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Herbivorous fish biomass and benthic composition around Rodrigues Island, Western Indian Ocean

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Abstract. *Ricot M, Jeetun S, Jogee SY, Anasamy M, Kaullysing D, Taleb-Hossenkhan N, Bhagooli R. 2025. Herbivorous fish biomass and benthic composition around Rodrigues Island, Western Indian Ocean. Indo Pac J Ocean Life 9: 79-89.* Herbivorous reef fish play a critical role in maintaining coral reef resilience by controlling algal growth and facilitating coral recovery. This study assessed the biomass of herbivorous fish and benthic composition across coral-dominated (high live hard coral cover >20%) and non-coral-dominated (low live hard coral cover <20%) habitats at five sites, namely, Aquarium, Plateau Bénitier, Ti Trou, Antonio's Finger, and Couzoupa around Rodrigues Island, Western Indian Ocean. Fish biomass was estimated using triplicate belt transects, focusing on key herbivorous families (Acanthuridae and Scaridae), while benthic composition was quantified to identify habitat-specific patterns. Results revealed higher herbivorous fish biomass in coral-dominated habitats (1028.54±847.78 kg/ha) compared to non-coral-dominated habitats (728.34±229.36 kg/ha). No significant differences (p>0.05) were observed in the biomass of the Acanthuridae (p=0.56) nor Scaridae (p=0.36) fish families between coral-dominated and non-coral-dominated habitats. Coral-dominated habitats exhibited higher live hard coral cover (64.03±9.55%) compared to non-coral-dominated habitats (7.3±1.32%). Additionally, a significant interaction between protection status and live coral cover was observed, indicating that both protection measures and coral cover levels jointly influence herbivorous fish biomass. These findings underscore the importance of benthic habitat structure, particularly coral cover, in shaping herbivorous fish communities and supporting higher fish biomass in coral-dominated habitats.

Keywords: Coral reef, functional groups, marine protected areas, reef fish, reef fish assemblages, reef resilience, tropical islands

Abbreviations: CCA: Canonical Correspondence Analysis, WIO: Western Indian Ocean

INTRODUCTION

Coral reefs are among the most biodiverse and productive ecosystems on Earth (Singh et al. 2022; Sobha et al. 2023). They provide numerous ecosystem services that are essential for human well-being (MEA 2005; Woodhead et al. 2019; Hafezi et al. 2021; Santavy et al. 2021; Sing Wong et al. 2022). However, coral reefs face growing threats from human activities, including overfishing, pollution, and the impacts of climate change, all of which are changing species composition and altering fundamental ecological processes (Mora et al. 2011; Hughes et al. 2017; Williams and Graham 2019; Obura et al. 2022).

Herbivorous fish play an essential role in maintaining coral reef health by regulating critical ecological processes (Green and Bellwood 2009; Adam et al. 2015a; Dromard et al. 2015; Fong et al. 2018; Robinson et al. 2018; Donovan et al. 2023; Sheppard et al. 2023). Their abundance, size, and feeding behavior make them significant contributors to the stability of coral reef ecosystems (Bellwood et al. 2004; Hughes et al. 2007; Bosch et al. 2022; Kindinger et al. 2024). They help control the growth of benthic algae, mediating competition between algae and scleractinian corals for reef space (Mumby et al. 2006; Hughes et al. 2007; Knoester et al. 2023; Sheppard et al. 2023), thereby promoting coral resilience and preventing shifts to less resilient states (Mumby et al. 2006; Hughes et al. 2007; Holbrook et al. 2016; Nash et al. 2016; Schmitt et al. 2019, 2022; Cook et al. 2024; Tebbett et al. 2024). Fishing pressure on herbivorous fish is increasing globally, reducing their populations and impairing their ecological roles (Bellwood et al. 2004; Hughes et al. 2007; Bonaldo et al. 2014; Vergés et al. 2016; Robinson et al. 2020; Foo et al. 2021; Akita et al. 2022; Feitosa et al. 2023; Leitão et al. 2023; Asbury et al. 2024; Cook et al. 2024). Given their taxonomic and functional diversity, herbivorous fish target various benthic algae at different growth stages, further highlighting their importance in ecosystem functioning (Bellwood et al. 2004; Hughes et al. 2007; Plass-Johnson et al. 2015; Kelly et al. 2016; Mumby 2016; Siqueira et al. 2019; Pombo-Ayora et al. 2020; Sheppard et al. 2023).

