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INTEGRATED ASSESSMENT OF CORAL REEFS AND REEF FISH ASSEMBLAGES IN KAIMANA MARINE PROTECTED AREAS, WEST PAPUA

PENILAIAN TERPADU TERUMBU KARANG DAN KOMUNITAS IKAN KARANG DI KAWASAN KONSERVASI PERAIRAN KAIMANA, PAPUA BARAT

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ABSTRACT

Coral reefs in the Kaimana Marine Protected Areas (MPAs) in West Papua are among Indonesia's most biodiverse ecosystems, but human activities and climate change increasingly threaten them. This study aimed to evaluate the condition of coral reefs and reef fish assemblages in the No-Take and Utilization Zones of Kaimana MPA using historical monitoring data. The data were collected from 24 sites across three periods: T0 (2012–2013), T1 (2015–2016), and T2 (2019), and analyzed in 2020. Benthic composition was assessed using the Point Intercept Transect method, while reef fish assemblages were surveyed via Underwater Visual Census. Ecological indicators included live hard coral cover, benthic substrate composition, and biomass of reef fish by trophic groups and families. Temporal and spatial differences among monitoring periods and between the No-Take and Utilization Zones were tested using one-way ANOVA and Kruskal–Wallis tests. Live hard coral cover differed significantly between management zones ($p < 0.001$), increasing in the No-Take Zone but declining in the Utilization Zone. Several benthic indicators, including crustose coralline algae, rubble, dead coral, and other algae, showed significant temporal variation, reflecting disturbance, eutrophication, and climate-related stress. In contrast, reef fish biomass declined across zones and monitoring periods, indicating that spatial protection alone has been insufficient to counteract persistent fishing pressure and limited enforcement. The contrasting trends in coral cover and reef fish biomass emphasize the need for adaptive MPA management through stronger enforcement, community participation, habitat restoration, and ridge-to-reef water-quality control.

Keywords: adaptive management, coral reefs, long-term monitoring, marine protected areas, reef fish assemblages

ABSTRAK

Terumbu karang di Kawasan Konservasi Perairan (KKP) Kaimana, Papua Barat, merupakan salah satu ekosistem dengan keanekaragaman hayati tertinggi di Indonesia, tetapi semakin terancam oleh aktivitas manusia dan perubahan iklim. Penelitian ini bertujuan untuk mengevaluasi kondisi terumbu karang dan komunitas ikan karang pada Zona Larang Tangkap dan Zona Pemanfaatan KKP Kaimana menggunakan data pemantauan historis. Data berasal dari 24 lokasi yang mencakup tiga periode, yaitu T0 (2012–2013), T1 (2015–2016), dan T2 (2019), dan dianalisis pada tahun 2020. Komposisi bentik dianalisis menggunakan metode *Point Intercept Transect*, sedangkan komunitas ikan karang diamati menggunakan metode *Underwater Visual Census*. Indikator ekologis meliputi tutupan karang keras hidup, komposisi substrat bentik, serta biomassa kelompok trofik dan famili ikan karang. Perbedaan temporal dan spasial antarperiode pemantauan serta antara Zona Larang Tangkap dan Zona Pemanfaatan dianalisis menggunakan ANOVA satu arah dan uji Kruskal–Wallis. Tutupan karang keras hidup berbeda secara signifikan antarzona pengelolaan ($p < 0{,}001$), meningkat di Zona Larang Tangkap tetapi menurun di Zona Pemanfaatan. Beberapa indikator bentik, termasuk alga koralin berkerak, puing karang, karang mati, dan alga lainnya, menunjukkan variasi temporal yang signifikan, mencerminkan gangguan, eutrofikasi, dan tekanan terkait perubahan iklim. Sebaliknya, biomassa ikan karang menurun pada seluruh zona dan periode pemantauan, menunjukkan bahwa perlindungan spasial saja belum memadai di tengah tekanan penangkapan dan keterbatasan penegakan aturan. Tren berlawanan antara tutupan karang dan biomassa ikan karang menegaskan pentingnya pengelolaan KKP secara adaptif melalui penguatan penegakan aturan, partisipasi masyarakat, restorasi habitat, serta pengendalian kualitas air dari hulu hingga pesisir (*ridge-to-reef*).

