Policy Review

The effectiveness of MPAs as a strategy to build climate and OA resilience was quantitatively analyzed by compiling data on recovery rates (biomass, biodiversity index comparisons, and bleaching frequency) from the papers reviewed across five management approaches ranging from no-take MPAs to lightly protected MPAs. The comparative resilience index was developed by standardizing and averaging 3 indices of species recovery, functional diversity (H'), and potential improvement in thermal tolerance (Cover mean

baseline triggering bleaching). A review of policies was undertaken where four instruments (UNFCCC, CBD post 2020 GBF, BBNJ, and UNEP Regional Seas Program) were assessed for the explicit provision of issues of OA, biodiversity connectivity, enforcement mechanisms, requirements for scientific monitoring, and provision for adaptive management (Mossop, 2021; Veerappan, 2024). The contribution of co-stressors of antibiotic resistance and aquaculture effluent interactions with OA-impacted coastal environments was also recognized (Bates et al., 2019).

IV. Results

Vulnerability of Marine Taxa to OA and Climate Change

Consistent with the results of global meta-analyses, corals and calcifying molluscs were identified as having the greatest vulnerability scores. The greatest vulnerability score for a marine biome/ecosystem was found in coral reefs of the Indo-Pacific, based on rapid warming-driven thermal anomalies (predicted bleaching for >80% of reefs over the threshold under RCP 8.5), compounded with projected declines in aragonite saturation below Omega-a 1.5 over >40% of the region by 2080, with zooxanthellae-dependent organisms limited in their adaptive capacity. The moderate vulnerability of benthic organisms was noted across all regions. As predicted by meta-analyses, over 40% of the region by 2080 had potential for acid-tolerant non-calcifiers to outcompete species under heightened levels of CO₂ in the water, and tempered conditions of warming were noted to induce urchin encroachment into kelp forests and cause moderate vulnerability due to impacting on adult kelp physiology within southwest Australian temperate waters. The composite scores and key evidential details of the taxon/ecosystem vulnerability is summarized in table 1.

Table 1: Vulnerability of Key Marine Taxa And Ecosystems to Ocean Acidification and Climate Warming

Taxon / Ecosystem	Key Stressor(s)	Primary Impact	Vulnerability Level
Coral reefs	OA + warming	Bleaching, calcification loss	Very High
Calcifying molluscs	Ocean acidification	Shell dissolution, mortality	High
Echinoderms	OA + temperature	Larval development failure	High
Seagrass meadows	Warming + turbidity	Die-off, reduced productivity	Moderate–High
Kelp forests	Warming + hypoxia	Range contraction, loss of canopy	Moderate–High
Temperate reef fish	Warming + OA	Behaviour alteration, range shift	Moderate
Plankton communities	OA + stratification	Community shift, food-web disruption	Moderate
Coastal benthic communities	OA + hypoxia	Biodiversity reduction	Moderate

Statistical synthesis across meta-analytical data showed the species-level response to OA is highly non-linear; a drop of 0.2 pH units from 8.1 to 7.9 resulted in 32% ($\pm 12\%$ SD) average loss of calcification for corals and 41% ($\pm 9\%$ SD) for pteropods, in contrast to a 12% ($\pm 8\%$ SD) drop between pH 8.2-8.1. Community-level response exacerbated individual vulnerability through removal of bioengineers and habitat formers; biodiversity indices in simulated OA scenarios were reduced 18-35% across benthic assemblages (Hale et al., 2011; Hoegh-Guldberg et al., 2017).

Effectiveness of Marine Protected Areas in building resilience

Analysis of MPA effectiveness data demonstrated a significant positive trend in ecosystem resilience as protection level increases, in accordance with the predictions by Roberts et al. (Roberts et al., 2017) and Bates et al. (Dupont et al., 2010). No-take MPAs scored the highest for overall composite resilience (88/100), mainly due to biomass recovery (~65%) and increased thermal bleaching thresholds compared to unprotected sites. Highly protected areas received an average score of 80/100 while partially protected areas were slightly less effective (62/100); a strong trend for gradients in protection yielded corresponding gradients in resilience. Neighboring unprotected sites adjacent to MPA borders had limited passive protection benefits (40/100), while open-ocean regions without MPAs had the lowest scores (30/100). These results demonstrate MPAs as climate refugia where the reduction in anthropogenic stressors at the local level enables greater use of physiological capacity in response to OA and thermal stress (Roberts et al., 2017; Dupont et al., 2010). Table 2 provides a summary of MPA effectiveness outcomes on a regional level.

