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Nutrient-Driven Macroalgae Proliferation on Coral reefs: Assessing the Resilience of Coral Communities at Bawe and Changuu Islands, Zanzibar

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Abstract

Coral reefs always suffer from natural and anthropogenic impacts that drive ecological shifts from coral to overgrowing dominat states such as macroalgae and corallimopharian dominance. This study explores the dynamics and ecological impacts of macroalgae proliferation on the coral reefs around Bawe and Changuu Islands in Zanzibar. Using Line Intercept Transect surveys, macroalgae cover and community are quantified, as well as coral health indicators across reef zones. Results revealed significantly higher macroalgae abundance at Changuu Island (4.34%) compared to Bawe (1.06%), with $p < 0.05$, strongly correlated with nutrient enrichment from proximate sewage discharge and tourism. The macrolgae observed was Phaeophyta (brown algae, specifically *Lobophora*) dominating the nutrient-enriched Changuu, while Chlorophyta (green algae, such as *Ulva*) was more prevalent at Bawe. Statistical correlations identified specific coral genera such as *Physogyra* and *Plerogyra* as potentially vulnerable to macroalgae interactions at Changuu, both reefs reserved moderately high hard coral cover (>58%), remarkably, coral recruit density was higher at Changuu (60.33 m^{-2} on reef flat) than at Bawe (43.67 m^{-2} on reef crest), and a Coral Reef Health Index (CRHI) >83, suggested a resilient but potentially risky state. The macroalgae expansion in Zanzibar is primarily caused by land-based nutrient pollution.

Keywords; Macroalgae, Coral Reefs, Nutrient Enrichment, Eutrophication, *Lobophora* ,

Introduction

Coral reefs are among the most biodiverse and economically vital ecosystems on Earth. For coastal communities in regions like Zanzibar, they provide indispensable services including fisheries production, shoreline protection, and substantial tourism revenue (Muzuka *et al.,* 2010; Spalding *et al.,* 2017). Ecologically, reefs function as complex biogeochemical engines, facilitating nutrient cycling and carbon sequestration through the symbiotic relationship between corals and zooxanthellae (Titlyanov,Titlyanova 2020; Drake *et al.,* 2020). However, these ecosystems are in global decline, facing a rising of threats from climate change (bleaching, acidification) and localized anthropogenic pressures (overfishing, pollution).

A critical sign of reef degradation is the phase shift from coral-dominated to macroalgae-dominated states (Norström *et al.,* 2009). While macroalgae are natural and functional components of healthy reefs, their excessive proliferation can suppress coral recruitment, growth, and survivorship through mechanisms including shading, abrasion, and allelopathy (Chadwick, Morrow, 2010; Zhao *et al.,* 2021). The drivers of such proliferation are multifaceted but often stem from a relaxation of top-down control (overfishing of herbivores) and a dramatic increase in bottom-up forcing, primarily nutrient enrichment from agricultural runoff and untreated sewage (Lapointe *et al.,* 2021).

In Zanzibar, the reefs near Stone Town, including those at Changuu and Bawe Islands, both are major tourist attractions and vulnerable sentinels of coastal pollution (Ngazy *et al.,* 2004). The absence of a comprehensive sewage treatment system in Stone Town results in the direct discharge of nutrient-rich effluents into coastal waters (Bergman, 2014). Concurrently, climate change stressors are weakening coral resilience, making them more susceptible to displacement. Despite the clear threat, contemporary, detailed assessments of macroalgae dynamics on these reefs are lacking.

This study addresses this gap by investigating the macroalgae communities on the reefs of Bawe and Changuu Islands, specifically to the quantify and compare macroalgae cover and community composition between the two islands, assess the correlation between macroalgae abundance and the health/status of coral communities, and evaluate the overall reef health in the context of macroalgae pressure. The findings provide a critical, updated baseline for understanding the course of these economically crucial reefs and inform targeted management interventions.