Kata kunci: kawasan konservasi perairan, komunitas ikan karang, pemantauan jangka panjang, pengelolaan adaptif, terumbu karang

INTRODUCTION

The sustainability of marine ecosystems is a primary concern on the global conservation agenda, particularly as increasing pressure on coastal resources threatens biodiversity, ecosystem functions, and fisheries productivity. Intensive fishing has contributed to declines in apex predators, disruption of trophic structures, and reduced ecosystem resilience (Lennox *et al.* 2022). Coral reefs, among the most species-rich tropical ecosystems, are especially vulnerable because many coastal communities depend on reef fisheries for food security and income. In this context, sustainability refers not only to short-term catch yields but also to the long-term reproductive capacity of fish stocks and the continued provision of ecosystem services.

Marine Protected Areas (MPAs), particularly No-Take Zones, have been promoted as ecosystem-based management strategies to restore fish populations, enhance ecosystem resilience, and generate spillover benefits to adjacent waters. However, MPA effectiveness remains highly context-dependent and is influenced by zoning design, age and size of protected areas, enforcement effectiveness, community engagement, and the availability of ecological data for evaluation (Grorud-Colvert *et al.* 2021).

In Indonesia, marine conservation area expansion has accelerated in line with Sustainable Development Goal 14 and national marine biodiversity policies. One critical region for marine conservation is the Kaimana Marine Protected Areas (MPAs) in West Papua Province. This area was initially designated by the Government of Kaimana Regency (2014) through Regional Regulation of Kaimana Regency Number 11 of 2014, followed by a formal conservation proposal by the Governor of West Papua through Decree Number 523/60/3/2018. It was subsequently established through Decree of the Minister of Marine Affairs and Fisheries Number 25/ KEPMEN-KP/2021, covering Buruway, Arguni, Kaimana (Triton), Etna Bay, Namatota, Maimai, Aiduma Island, and surrounding waters. The Kaimana MPAs cover approximately 121,742 ha of coastal waters and form part of the Bird's Head Seascape, a globally recognized center of marine biodiversity with at least 471 coral species and more than 1,000 reef fish species (Allen and Erdmann 2009).

Although the Kaimana MPAs have an official zoning system (including No-Take Zones and Utilization Zones), integrated scientific evaluation of zoning effectiveness remains limited. Much of the available information is generalized or lacks spatial structure. Biological information on differences in reef fish community structure and coral cover across zones is particularly scarce, even though such data are essential for evaluating conservation effectiveness. This gap is especially relevant because coral reefs in Eastern Indonesia face simultaneous pressure from fishing, land-based sedimentation, destructive fishing legacies, and climate change (McClanahan *et al.* 2020; Purwanto *et al.* 2021).

Previous studies have shown that successful marine zoning depends on clear boundaries, effective enforcement, and strong community support (Campbell *et al.* 2013). Studies in Raja Ampat and Cenderawasih Bay demonstrated that No-Take Zones can produce differences in reef fish communities and benthic conditions compared with use zones when supported by consistent monitoring and governance (Boli *et al.* 2014; Sala *et al.* 2017; Bawole *et al.* 2019). However, comparable integrated coral-fish assessments remain limited for Kaimana MPAs, making it difficult to understand whether coral reefs and reef fish assemblages follow similar recovery trajectories under existing zoning.

The novelty of this study lies in its integrated biological approach, which simultaneously evaluates two key ecosystem components, benthic substrates and reef fish assemblages, within a spatial conservation-zoning framework. Many MPA assessments emphasize a single ecological component, either coral cover or fish assemblages, without examining potential divergence between sessile benthic communities and mobile reef-associated fishes (McClanahan *et al.* 2020; Stuart-Smith *et al.* 2022). Therefore, this study addresses the ecological interplay between habitat condition and reef fish biomass in a data-deficient but biodiversity-rich region.

This study aimed to evaluate the ecological effectiveness of zoning within the Kaimana MPAs by comparing live hard coral cover and reef fish biomass between No-Take Zones and Utilization Zones and by assessing temporal changes in these ecological indicators across the monitoring period. Specifically, the study examined whether No-Take Zones supported better ecological conditions than Utilization Zones and whether coral reef and reef fish conditions improved over time in response to protection. The study tested two hypotheses: (1) No-Take Zones would have higher live hard coral cover and reef fish biomass than Utilization Zones; and (2) ecological conditions would improve over the monitoring period in response to protection. By testing these hypotheses, the study provides an empirical basis for evaluating zoning effectiveness and identifying adaptive management priorities for Kaimana MPAs and other MPAs in the Coral Triangle.

