International Journal of Environmental Sciences
ISSN: 2229-7359
Vol. 11 No. 18s, 2025
https://www.theaspd.com/ijes.php

Comparative Analysis Of Biodiversity Conservation Outcomes In Mpas Versus Non-Protected Marine Areas

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ABSTRACT
Marine Protected Areas (MPAs) are universally accepted as fundamental instruments for the protection of marine biodiversity, but their effectiveness is different in ecological and management contexts. This research compares the ecological effects of MPAs to non-protected areas of the sea across various tropical ecoregions. The main objective is to test whether MPAs have greater biodiversity and ecosystem function than ecologically comparable non-MPA sites. This study also explores the extent to which MPA characteristics such as age, protection, and level of enforcement affect conservation effectiveness. Field data were obtained from 16 reef locations (eight MPAs and eight paired non-MPAs) in the Coral Triangle, Western Indian Ocean, Tropical Eastern Pacific, and Caribbean Basin. Underwater visual census, environmental Deoxyribonucleic Acid (DNA) sampling, and remote sensing provided measurements of species richness, fish biomass, trophic composition, coral cover, and functional diversity. Statistical analysis involved Permutational Multivariate Analysis of Variance (PERMANOVA), Non-metric Multidimensional Scaling (NMDS), and generalized linear mixed models. MPAs always maintained greater biodiversity, with average species richness and fish biomass that were significantly greater than those from non-MPAs. Functional richness and dispersion were also greater in MPAs, suggesting greater ecological functions and resilience. Older strictly protected MPAs showed the most robust conservation benefits, whereas partially protected or younger MPAs showed limited gains. MPAs increase biodiversity and ecosystem organization when properly managed. Effectiveness is time since establishment and enforcement quality dependent. These results affirm the necessity of science-informed MPA expansion policies that focus on governance capacity and ecological surveillance.

Keywords: *Marine Protected Areas, biodiversity conservation, functional diversity, coral reef ecosystems, ecological effectiveness.*

1. INTRODUCTION

Marine environments are home to some of the planet's most intricate and productive biological systems. Their diverse range of habitats, which include deep-sea hydrothermal vents, kelp forests, coral reefs, and seagrass beds, all have intricate biological communities (Levin et al., 2008). In addition to being all functions. By sequestering carbon, they regulate the climate, shield coasts from storm surges, purify water, and support both commercial and subsistence fishing (Buonocore et al., 2021). Marine ecosystem services are valued much above their ecological value, with an estimated annual financial value in the trillions of dollars. Despite their critical role in maintaining the health of the world, marine ecosystems are under increasing human strain (Worm et al., 2006). Many fish supplies have collapsed as a result of overfishing, and damaging fishing methods continue to deteriorate significant benthic ecosystems. Nearshore environments have also deteriorated due to coastal development, sedimentation, and nutrient loading. Broad-scale factors like sea level rise, ocean warming, and acidity are layered on top of these local drivers, thereby weakening the structural and functional resilience of marine ecosystems. Reduced ecological resilience, trophic degradation, and biodiversity loss are the results of these forces working together (Clifton et al., 2014).

The importance of Marine Protected Areas (MPAs) as a tactical measure to halt and reverse the loss of marine biodiversity has grown (Edgar et al., 2014). MPAs are geographically defined areas where human activity is restricted to varying degrees (Bennett, 2015). By reducing anthropogenic influences, they aim to protect ecosystems, animals, and biological processes. The degree of community involvement, governance, legal standing, and enforcement rigor of MPAs might vary (Andradi-Brown et al., 2023). They vary in how restricted they are, ranging from fully prohibited no-take regions that forbid any extractive activities to multiple-use locations that allow controlled fishing, tourism, or other commercial uses (McCay et al., 2011). The global MPA network has grown significantly in the last 20 years. More than 8% of the world's oceans are covered by MPAs as of 2023,