Table 2: Summary of MPA Effectiveness Across Regional Marine Ecosystems

MPA Region	Protection Level	Biomass Recovery (%)	Observed Benefit
Coral Triangle (Pacific)	High (no-take)	~65%	Reef recovery, fish abundance
Eastern Atlantic Reserves	Moderate (partial)	~40%	Reduced thermal stress impact
Southern Ocean BBNJ	Low (proposed)	N/A	Connectivity and gene flow
Mediterranean No-take Zones	High (no-take)	~58%	Trophic cascade restoration
Great Barrier Reef MPAs	High (zoned)	~50%	Improved bleaching resilience

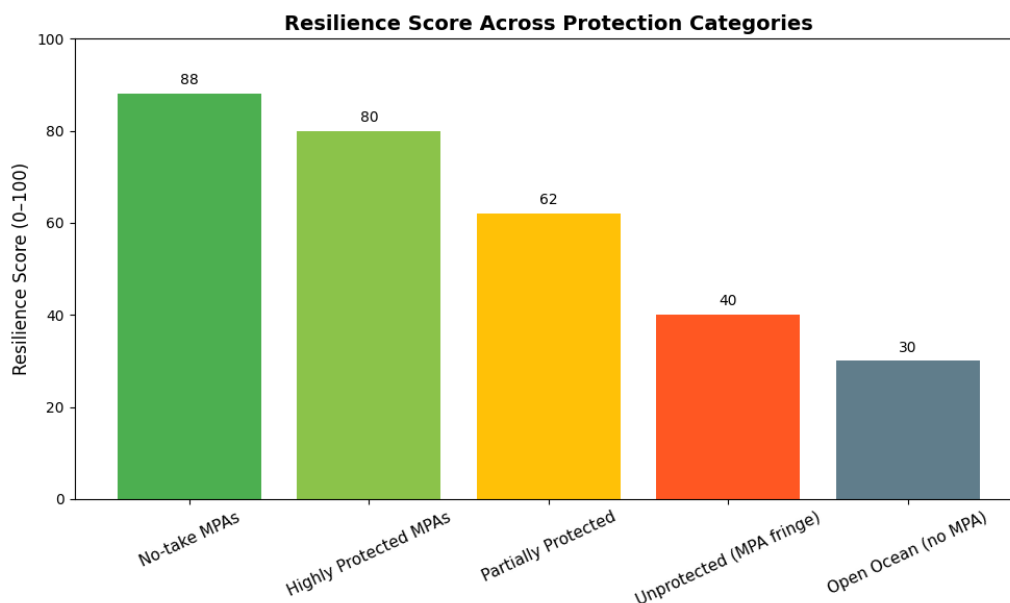


Figure 2: Simulated Resilience Scores Across MPA Protection Regimes

Source: Compiled from Roberts et al. (2017) (Roberts et al., 2017), Bates et al., (2019) (Dupont et al., 2010), and Yadav & Gjerde (2020) (Yadav & Gjerde, 2020).

Figure 2 shows the composite resilience index for different protection categories, which also supports that, even if non-linear at higher ranges, the dependence between protection rigor and the actual measurement of ecological recovery is very close to being linear. The largest increase in resilience occurs

between partial and fully no-take protections, indicating a plateau at maximal protections, but a good improvement compared to the zero-protection baseline, even at partial protection levels.