METHODS

Study area and sampling design

This study analyzed historical ecological monitoring data collected from the Kaimana Marine Protected Areas (MPAs), West Papua Province, Indonesia, during three monitoring periods: T0 (2012–2013), T1 (2015–2016), and T2 (2019). Data processing and statistical analysis were conducted in 2020. The study area covered reef systems around Triton Bay, Namatota, Maimai, and Aiduma Island within the Kaimana MPA network (Figure 1).

The management zones compared in this study were the No-Take Zone (NTZ) and the Utilization Zone (UZ). The NTZ is intended to prohibit extractive activities and function as a biodiversity and fish-stock refuge, whereas the UZ allows controlled community use and regulated fishing activities in accordance with MPA management rules. A total of 24 monitoring sites were included in the analysis, consisting of 8 sites in the NTZ and 16 sites in the UZ. Each site was surveyed once during each monitoring period using standardized protocols to ensure temporal comparability (Table 1). The 8–10 m depth range was selected because it represents the main reef-slope habitat surveyed in the monitoring program and reduces depth-related bias in benthic cover and reef fish observations.

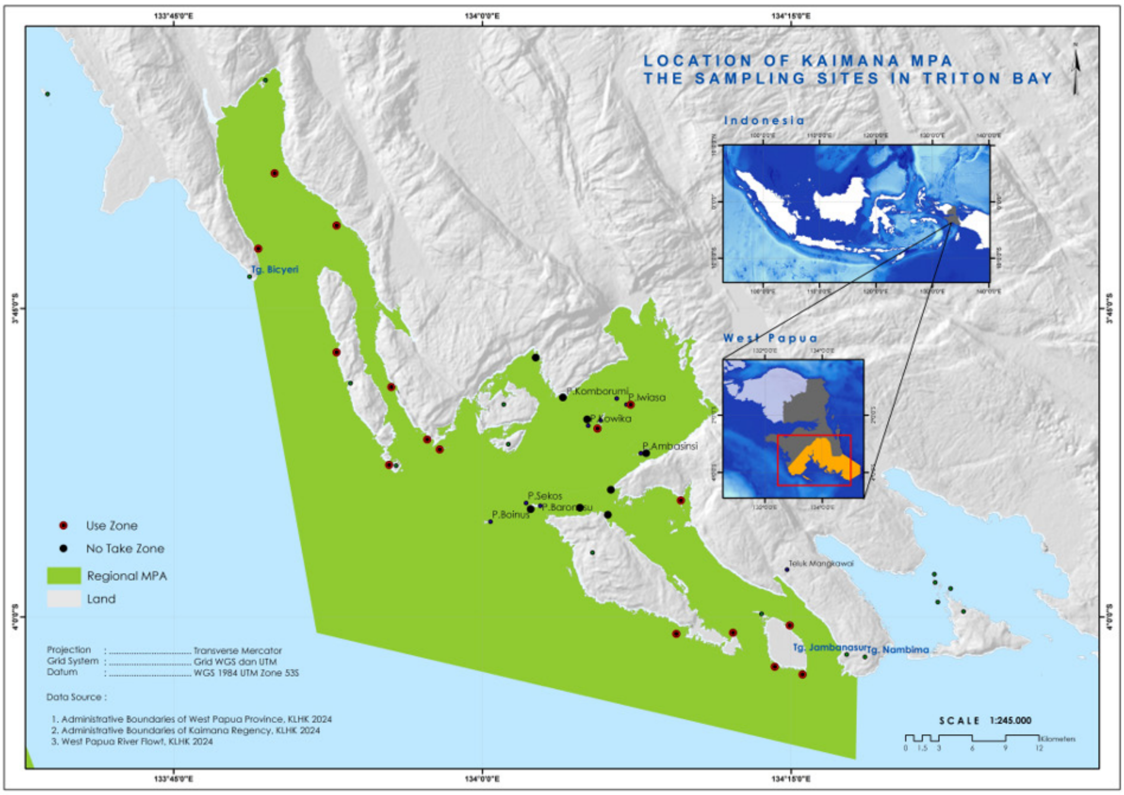

Figure 1. Distribution of monitoring sites in Triton Bay, Kaimana MPAs, West Papua Province. Black dots indicate No-Take Zone sites and red dots indicate Utilization Zone sites. Data were collected during T0 (2012–2013), T1 (2015–2016), and T2 (2019).