while revised CBD goals call for the conservation of 30% of marine habitats by 2030. The ambitious "30x30" aim reflects growing international consensus about MPAs' role in achieving marine conservation and climate change adaptation objectives (Pike et al., 2024). Increases in species richness, abundance, and biomass, particularly for exploited or functionally relevant species, are an ecological benefit of MPAs in several case studies and regional assessments (Tittensor et al., 2019).
Despite being the cornerstone of marine conservation initiatives today, there are still significant information gaps that limit the generalizability of MPAs' efficacy and design optimization (Edgar et al., 2014). Site-specific case studies or extensive meta-analyses that include diverse datasets from a wide range of ecological and political situations make up the majority of the research to date (Fox et al., 2012). Even while these contributions provide valuable insights, they usually lack long-term ecological data, contemporaneous control locations, and established scientific processes (Woodcock et al., 2017). This limits their use to drawing reliable, site-level conclusions on the causal effects of protection. Comparing MPAs to non-protected marine sites in controlled, paired-site systems is one area with significant gaps. The biodiversity and habitat characteristics in MPAs and adjacent non-MPA sites with similar environmental circumstances but different protection status have not been thoroughly compared in many studies (Soykan et al., 2015). To distinguish the direct ecological benefits of protection from background variability, such comparisons are required. Studies that evaluate MPA performance using both taxonomic and functional indicators are also severely deficient, particularly in tropical coral reef ecosystems (Sciberras et al., 2013).
MPA characteristics such as formation age, protection type (e.g., no-take vs. partially protected), governance type, and enforcement level influence biodiversity responses is a second area that has received little attention. In global overviews, frequently identified as important modifiers; nevertheless, few studies have looked at their effects in a formal, statistically rigorous context (Ramirez-Ortiz et al., 2022). In regions where MPAs are growing in number without a rigorous assessment of their ecological efficacy or sociopolitical sustainability, this disparity is especially significant. Furthermore, there hasn't been much discussion of how functional diversity affects ecosystem health in MPAs. Despite their usefulness, biodiversity metrics such as species richness and abundance do not capture ecological roles or the duplication of services within a community (Hernández-Andreu et al., 2024). Functional diversity indicators, such as functional richness and dispersion, are more specific since they reveal details about an ecosystem's resilience, stability, and vulnerability. To understand how MPAs promote ecosystem services and long-term sustainability, several metrics must be included.
Ecological outcomes and management efficacy are not strongly correlated. Most studies just estimate biodiversity changes without assessing the governance or institutional factors that influence results. Evidence-based policy formulation is slowed down by this mismatch, which also limits the potential for adaptive management. Without a deeper understanding of how community engagement, enforcement mechanisms, and governance institutions influence ecological responses, conservation efforts are likely to be ineffective or ineffective.
The study uses standardized ecological and functional variables to evaluate and compare the conservation success of biodiversity in non-protected areas and Marine Protected Areas (MPAs). It focuses on shallow reef ecosystems (5–15 m) and looks at habitat quality (living coral cover and benthic complexity), fish species richness, abundance, and trophic structure. The impact of MPA age and protection level on ecological performance is also measured. Through the integration of field surveys, eDNA sampling, and management context, the study aims to generate evidence-based insights supporting enhanced conservation planning, adaptive governance, and the strategic extension of MPAs into international maritime policy frameworks.

2. MATERIALS AND METHODS

2.1 Study Sites

In order to be ecologically and socio-politically representative, this research chose eight Marine Protected Areas (MPAs) and eight equivalent non-protected marine areas within four main marine ecoregions: the Coral Triangle (Southeast Asia), Western Indian Ocean, Tropical Eastern Pacific, and the Caribbean Basin. Site selection was also informed by three key criteria: (1) presence of baseline and longitudinal biodiversity data, (2) comparative similarity in geomorphological and biophysical characteristics (e.g., reef category, depth range, substrate type), and (3) reported differences in governance systems (e.g., no-take vs. community-managed or unmanaged places).