Literature Review

The macroalgae-Coral Dynamic

Coral reef communities exist in a dynamic equilibrium, and natural biotic interactions, such as herbivory by fish and urchins, historically maintained macroalgae at levels that allowed for coral dominance (Ostrander *et al.,*2000). The macroalgae (Chlorophyta, Phaeophyta, and Rhodophyta) play beneficial roles as primary producers and habitat providers (Robin *et al.,* 2017). However, this balance is easily disrupted. Anthropogenic nutrient loading fundamentally alters competitive interactions by providing macroalgae, which often have higher nutrient uptake rates and growth capacities than corals, with a crucial advantage (Voss, 2016). This eutrophication, combined with the physical space made available by coral mortality from bleaching or disease, creates an ideal environment for macroalgae blooms (Lesser, 2021)

Macroalgae growth is optimized under specific conditions; Nutrient availability, raised concentrations of dissolved inorganic nitrogen (ammonia, nitrate), and phosphorus are the primary catalysts formacroalgae blooms (Young, Gobler, 2016). Sources include sewage, agricultural fertilizer, and aquaculture effluent. Light and Substrate, adequate light for photosynthesis and available hard substrate, are essential formacroalgae colonization (Zainee, Rozaimi, 2020). Reduced Herbivory, overfishing such as parrotfish and surgeonfish, removes the primary top-down control onmacroalgae populations (Ober, 2016).

Climate Change as a force multiplier

Climate change exacerbates macroalgae threats synergistically with local stressors. Rising sea temperatures can directly stress corals (causing bleaching) while potentially enhancing the growth rates of some warm-adapted macroalgae (Macreadie *et al.,* 2017). Ocean acidification, driven by increased atmospheric CO_2, weakens coral calcification but may benefit non-calcifying, fleshy macroalgae by elevating the availability of aqueous CO_2 for photosynthesis (Ji, Gao, 2021). This creates a dual attack where corals are weakened and their competitors are strengthened (Celis-Plá *et al.,* 2017).

Ecological impacts of macroalgae dominance

Direct Coral Impacts, contact with macroalgae can cause coral tissue necrosis, reduce growth and fecundity, and inhibit larval recruitment through chemical (allelopathic) and physical mechanisms (Bender *et al.,* 2012; Lirman, 2001). Ecosystem-Level Shifts: Densemacroalgae mats alter reef biochemistry, promoting microbial respiration that leads to localized hypoxia and further acidification conditions lethal to corals (Mueller *et al.,* 2022). This can catalyze a persistent, alternative stable state where reef recovery to a coral-dominated system becomes exceedingly difficult (Bruno *et al.,* 2014).

Methodology

Study Site

The study was conducted at two reef sites in the Bawe and Changuu Islands, located west and northwest of Stone Town, Zanzibar, respectively. The data was collected at three points at each study site. Bawe (6°09’72.3"S, 39°08’19.2"E, 6°09’07.2"S, 39°08’24.3"E, 6°09’30.8"S, 39°08’08.8"E) and Changuu (6°06’55.1"S, 39°10’02.0"E, 6°07'01.9"S 39°10'04.8"E, 6°07'09.1"S 39°10'12.5"E). Changuu is a popular tourist destination with a history of intensive use, while Bawe is slightly more distant from the direct outflow of Stone Town's urban center.