Table 1. Summary of sampling design used for the integrated ecological assessment of Kaimana MPAs.

Management Zone	Number of Sites	Monitoring Periods	Allowed/Prohibited Activities	Main Methods
No-Take Zone	8	T0: 2012–2013; T1: 2015–2016; T2: 2019	Extractive activities prohibited; conservation and monitoring prioritized	PIT for benthos; UVC for reef fish
Utilization Zone	16	T0: 2012–2013; T1: 2015–2016; T2: 2019	Controlled community use and regulated fishing permitted	PIT for benthos; UVC for reef fish
Total	24	Three monitoring periods	Zoning-based comparison	Standardized long-term monitoring

Benthic and reef fish surveys

Benthic data, provided by the Institute for Research and Community Service at the University of Papua, were collected using the Point Intercept Transect (PIT) method following reef-health monitoring protocols (Ahmadia *et al.* 2013; Giyanto *et al.* 2014). At each site, a 50 m transect was placed along the reef-slope contour at 8–10 m depth, with benthic categories recorded at 0.5 m intervals. Recorded life forms included hard coral, soft coral, crustose coralline algae (CCA), bleached coral, dead coral, rubble, non-coral algae, sand, and other dead substrates. Live hard coral cover was used as a key indicator of coral reef condition and was interpreted using the classification of Giyanto *et al.* (2014): poor (0–24.9%), moderate (25–49.9%), good (50–74.9%), and excellent (75–100%).

Reef fish assemblages were surveyed via the Underwater Visual Census (UVC) method following Ahmadia *et al.* (2013) and Giyanto *et al.* (2014). Observers recorded target reef fish within standardized belt transects, focusing on ecologically and economically important families, including Serranidae, Lutjanidae, Haemulidae, Scaridae, Acanthuridae, and Siganidae. Fish were identified to the lowest possible taxonomic level, generally species for major target families; genus- or family-level identification was retained when underwater species-level identification was uncertain. Visual length estimates were converted to biomass using the length-weight relationship $W = aL^b$, where W is fish weight, L is total length, and a and b are species- or genus-specific coefficients obtained from FishBase and related reef fish length-weight compilations (Kulbicki *et al.* 2005). Biomass estimates were standardized to kg ha^{-1} to enable comparison among sites, monitoring periods, and management zones.

Data quality control followed the monitoring protocol through observer training, calibration of underwater length estimates, standardized transect placement, and consistency of survey depth and methods among years. These steps reduced inter-observer and habitat-depth bias and improved comparability across the long-term monitoring dataset.

Data analysis

Benthic cover and reef fish biomass were summarized by management zone and monitoring period. The analysis examined two main sources of variation: temporal differences among T0, T1, and T2, and spatial differences between NTZ and UZ. Data normality and homogeneity of variance were tested using Shapiro–Wilk and Levene tests, respectively. One-way ANOVA was applied when assumptions were met; otherwise, Kruskal–Wallis tests were used as a non-parametric alternative (Zar 2010). Post hoc comparisons using Tukey HSD or Dunn–Bonferroni procedures were applied only when omnibus tests indicated significant differences. Statistical significance was evaluated at $p < 0.05$. Results are presented as mean values with variability among monitoring sites in the figures and as p-values in the statistical summary table.

RESULTS AND DISCUSSION

Dynamics of benthic indicators by management zone

Temporal comparison of live hard coral cover showed contrasting patterns between management zones (Figure 2). In the NTZ, live hard coral cover increased from 17% at T0 to 24% at T1 and 32% at T2, indicating a positive habitat response under stronger protection. In contrast, the UZ increased from 14% at T0 to 18% at T1 but declined to 13% at T2. These patterns suggest that strict protection has supported reef habitat recovery in the NTZ, whereas continued disturbance and lower enforcement effectiveness may have constrained recovery in the UZ. Similar patterns have been reported from MPA evaluations showing that fully protected, well-enforced areas tend to generate stronger conservation outcomes than partially protected areas (Grorud-Colvert *et al.* 2021).

The multi-indicator benthic results further demonstrate that reef condition in Kaimana MPAs is not driven only by live coral cover. Hard coral cover was consistently higher in the NTZ than in the UZ, whereas rubble and algae showed temporal variation that may reflect both disturbance history and broader environmental pressure. No-Take Zones maintained reef conditions within the moderate category throughout the monitoring period, while Utilization Zones generally remained in the poor category. Nevertheless, field observations from 2019 recorded evidence of blast fishing at two NTZ sites, indicating that zoning designation alone does not guarantee ecological protection. Enforcement, compliance, and community surveillance are therefore critical for maintaining reef recovery.