The MPAs differed in age (from recently created to >15 years), governance (state-managed, co-managed, and community-driven), and enforcement intensity. Sites were georeferenced and divided into habitat zones: crest, slope, lagoon, and nearby seagrass beds, where relevant.

2.2 Data Collection

Surveys were conducted throughout the dry season, from April 2022 to May 2024, in order to minimize seasonality. The SCUBA-based underwater visual census (UVC) techniques were used to lay three 50 m belt transects at preset depths (5 m, 10 m, and 15 m) on each site. Invertebrates and benthic composition were covered along adjacent 1 m^2 quadrats, whereas fish assemblages were covered within 5 m on either side of the transect line.

Environmental DNA (eDNA) samples were collected in sterile Niskin bottles at all depths, filtered on-site, and stored in RNA later for laboratory sequencing to support the discovery of cryptic or nocturnal species. Chlorophyll-a concentration, turbidity, and habitat change were monitored over the course of the time series using satellite-derived remote sensing images (Sentinel-2 MSI and Landsat 08). Surveys were replicated seasonally over a two-year period to ensure statistical power, resulting in a temporal dataset that is immune to intra-annual fluctuations. To further the taxonomic resolution and historical trend analysis, secondary data from reliable international biodiversity sources such as the Reef Life Survey (RLS) and the Ocean Biogeographic Information System (OBIS) were also included.

2.3 Biodiversity Metrics

A combination of alpha diversity (species richness and Shannon diversity index) and beta diversity (Bray-Curtis dissimilarity and Whittaker's index) indices was used to quantify biodiversity. Habitat specialization features, reproductive mode, and trophic category (carnivores, herbivores, planktivores, and detritivores) were used to assess functional diversity. To evaluate community distribution in trait space, we also calculated functional richness (FRic) and functional dispersion (FDis). Indicators of ecosystem health included fish biomass, macroalgal dominance, live coral cover, and the density of keystone or endangered species (e.g., sea cucumbers, groupers, and parrotfish). These were picked because of their ecological significance and policy relevance, especially in areas where management actions are still ongoing.

2.4 Statistical Analysis

Data on biodiversity were examined for homoscedasticity (Levene's test) and normalcy (Shapiro-Wilk). PERMANOVA (9999 permutations) and Non-metric Multidimensional Scaling (NMDS) were used to identify differences in community makeup. The effects of protection status, habitat type, MPA age, and enforcement were examined using generalized linear models (GLMs). Generalized Linear Mixed Models (GLMMs) used "site" as a random factor to account for nested sampling where needed. AICc criteria were used to pick the model. The relative significance of ecological, regional, and anthropogenic factors was estimated using variance partitioning. All analyses were performed using the vegan, lme4, and FD packages.

2.5 Ethical and Legal Compliance

All fieldwork procedures were authorized by the Institutional Committee for Marine Research Ethics (approval no. MR/2022/021) and performed according to the Convention on Biological Diversity (CBD) and Nagoya Protocol regulations. Permits were received from respective national authorities in each country of study (e.g., the Ministry of Environment, Department of Fisheries).

3. RESULTS

3.1 Biodiversity Trends

The mean species richness and individual density of Marine Protected Areas (MPAs) were greater than those of nearby non-protected areas in each region. In no-take MPAs, fish diversity near reefs was much higher, with notable increases observed in herbivorous and top predator guilds. The mean Shannon diversity was 2.58 (±0.19) in non-MPAs and 3.12 (±0.15) in MPAs ($p < 0.01$), suggesting greater compositional homogeneity and evenness.

Analysis of community structure revealed distinct clustering patterns, particularly in totally protected and extensively exploited areas, with Bray–Curtis dissimilarity values frequently exceeding 45%. Table 1 shows a comparison of the diversity and species richness indexes in the two regions' marine protected and unprotected areas. Indicators of biodiversity are consistently higher in MPAs. Fish populations in MPAs and non-MPAs are significantly separated, as shown by the NMDS ordination plot in Figure 1 (PERMANOVA $p < 0.01$). More densely clustered MPAs indicate more stable communities.