Through top-down control, herbivorous fish regulate benthic structure and habitat complexity via algal consumption (Mumby et al. 2006; Bonaldo et al. 2014; Adam et al. 2015b; Bozec et al. 2016; Campbell et al. 2018; Ruttenberg et al. 2019). However, much of the research supporting this idea has focused on Caribbean reefs, and it is uncertain whether these mechanisms apply equally in other regions (Roff and Mumby 2012). In some cases, bottom-up processes, such as benthic habitat characteristics, may play a more significant role in determining fish populations (Friedlander and Parrish 1998; Friedlander et al. 2003; Messmer et al. 2011; Russ et al. 2021; Tony et al. 2021; Zuercher et al. 2023; Rempel et al. 2024). Studies conducted in the Philippines have highlighted strong bottom-up effects on parrotfish populations (Russ et al. 2015, 2018), with similar patterns observed in the Indian Ocean (Samoilys et al. 2018; Ricot et al. 2024). These system-specific differences suggest the need for more research to better understand the mechanisms at play in different coral reef ecosystems, as such patterns may vary across different parts of the Western Indian Ocean (WIO), depending on habitat type and the degree of fishing pressure.

Rodrigues Island hosts some of the most extensive coral reefs in the Indian Ocean (Bhagooli and Kaullysing 2019). The island's population has been engaged in fishing activities since the mid-18th century, with overfishing becoming an important issue by the early 20th century (Heemstra et al. 2004). Fishing methods, including seine nets, basket traps, and hook and line, have contributed to the decline of coral reef health, compounded by additional pressures from sedimentation, sea-level rise, cyclones, agricultural runoff, coral bleaching, coral diseases, and climate change (Heemstra et al. 2004; Turner and Klaus 2005; Klaus 2017; Bhagooli and Kaullysing 2019; Bhagooli et al. 2021; Jogee et al. 2023). This study aimed to explore the relationship between benthic characteristics and herbivorous fish populations around Rodrigues Island. Specifically, we examined herbivorous fish communities in two different habitat types: one with high live coral cover and low algal cover ("coral-dominated") and another with intermediate coral cover and intermediate or high algal cover ("non-coral-dominated"). We hypothesize that the composition of herbivorous fish assemblages and their foraging patterns will vary between these two habitat types.

MATERIALS AND METHODS

Site description

Rodrigues Island (19°42′59.99″ S, 63°24′59.99″ E) (Figure 1) is an outer autonomous island of the Republic of Mauritius that forms part of the Mascarene Islands. The island is situated in the southwestern part of the Indian Ocean (Figure 1.A) at around 560 km to the east of the island of Mauritius. The island measures 18 km in length and 6.5 km in width, with a total land area of 108 km^2. The island is surrounded by a large fringing reef, with an estimated area of 230.6 km^2 (Turner and Klaus 2005; Bhagooli and Kaullysing 2019). There are also four marine reserves (Passe Demie, Grand Bassin, Anse aux Anglais, and Rivière Banane) and one multiple-use marine protected area (South East Marine Protected Area - SEMPA) around the island (Figure 1.B). The chosen survey sites exhibited diverse levels of conservation measures and were subsequently categorized as either protected or non-protected based on their respective management protocols.