These hard coral distribution patterns may result from varying intensities of anthropogenic pressure, including destructive fishing, sedimentation from land-use change, and local oceanographic dynamics (currents, depth, and wave exposure). The persistence of notable coral cover at several UZ sites also indicates that some utilized reefs retain recovery potential, especially if community-based conservation, anchoring control, and ridge-to-reef sediment management are strengthened.

Ecological responses of benthic substrate indicators

The analysis of benthic indicators revealed that coral reef ecosystem dynamics were shaped by both spatial and temporal factors (Table 2). Hard coral cover showed a significant spatial difference between management zones ($p < 0.001$), confirming the importance of zoning in maintaining reef-building coral structure. By contrast, CCA, rubble, dead coral, and other algae showed significant temporal differences, suggesting that several benthic components respond to broader disturbance-recovery processes, climate-related stress, sedimentation, and nutrient enrichment. Soft coral and bleached coral did not differ significantly across either time periods or zones, indicating relatively stable or highly variable patterns at the monitoring scale.

Hard coral cover showed a significant difference between zones but not among monitoring periods. This indicates that spatial protection was more strongly associated with live coral condition than temporal change alone. In practical terms, NTZs appear to reduce local disturbance to reef structure, although recovery may still require more than one monitoring cycle and may be slowed by repeated thermal stress, blast-fishing legacies, and sedimentation. Similar findings from other Indonesian MPAs highlight the need for sustained enforcement and long-term monitoring to detect year-to-year recovery trends (Sala *et al.* 2017; Kennedy *et al.* 2020).

Soft coral and bleached coral showed no significant differences across periods or zones. Soft corals can tolerate a wider range of physical and environmental conditions than hard corals and often persist in shaded or high-current habitats (Rozirwan *et al.* 2014; Maucieri and Baum 2021). The absence of a significant bleaching pattern should be interpreted cautiously because this study did not directly measure sea surface temperature, heat-stress exposure, or bleaching-recovery trajectories. Therefore, thermal stress is discussed here as an ecological context supported by regional observations, not as a directly measured driver. Continued monitoring remains important because Western Pacific reefs, including those in eastern Indonesia, are increasingly exposed to marine heatwaves and coral bleaching risk (IPCC 2023; Reimer *et al.* 2024).

CCA showed significant temporal but not spatial differences. Because CCA contributes to coral larval settlement and substrate stabilization, temporal changes in CCA may influence future coral recruitment capacity. The absence of spatial differences suggests that CCA dynamics may be driven by regional or system-wide pressures, such as water quality, sedimentation, herbivory, or seawater chemistry, rather than by zoning alone (Golbuu *et al.* 2012; Johnson *et al.* 2019).

Rubble and dead coral showed significant temporal differences but no significant spatial differences. This pattern suggests that reef degradation may be systemic and may occur more rapidly than recovery. Rubble commonly indicates previous physical disturbance, blast fishing, storms, or coral mortality, and its persistence reduces structural complexity for coral recruitment and reef fish habitat (Fox *et al.* 2003). Similar patterns have been reported in protected and unprotected reefs affected by severe disturbances, where local zoning alone is insufficient to prevent mortality associated with broader environmental stress (Kennedy *et al.* 2020).