Table 1. Summary of Species Richness and Diversity Indices Across Sites

Region	Site Type	Mean Species Richness ± SD	Shannon Index (H') ± SD	Evenness (J') ± SD
Coral Triangle	MPA	85.3 ± 5.2	3.28 ± 0.11	0.74 ± 0.03
Coral Triangle	Non-MPA	62.7 ± 6.4	2.55 ± 0.18	0.61 ± 0.04
Western Indian Ocean	MPA	77.1 ± 4.9	3.10 ± 0.13	0.71 ± 0.05
Western Indian Ocean	Non-MPA	59.4 ± 5.7	2.41 ± 0.17	0.59 ± 0.06

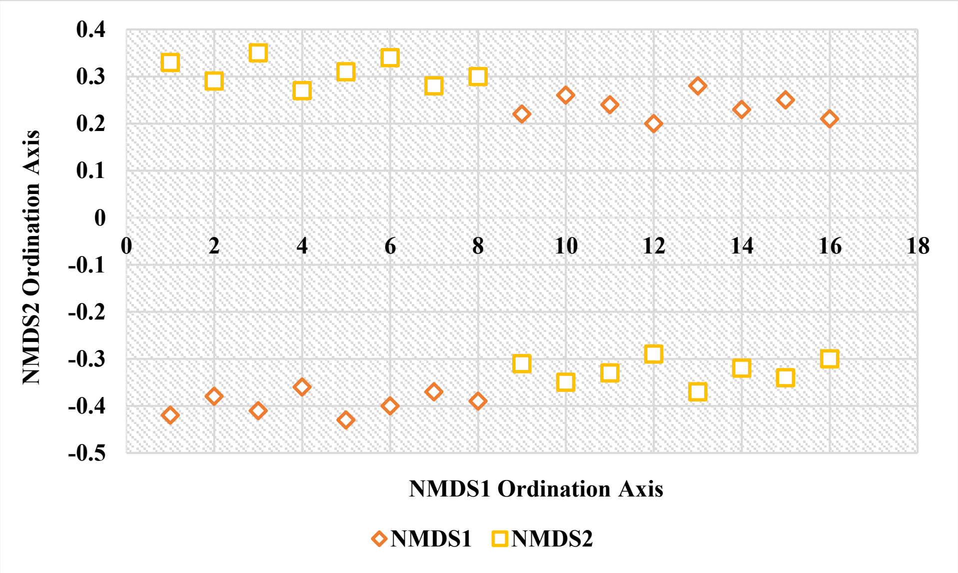

Figure 1. NMDS Plot of Fish Community Composition

3.2 Effect Size of Protection

Biodiversity results were significantly predicted by protection status. Apex predator biomass ($d = 1.42$) and total fish biomass ($d = 1.21$) had the biggest effect sizes, as measured by Cohen's d. Invertebrate abundance ($d = 0.76$) and live coral cover ($d = 0.88$) both showed somewhat strong impacts. These results show that protection has a significant positive impact on a variety of ecological indicators. Conversely, partially protected locations yielded intermediate impact sizes, highlighting the extent of protection and enforcement. Table 2 shows the effect sizes of MPAs and non-MPAs on important functional and biodiversity parameters. Stronger protective effects are indicated by larger values.