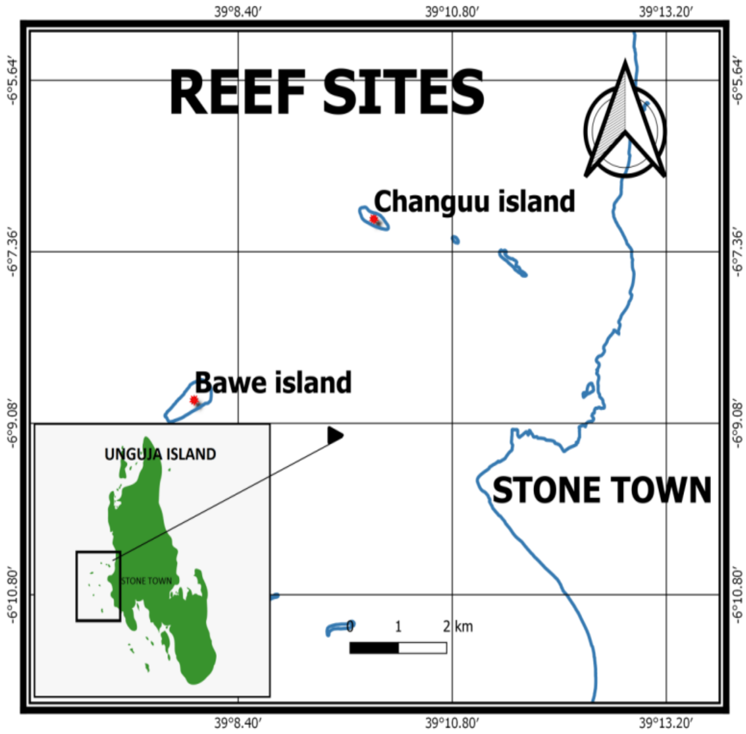

Figure 1 A Map of Unguja Island showing the location of the study

Data Collection

Benthic community data were collected using the Line Intercept Transect (LIT) method. At each island, 18 transects (20m in length) were randomly deployed across three reef zones: reef flat, crest, and slope. All benthic categories (hard coral, soft coral, macroalgae, corallimorpharians, sand, etc.) intercepting the tape were recorded to the nearest centimeter. Macroalgae were identified in situ to functional group (Chlorophyta, Phaeophyta, Rhodophyta) and, where possible, to genus level. Photographs were used for check specimens. Coral recruitment was assessed using 1m² quadrats placed at fixed intervals (4 meters) along each LIT. All coral recruits (colonies ≤10 cm in length) within each quadrat were counted. Sampling was conducted in December 2023 and January 2024.

Data Analysis

Benthic Cover: The percent cover of each benthic component was calculated per transect and averaged per site and reef zone. Statistical Testing: A t-test was used to compare mean macroalgae cover between islands. Pearson correlation analysis was performed between macroalgae cover and the abundance of individual coral genera to identify potential competitive interactions. Reef Health Assessment: A site-specific Coral Reef Health Index (CRHI) was adapted from the AGRRA protocol, integrating key metrics: hard coral cover, macroalgae cover, corallimorpharian cover, and coral recruitment density. Each metric was scored and aggregated.

Results

Macroalgae Cover and Community Composition

Three major macroalgae divisions were recorded across the study sites: Chlorophyta, Phaeophyta, and Rhodophyta, reflecting a diverse macroalgae assemblage on coral reef ecosystems. Identified taxa included *Ulva reticulata, Ulva pertusa*, and *Halimeda macroloba* (Chlorophyta); *Lobophora variegata, Padina boryana,* and *Sargassum oligocystum* (Phaeophyta); and *Eucheuma denticulatum* (Rhodophyta). The presence of fast-growing chlorophyta such as *Ulva spp*. The results are due to localized nutrient availability, while the dominance of brown algae, particularly *Lobophora variegata*, indicates tolerance to moderate sedimentation and environmental stress. Calcareous algae such as *Halimeda macroloba* contribute to reef sediment production and structural complexity whereas rhodophytes like *Eucheuma denticulatum* play a role in benthic habitat formation and nutrient cycling. Together, these taxa highlight functional diversity within the macroalgae community and provide insight into the environmental conditions shaping reef benthic composition at the study sites.

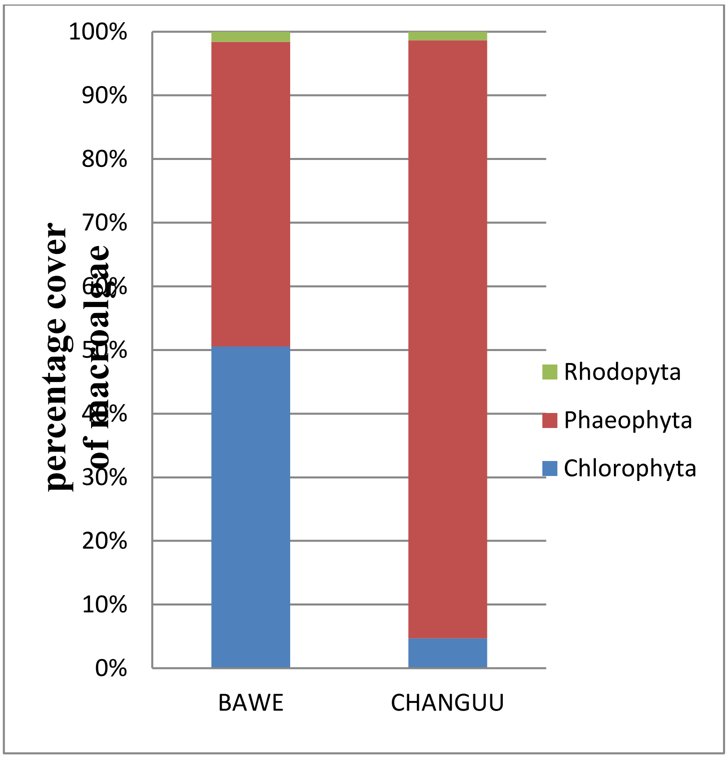

Figure 1. Macroalgae cover in study sites.