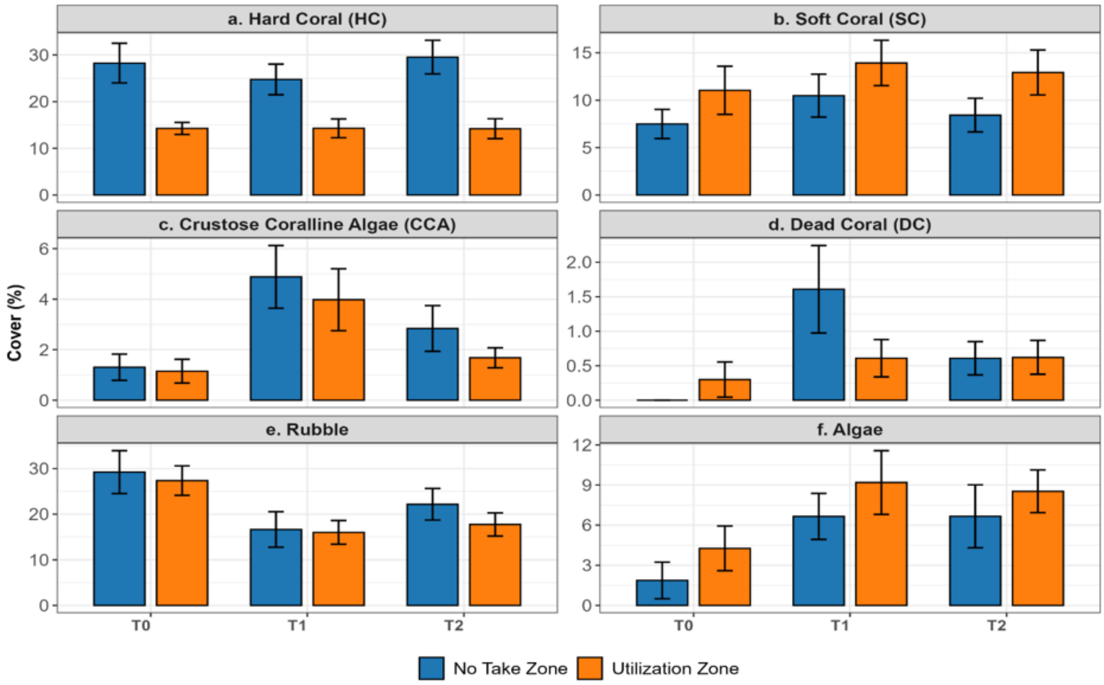

Figure 2. Mean cover (%) of major benthic indicators across No-Take and Utilization Zones during T0, T1, and T2. Error bars indicate variability among monitoring sites.

Table 2. Results of ANOVA tests showing differences in benthic community indicators across time periods and management zones. Significant differences ($p < 0.05$) are highlighted, indicating temporal or spatial variability in specific benthic components.

Benthic Indicator	Difference Across Time Periods	P-value	Difference Across Management Zones	P-value	Statistical Test
Hard coral	Not significant	0.8280	Significant	<0.0010	ANOVA
Soft coral	Not significant	0.3000	Not significant	0.3240	ANOVA
CCA	Significant	0.0040	Not significant	0.2676	ANOVA
Bleached coral	Not significant	0.3680	Not significant	0.2677	ANOVA
Rubble	Significant	0.0002	Not significant	0.4860	ANOVA
Dead coral	Significant	<0.0010	Not significant	0.4312	ANOVA
Other algae	Significant	<0.0010	Not significant	0.0598	ANOVA

Other algae showed significant temporal variation and a near-significant spatial difference. An increase in non-coral algae can indicate a shift from coral-dominated to algae-dominated reef states, often associated with coral cover loss, nutrient enrichment, or reduced herbivory (Sotka and Hay 2009). Given the observed decline in herbivorous fish biomass, algal dynamics in Kaimana MPAs may reflect weakening grazing pressure in addition to land-based nutrient inputs. Maintaining herbivore populations and reducing nutrient and sediment runoff should therefore be treated as complementary management priorities (Green *et al.* 2014; Williams *et al.* 2015).

Dynamics of reef fish biomass

Reef fish biomass displayed a marked decline across monitoring periods in both management zones (Figure 3). Carnivorous fish biomass in the NTZ declined from 672.58 kg ha^{-1} at T0 to 182.02 kg ha^{-1} at T1 and 97.52 kg ha^{-1} at T2. The UZ showed a similar decline from 321.48 kg ha^{-1} at T0 to 115.81 kg ha^{-1} at T2. Herbivorous fish biomass also declined sharply, from 1997.09 kg ha^{-1} at T0 to 578.75 kg ha^{-1} at T1 and 178.84 kg ha^{-1} at T2 in the NTZ and from 754.19 kg ha^{-1} at T0 to 415.75 at T1 and 97.65 kg ha^{-1} at T2 in the UZ over the same period.

The consistent reduction of fish biomass in both zones indicates that existing zoning has not fully maintained or restored fish assemblages, particularly herbivorous fishes that play important roles in algae control and coral resilience. This pattern may reflect insufficient enforcement, spillover of fishing pressure into protected areas, mobile fish behavior, and external fishing pressure outside MPA boundaries. It also suggests that coral habitat recovery does not automatically translate into reef fish recovery, especially where fishing pressure continues or where larger-bodied target species require longer recovery periods (Green *et al.* 2014; Nash *et al.* 2016; Cammen *et al.* 2019).