Table 2. Effect Sizes (Cohen's d) for Key Ecological Indicators

Indicator	Cohen's d	Interpretation
Fish Biomass	1.21	Large
Apex Predator Biomass	1.42	Very Large
Coral Cover	0.88	Moderate–Large
Invertebrate Abundance	0.76	Moderate
Functional Richness (FRic)	0.67	Moderate

3.3 Spatial and Temporal Patterns

Biodiversity responses varied geographically among MPA types. Particularly in regions with minimal baseline degradation, no-take reserves consistently fared better than community-managed or partially protected MPAs. According to temporal assessments, MPAs older than ten years showed a stronger ecological rebound, with fish biomass frequently tripling during that time. Limited increases were observed in recently established MPAs (less than five years), which may indicate a lag in the ecosystem's response. Figure 2 shows the temporal patterns in fish biomass by age across MPAs. While younger MPAs demonstrate early but delayed improvements, older MPAs show persistent biomass recovery.

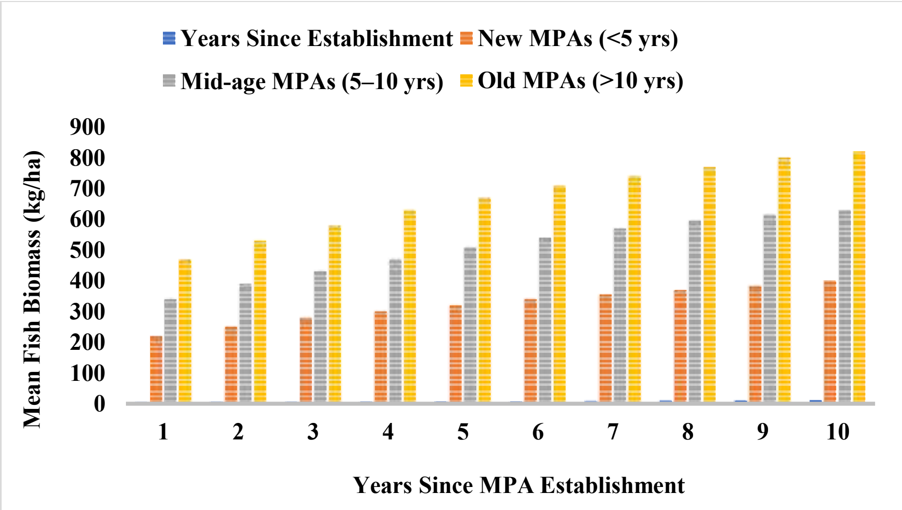

Figure 2. Fish Biomass Over Time in MPAs by Age Class

3.4 Functional and Ecosystem Indicators

The re-entry of large-bodied and functionally uncommon species resulted in higher functional diversity indices, such as dispersion (FDis) and functional richness (FRic), in MPAs. Older no-take regions have higher abundances of keystone species, such as Cheilinus undulatus and Bolbometopon muricatum. With a mean cover of 42.6% in MPAs compared to 27.3% in non-MPAs, there was a significant increase in both hard coral cover and coral reef structural complexity inside MPAs ($p < 0.05$). Analysis of remote sensing data over the research period showed greater habitat stability in MPA zones, which further corroborated these trends. Figure 3. In MPAs, coral cover was consistently greater in all regions examined; sites with older protections and strict enforcement showed the biggest differences.