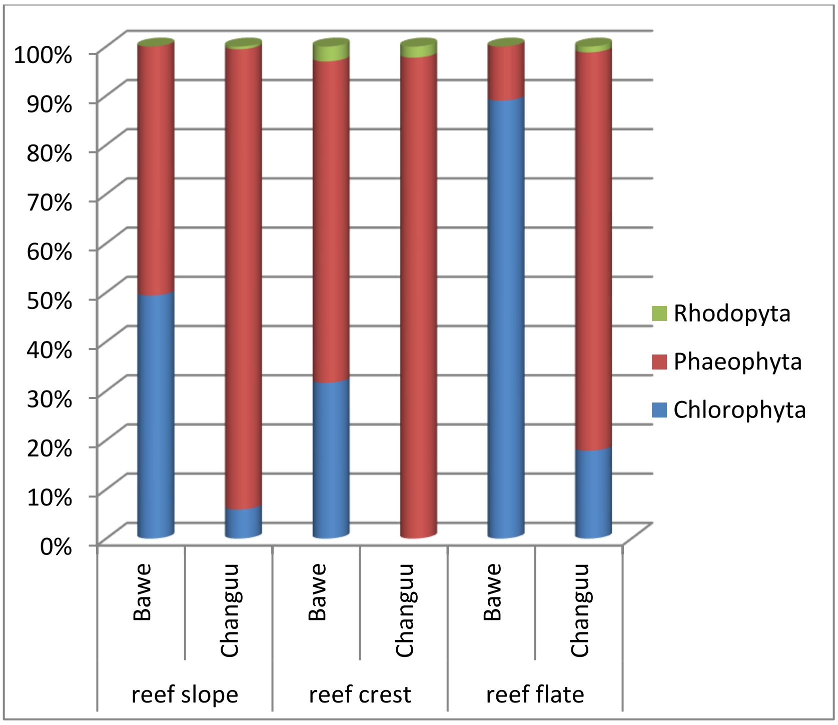

Figure 2 Percentage cover of macroalgae in reef zones

A highly significant difference (p = 0.0109) in macroalgae cover was found between islands. Changuu Island exhibited over four times the macroalgae cover (4.34% ± 1.2 SE) of Bawe Island (1.06% ± 0.4 SE). The community composition also fluctuated markedly (Fig. 1, 2).

Changuu: Dominated by Phaeophyta, particularly the genus *Lobophora variegata*, across all reef zones. These genera are known for their tolerance to moderate nutrient enrichment and sediment. Bawe; Exhibited a higher relative proportion of Chlorophyta (green algae), notably the fast-growing, nutrient-responsive genus *Ulva* (*U. reticulata, U. pertusa*), especially on the reef crest.

Correlation with Coral Genera

Correlation analyses between macroalgae cover and coral genera revealed generally weak to moderate positive relationships at both study sites, indicating limited direct competitive exclusion between macroalgae and corals. At Bawe Island, correlations between macroalgae cover and most coral genera were weak (r < 0.30), including *Acropora* (r = 0.271), *Echinopora* (r = 0.065), *Favia* (r = 0.147), *Favites* (r = 0.123), *Galaxea* (r = 0.143), and *Porites* (r = 0.210). Moderate correlations were observed only for *Montipora* (r = 0.393) and *Fungia* (r = 0.322), suggesting a limited tendency for these genera to co-occur with macroalgae. The overall weak associations at Bawe are consistent with the site's low macroalgae cover and indicate minimal interaction or competition between macroalgae and coral assemblages. In contrast, Changuu Island exhibited several moderate positive correlations, reflecting stronger co-occurrence patterns. Notably, macroalgae cover showed moderate relationships with *Physogyra* (r = 0.567), *Plerogyra* (r = 0.457), *Pavona* (r = 0.340), *Goniastrea* (r = 0.343), and *Pocillopora* (r = 0.335). These associations suggest that certain coral genera may tolerate or persist alongside macroalgae under shared environmental conditions, such as increased sedimentation or nutrient availability. Many other genera at Changuu, including *Acropora, Favia, Fungia*, and *Galaxea*, displayed weak correlations (r < 0.30), indicating variable responses among coral taxa.

Reef Health Assessment

Table 1 Reef Composition Assessment at Bawe

Reef Composition Assessment at Bawe			
Indicator	Value	Health Implication	Rating
Hard Coral	62.1%	Excellent primary builder	Excellent
Dead Coral	4.58%	Low mortality rate	Good
Corallimorpharians	12.4%	High - may indicate past stress	Concern
Macroalgae	1.06%	Very low competition	Excellent
Sand	9.78%	Normal for reef zones	Normal
Soft Coral	3.07%	Moderate diversity	Good
Other Biotic	7.02%	Includes sponges, etc.	Normal

Table 2 Reef Composition Assessment at Changuu.