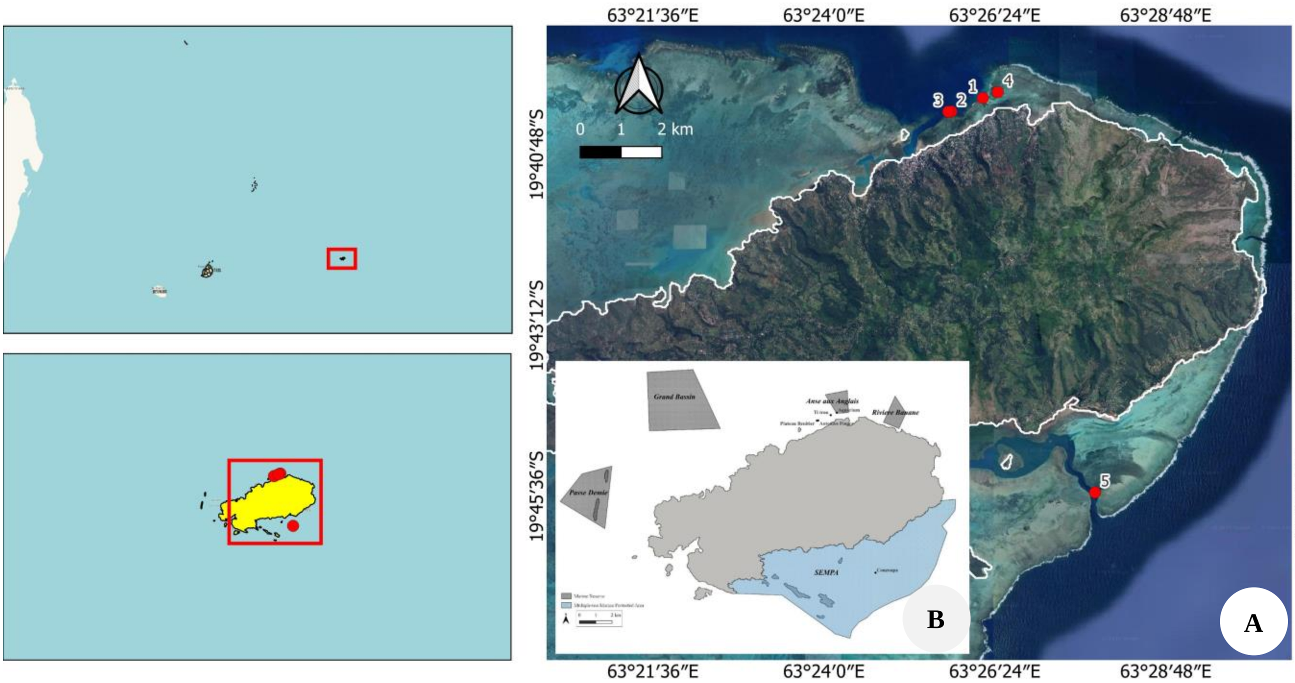

Figure 1. A. Location of Rodrigues Island in the Indian Ocean. B. Map of Rodrigues showing study sites around Rodrigues Island, Republic of Mauritius. 1. Ti Trou, 2. Antonio's Finger, 3. Plateau Bénitier, 4. Aquarium, 5. Couzoupa

Table 1. Summarized description of surveyed sites around Rodrigues Island

Sites	Depth (m)	Protected/non-protected	Coral-dominated/non-coral-dominated
Ti Trou	6-9	Non-protected	Coral-dominated
Antonio's Finger	6-9	Non-protected	Non-coral-dominated
Plateau Bénitier	6-9	Non-protected	Non-coral-dominated
Aquarium	6-9	Protected	Non-coral-dominated
Couzoupa	9-12	Protected	Coral-dominated