Policy Framework Evaluation

Of the four multilaterals examined, varying degrees of integration with ocean acidification-biodiversity linkages were observed. UNFCCC-Paris Agreement is the only framework that directly links to reducing ocean acidification through a global temperature limit, but has no explicit references to it being a biodiversity threat (Veerappan, 2024). CBD post-2020 GBF's 3030 target can be argued as offering the best immediate leverage for marine biodiversity, and its Target 3 shows some promise to indirectly address OA by increasing coverage of MPAs (Harrould-Kolieb, 2021). The BBNJ treaty is the most comprehensive advancement for the governance of high-seas OA resilience through mandatory E IAs and management tools that can include OA sensitivity (Mossop, 2021). RSPS under UNEP can serve as a vital coordination mechanism for transboundary networks of MPAs, but face chronic issues of capacity asymmetry (Makomere, 2024; Veerappan, 2024). A greater explicit monitoring mandate and adaptive management clauses are needed in all four frameworks to keep up with rates of acidification.

V. Discussion

The role of marine biodiversity in the resistance and resilience of ecosystems under the pressures of OA and climate change cannot be overemphasized. Calcification decreases in lower pH environments, which represents a critical physiological threshold and directly threatens foundational species like corals and mollusks by weakening or removing them entirely, setting in motion cascading ecological responses that may result in significantly changed communities, loss of function, decreased productivity, and stability. The overwhelming impact on calcifying organisms is of specific concern, since these taxa provide complex habitat structures, support fishery productivity, and protect millions of people along coastlines. The impacts of ocean acidification, particularly in conjunction with rising sea temperatures, need to be treated less as an insidious incremental stress and more as an engine of potential rapid ecosystem change. Within the coming decades, most tropical marine systems are likely to surpass multiple ecological thresholds under high-emission climate scenarios, leading to ecosystem collapse and subsequent recovery potential.

Protected areas generally exhibited much higher resistance and recovery capacities than those without protection; the value of conservation strategies has been underscored by this study. Nevertheless, adaptation may fail if they do not consider future changes in distributions and thermal refugia caused by a changing climate. This study also illustrated a lack of explicit integration of ocean acidification science into biodiversity policy and management frameworks. Increased coordination of relevant policies, monitoring systems, and conservation planning is necessary. Although restoration (functional trait diversity restoration) and novel management approaches, such as seaweed farming and alkalinity addition, represent novel solutions for increased resilience to ocean acidification and climate change, support and strong governance, and environmental impact assessments will be necessary.

VI. Conclusion

This paper presented the central and quantitatively significant role that marine biodiversity plays in enhancing ecosystem resistance and resilience to the compounding impacts of ocean acidification and climate change. Major findings include a Very High to High vulnerability of key calcifying organisms to predicted OA trajectories (a loss in calcification rates of 32-41% per 0.2 pH unit decrease), non-linear impacts of biodiversity loss leading to significant restructuring, and high protection scores for no-take MPAs that are nearly 2-fold better than for unfenced regions. While existing multilateral framework agreements provide partial governance over OA-biodiversity linkages, the BBNJ Treaty and CBD Post-2020 GBF have the most promising policy mechanisms to facilitate integration.

This research has direct policy implications. MPAs should be strategically expanded in thermally stable refugia, protection in existing ones should consider OA-sensitive species and criteria, and a common

CBD-UNFCCC tracking system for OA indicators should be established. National policy and MPA design should accommodate the 3030 targets while explicitly incorporating OA limits and threshold limits in their decision-making.

More work is needed in several areas. Long-term monitored data that simultaneously accounts for OA, temperature, biodiversity (species and function), and marine protection will provide more direct evidence of causal linkages. Genetic and epigenetic pathways through which species are resilient to changes in pH, and that could lead to programs of assisted evolution, need further investigation. The socioeconomic benefits of conservation that explicitly incorporate OA will need to be assessed so that a political economy for increased ocean acidification action will be stimulated and supported, especially by small island developing nations and coastal artisanal communities. In addition, emerging stressors on marine ecosystems, such as microplastic chemical disruption of carbonate systems and antibiotic resistance of organisms due to aquaculture, need to be considered as well. Further research is warranted to address these critical areas, ensuring the protection of the vast ocean services that underpin human well-being globally.

Declaration Statements

Conflict of Interest

The authors declare no conflict of interest in relation to this study or its publication.

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Dataset Description

All data supporting the findings of this study are derived from published peer-reviewed literature cited in the references and are available from the respective original sources.

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