Reef Composition Assessment at Changuu			
Indicator	**Value**	**Health Implication**	**Rating**
Hard Coral Cover	58.3%	Primary builder abundant	Excellent
Dead Coral	3.97%	Low mortality rate	Very Good
Corallimorpharians	12.1%	Competitive pressure	Concern
Macroalgae	4.34%	Minimal competition	Excellent
Sand	11.06%	Normal reef zone amount	Good
Coralline Algae	1.28%	Poor reef cementation	Low
Soft Coral Diversity	0.87%	Limited functional diversity	Low
Sea Grass Proximity	3.36%	Adjacent productive habitat	Positive

The result shown disproportion in macroalgae cover; both reefs displayed surprisingly healthy coral cover (Changuu: 58.3%, Bawe: 62.1%) and low dead coral cover (<5%) (Tables 1, 2). The adapted CRHI scores were high: 88/100 for Changuu and 83/100 for Bawe. The primary concern flagged by the index for both sites were the notable cover of corallimorpharians (~12%), a competing benthic group.

Coral recruitment

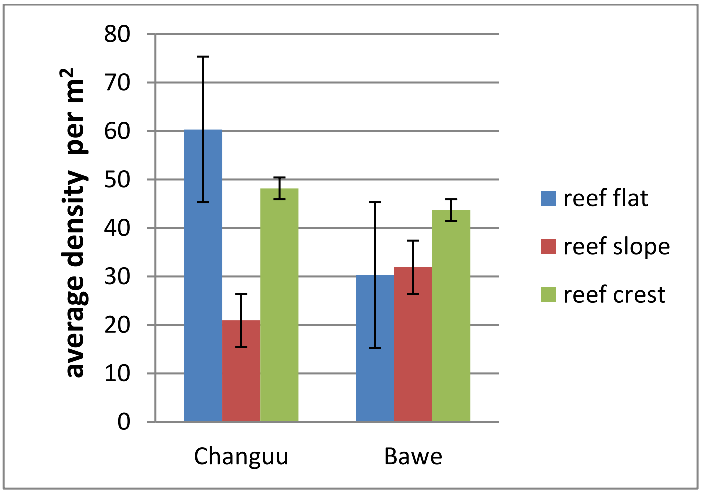

Figure 3. Coral recruitment at reef zone

The highest coral recruit density at Bawe Island was recorded on the reef crest (43.67 m^{-2}). By contrast, at Changuu Island, the reef flat exhibited the highest recruit density (60.33 m^{-2})

Discussion

Primary Driver: Land-Based Nutrient Pollution

The significantly higher macroalgae cover at Changuu Island is most parsimoniously explained by its greater exposure to land-based nutrient pollution. Its proximity to Stone Town, the source of untreated sewage discharge rich in ammonia and phosphates (Bergman, 2014), creates a chronic eutrophic condition, which supportsmacroalgae proliferation (Lapointe *et al.,* 2021). The dominance of Phaeophyta (*Lobophora*) at Changuu is indicative of a more recognized, chronic nutrient enrichment state, as these algae are competitive under sustained moderate nutrient loads. In contrast, the Ulva-dominated community at Bawe suggests a system responding to more diffuse nutrient inputs, as *Ula* is a classic opportunistic bloom genus.

A Resilient but Risky State

Reefs have not yet undergone a catastrophic phase shift and retain significant ecological function and resilience. The elevated macroalgae and corallimorpharian cover represents an alternate path of benthic succession. The reefs may be in a transitional state, where coral resilience is being slowly eroded. The high coral recruitment is a positive sign, but does not guarantee recovery if recruits are consequently competed by overgrowth of macroalgae and corallimorpharian.

Conclusion

This study shown that both Bawe and Changuu Islands support generally healthy coral reef ecosystems, despite significant differences in macroalgae cover and community composition. Macroalgae cover was higher at Changuu Island than at Bawe Island, but remained low at both sites and did not appear to impose strong competitive pressure on hard corals. Changuu reefs were dominated by stress-tolerant brown algae, particularly *Lobophora variegata*, whereas Bawe Island exhibited a higher relative abundance of fast-growing green algae (*Ulva spp*.), reflecting localized environmental conditions rather than reef degradation. Importantly, both reefs maintained high hard coral cover (>58%), low dead coral cover (<5%), strong coral recruitment across reef zones, and high Coral Reef Health Index scores, indicating good resilience and recovery potential. The main concern at both sites was the relatively high cover of corallimorpharians (~12%), which may signal past disturbance and poses a potential long-term competitive threat to scleractinian corals.

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