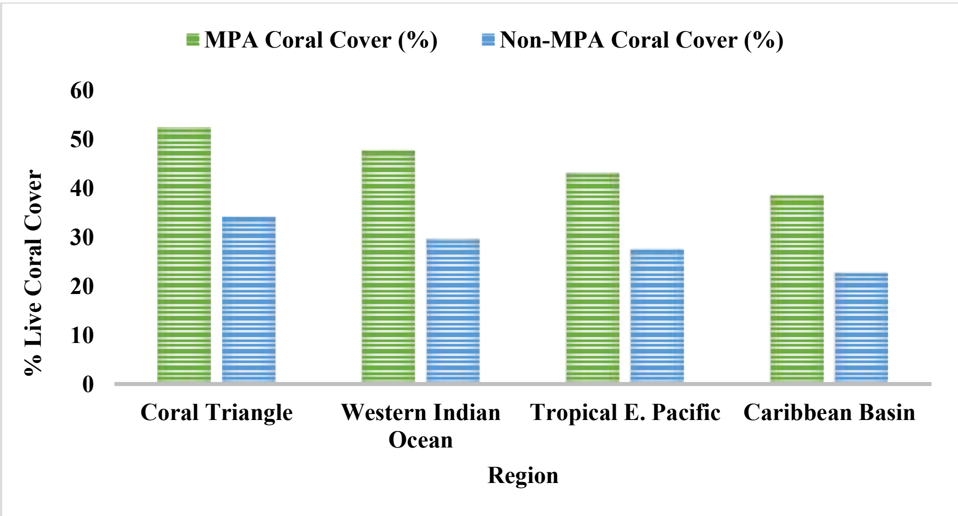

Figure 3. Coral Cover Comparison by Region and Protection Status

4. DISCUSSION

Comparing maritime Protected Areas (MPAs) to ecologically comparable non-protected maritime regions, the research findings demonstrate the ecological efficacy of MPAs in fostering biodiversity and restoring functioning ecosystem constituents (Cheng et al., 2019). MPAs outperformed non-MPAs on all the parameters that were being studied, including habitat condition, fish biomass, species richness, and functional diversity (Topor et al., 2019). In older, well-managed MPAs, where coral cover showed more consistency and apex predators and functionally significant species like herbivores and carnivores were more prevalent, this tendency was especially noticeable (Sala et al., 2018).

Reduced anthropogenic stress in MPAs, particularly from extractive effects like fishing and harmful tourism, is the cause of these findings. MPAs establish refuges that allow natural populations to recover from historical overexploitation by lowering direct stresses. Furthermore, higher functional richness and dispersion values in MPAs show that ecological functions, which boost resistance to shocks, are more balanced and diversified than species counts. However, MPAs' performance differed (Ziegler et al., 2022). Younger or partly protected areas exhibited smaller benefits, whereas older and no-take MPAs tended to exhibit robust ecological recovery. This difference emphasizes how important enforcement time and intensity are as complementary elements in conservation success. Their efficacy was likely limited by enforcement shortcomings, unclear borders, and the absence of local participation in many partially protected regions.

The findings of worldwide meta-analyses, which show improved ecological performance in MPAs with strong protection and enforcement, are usually consistent with our results. Our results confirm the broad trend that fish volume and species richness both significantly increase within MPAs, particularly at older sites with continuously implemented regimes. However, by adding functional diversity assessments and employing a paired-site study design that maintains consistent habitat and biogeographic variety, our research offers even more refinement. Our technique enables more controlled comparison than most previous studies, which have been based on composite datasets within extremely varied ecological environments. The use of NMDS ordination shows that MPA fish assemblages differ from their non-MPA counterparts in terms of composition and cluster more closely, both of which are signs of more stable and organized assemblages.

In particular, the results differ significantly from those of earlier studies that questioned the universality of MPA efficacy, especially when there is a lot of external pressure or lax enforcement. Our study demonstrated that weakly enforced partially protected MPAs did see some slight changes, supporting the notion that formal designation does not necessarily translate into ecological success (Rudd, 2015). As a result, our results close the gap between positive and negative assessments of MPAs by highlighting implementation quality and contextual variation.

These findings have immediate and useful policy implications for marine conservation. Perhaps most immediately, the viability of MPAs depends on design features like no-take status, governance type, enforcement level, and community engagement rather than being directly related to the size of the area blocked. The creation of "paper parks" with little to no biological value is threatened when MPA networks are expanded without first making an effort to alter these structural components. Results show the need for adaptive management plans. Ecological and functional indicators must be used to monitor MPAs over time so that trends may be seen and management decisions can be made accordingly. MPA success should be evaluated using keystone species presence, fish biomass recovery, and habitat quality as benchmarks. Stakeholders and the local community must be heavily involved. Co-managed MPAs with local fishermen and indigenous peoples tended to have higher legitimacy and compliance rates. Enhancing management strategy and encouraging stewardship may also be achieved by fusing scientific monitoring with traditional ecological knowledge. The cumulative and synergistic impacts of ecological environment, enforcement history, and MPA age must all be considered in spatial design (Gallacher et al., 2016). The location of MPAs, as well as their post-designation maintenance, must be given top priority by decision-makers. The MPA policy framework's toolset should include funding for stakeholder engagement, training, and enforcement.