Family-level patterns highlight the need for targeted management. Declines in families such as Serranidae, Scaridae, Acanthuridae, Siganidae, Lutjanidae, and Haemulidae can affect both fisheries productivity and reef ecological function. Herbivore protection is particularly important because grazing fishes suppress algal overgrowth and support coral recruitment. Therefore, management actions should combine no-take enforcement with gear control, community-based patrols, protection of spawning and nursery habitats, and monitoring of catch and fishing effort in adjacent areas.

Ecological divergence and integrated dynamics of coral and fish communities

The integrated biological assessment revealed an important ecological divergence: coral habitat indicators showed signs of improvement in No-Take Zones, whereas reef fish biomass declined across zones and monitoring periods. This divergence suggests that benthic communities and mobile reef fish may respond to conservation interventions at different rates and may be affected by different stressors. Sessile benthic organisms can benefit from reduced local physical disturbance, whereas mobile fishes remain vulnerable to fishing pressure, weak compliance, and movement across management boundaries.

This result is important for interpreting MPA performance. If evaluation focuses only on coral cover, Kaimana MPAs may appear to be progressing positively. However, when fish biomass is considered simultaneously, the system shows incomplete ecological recovery. The heatmap summary (Figure 4) emphasizes this contrast: hard coral was spatially significant, several benthic indicators were temporally significant, and selected fish groups or families showed temporal or spatial responses. Therefore, MPA evaluation should not rely on a single indicator but should integrate benthic habitat, fish biomass, trophic structure, enforcement, and socioeconomic data. Socioeconomic incentives, such as livelihood diversification, sustainable fisheries support, and equitable benefit sharing, may also reduce fishing pressure and improve conservation outcomes.

These findings support adaptive management in which enforcement and ecological restoration are treated as complementary strategies. Priority actions include strengthening patrols in high-risk sites, documenting and preventing blast fishing, improving compliance through customary and community-based surveillance, protecting herbivorous fish, and controlling land-based sediment and nutrient inputs through a ridge-to-reef approach. Such actions are relevant not only for Kaimana MPAs but also for other MPAs in the Coral Triangle where coral cover and fish biomass may recover at different rates.

Management implications and study limitations

The results provide several management implications. First, the positive trajectory of hard coral cover in NTZs supports the ecological value of strict protection, but the recorded blast-fishing evidence indicates that enforcement must be strengthened. Second, declining fish biomass indicates that MPA management should incorporate fisheries-specific measures such as catch and effort monitoring, gear regulation, protection of herbivorous fishes, and community-based compliance mechanisms. Third, the temporal changes in rubble, dead coral, CCA, and algae indicate that habitat protection should be paired with water-quality management, watershed sediment control, and active habitat restoration at degraded sites.

This study also has limitations. The analysis relied on historical monitoring data with three monitoring periods, so temporal resolution was limited. Direct measurements of fishing pressure, enforcement intensity, socioeconomic drivers, water quality, and thermal stress were not available for all sites and periods. Therefore, the mechanisms proposed in the discussion should be interpreted as plausible explanations supported by ecological patterns and literature, not as direct causal proof. Future research should integrate ecological monitoring with fishing-effort data, compliance records, socioeconomic surveys, water-quality indicators, and remotely sensed thermal-stress metrics to strengthen causal interpretation and management evaluation.