Despite its advantages, this study has many drawbacks. Despite their diversity, the spatial focus on four ecoregions could not accurately represent the entire heterogeneity present in marine systems across the world (Turner et al., 2017). Because tropical reefs were given priority, the findings might not apply to deep-sea or temperate MPAs. Furthermore, the study may have overlooked biodiversity trends in deeper regions or more complex reef geometries because it focused mostly on shallow reef ecosystems (5–15 meters). There are also temporal restrictions. Longer-term changes in species composition and ecosystem function remain unclear, even though surveys were conducted periodically over two years. Our research period did not allow for the possibility of lag reactions to protection by specific species or processes (Eyal et al., 2020).

In terms of methodology, despite their widespread usage, underwater visual census techniques are vulnerable to observer bias and detection limitations, particularly for cryptic or nocturnal species. We countered this by combining eDNA analysis with field surveys; nevertheless, further integration of acoustic or remote sensing technologies might improve future research. Decadal timeframe longitudinal studies that map out ecological and functional recovery trajectories should be given top attention in order to expand on the current body of knowledge. Such studies will direct the ideal monitoring and management planning durations and offer priceless insights into the temporal dynamics of MPA efficacy. Examining how MPAs contribute to climate change resistance is another exciting avenue. Protected habitats may serve as stress buffers or recolonization source populations when ocean temperatures rise and acidity persists. It might be very instructive to compare MPAs to non-MPAs in terms of coral bleaching resilience, reproductive capacity, and larval dispersion.

Future studies should examine the relationship between ecosystem service value and biodiversity protection. A stronger economic argument for the establishment and sustained maintenance of MPAs would be made if quantifiable assessments of the benefits they provide, such as fisheries production, tourism revenue, coastal protection, and carbon sequestration, were established. The next generation of marine conservation plans will require a multidisciplinary approach that integrates ecology, economics, and governance.

5. CONCLUSION

Comparing Marine Protected regions (MPAs) to comparable non-protected marine regions, this study provides compelling empirical evidence that MPAs significantly enhance marine biodiversity and ecological function when established and appropriately implemented. MPAs exhibited greater fish biomass, greater species richness, improved functional diversity, and more affluent benthic environments across four biogeographically distinct locations. The cumulative advantages of sustained protection and governance continuity were highlighted by the fact that older and closely protected MPAs had the largest ecological gains in comparison to the most improved ecological indices. The findings support MPAs' ecological rationale as essential elements of marine conservation strategy. Well-designed MPAs contribute to the achievement of biodiversity and ecosystem resilience objectives by facilitating species recovery, avoiding community homogeneity, and preserving significant biological processes. These impacts are particularly significant in light of the rapidly changing global environment, which makes intact marine ecosystems essential for both climate adaptation and mitigation. However, this study also shows that designation is not a guarantee of conservation success. The need for enforcement capabilities, stakeholder involvement, and adaptive management is highlighted by the differences in performance by MPA type. Without community support, legal clarity, or consistent monitoring, MPAs may not achieve their desired conservation goal. We thus highly urge the development of MPA industrial networks that are not only industry-wide but also environmentally representative, fairly administered, and strategically assessed in light of such an industry. To provide the greatest possible conservation benefits and profits, industry cooperation, infrastructure enforcement, and extensive ecological evaluation will be essential. Both quantity and quality must be prioritized as countries work toward the "30 by 30" biodiversity targets. In order for MPAs to fulfil their promise as pillars of ocean sustainability, a science-based design and implementation worldwide approach will be necessary.

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