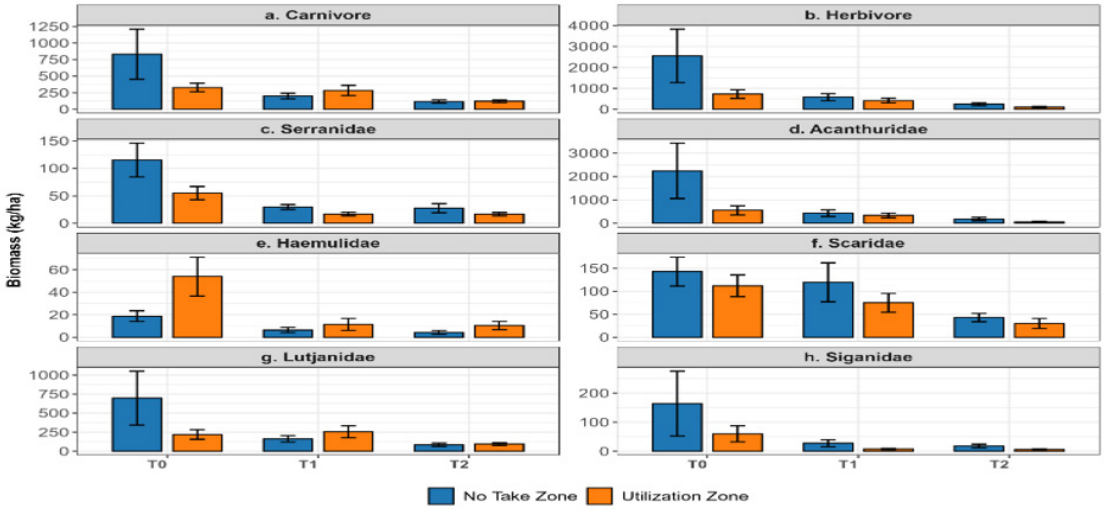

Figure 3. Mean biomass (kg ha^{-1}) of trophic groups and selected reef fish families across No-Take and Utilization Zones during T0, T1, and T2. Error bars indicate variability among monitoring sites.

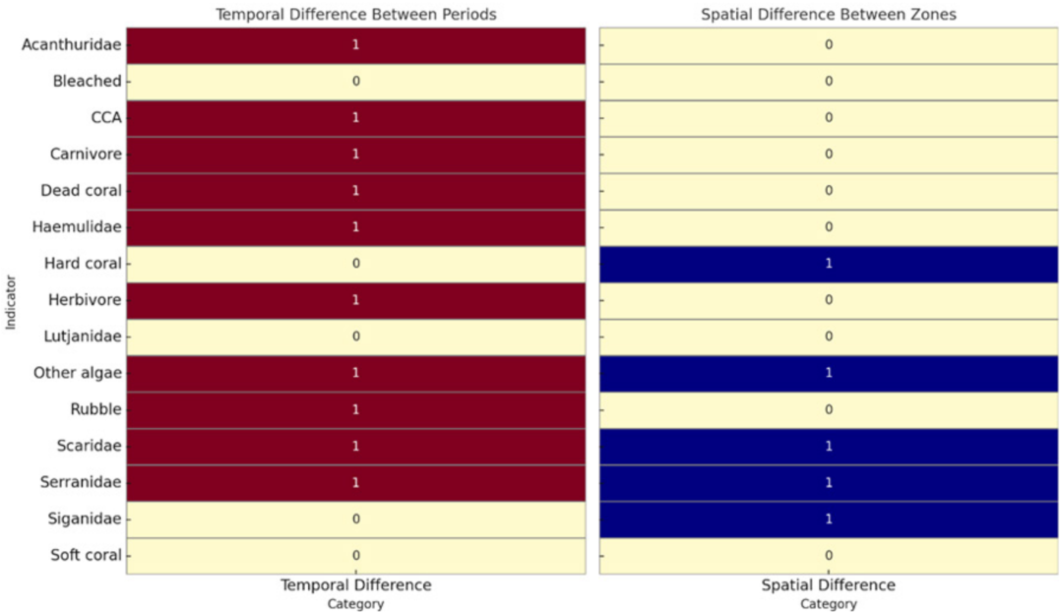

Figure 4. Temporal and spatial comparison of benthic and fish indicators in Kaimana MPAs. The bar graph illustrates statistically significant differences in benthic components (hard coral, CCA, algae) and fish families (e.g., Scaridae, Serranidae) between zones and monitoring years. Dark colors (value 1) indicate a significant difference, while light colors (value 0) represent no significant difference.

CONCLUSION

Kaimana MPAs show contrasting ecological trajectories: live hard coral cover increased in No-Take Zones, while reef fish biomass declined in both No-Take and Utilization Zones. This indicates that spatial zoning can promote habitat recovery but is insufficient to restore fish communities when fishing pressure, weak enforcement, and external stressors persist. Therefore, effective management requires an adaptive, integrated approach combining strict protection, stronger enforcement, community participation, habitat restoration, herbivore conservation, long-term monitoring, and ridge-to-reef water-quality management. The findings also highlight the need to evaluate MPA performance using multiple ecological indicators rather than coral cover alone. Future research should incorporate fishing pressure, socioeconomic conditions, enforcement effectiveness, and climate-related stressors.

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