Table 2. Description of the different benthic categories

Benthic category	Definition
Live Hard Coral	Living stony corals with visible tissue and intact structure.
Dead Coral	Standing coral skeletons without living tissue.
Coral Rubble	Loose or broken pieces of dead coral lying on the seafloor.
Algae	Includes turf algae and macroalgae growing on the reef surface.
Sand	Unconsolidated, soft substrate made of fine particles or sediment.
Red coralline algae	Hard, encrusting or branching algae with a pink to deep red, often rough and calcareous surface that forms crusts or plates on rocks and coral reefs

This study was conducted from 17 to 20 December 2020. Five study sites (Table 1), namely Aquarium, Plateau Bénitier, Ti Trou, Antonio's Finger, and Couzoupa, were chosen around the island. Sites were selected based on logistical accessibility and prevailing daily weather conditions. Couzoupa is situated in the SEMPA and Aquarium in the Anse aux Anglais Marine Reserve. At the same time, all the other sites are located in a non-protected area in the northeast of Rodrigues. The classification of sites as coral-dominated or non-coral-dominated was based on the criteria established by McField and Kramer (2007), which define high live coral cover as hard coral accounting for more than 20% of the total benthic cover. Accordingly, sites with live coral cover exceeding 20% were classified as coral-dominated, while those with less than 20% were categorized as non-coral-dominated. The classification of sites as coral-dominated or non-coral-dominated was determined after data collection, based on the measured percentage of live hard coral cover recorded during the benthic surveys.

Benthic survey

The benthic cover was assessed in situ using visual estimation by a diver conducting surveys along a 50 m line-intercept transect. Surveys were conducted across sites with depths ranging from 6 m to 12 m. At each site, three 50 m transects were deployed, maintaining a minimum spacing of 15 m between transects. The percentage cover of live hard coral, dead coral, coral rubble, algae, red coralline algae and sand (each benthic category recorded is detailed in Table 2) was recorded following the methodology outlined by English et al. (1997). The number of transects per site was limited to three due to time constraints.

Fish surveys

Surveys were performed using scuba diving along 50×2 m belt transects, with three replicate transects deployed per site. Hence, to minimize potential biases associated with diver presence, such as fish displacement (push-pull effects), transects were spaced at least 15 m apart.

All individuals from the families Acanthuridae and Scaridae with a total length ≥3 cm were recorded and identified to species level. The Acanthuridae and Scaridae families were selected, as they represent two of the most frequently encountered reef fish families within the herbivorous trophic group. To ensure methodological consistency and minimize observer-related variability, a single observer conducted all surveys. Herbivorous fish were classified following criteria established by Ferreira et al. (2004) and Samoilys et al. (2018).

Fish biomass was estimated using species-specific length-weight relationships (Letourneur 1998). All recorded individuals from the Acanthuridae and Scaridae families with a total length (TL)≥3 cm were categorized into five size classes: 3-10 cm, 11-20 cm, 21-30 cm, 31-40 cm, and >40 cm. A representative length was assigned to each size category to facilitate biomass calculation. Individual weights were derived using the appropriate length-weight coefficients for each species. Estimated weights were calculated for each individual and subsequently aggregated at the transect level. Biomass was expressed in kilograms per hectare (kg/ha).

Data analysis

The data were organized into a series of matrices: benthic cover variable percentage, biomass of Acanthuridae, biomass of Scaridae. The Shapiro-Wilk test was used to assess the normality of the data. Natural $\log_{10}$ transformation was conducted on non-normal data (p<0.01) prior to conducting additional statistical analysis. The raw data failed to pass normality tests. Then, to determine any significant differences in biomass of Acanthuridae and Scaridae and benthic variable percentage among the surveyed sites around Rodrigues, the non-parametric Kruskal-Wallis test was utilized. The Mann-Whitney U Test (with Bonferroni correction) was used to test for any significant differences (α=0.05) in the benthic variable percentage and the biomass of Acanthuridae and Scaridae between the coral-dominated and non-coral-dominated sites. A two-way ANOVA was used to test for the effects of protection status, live coral cover, and their interaction on the biomass of Acanthuridae and Scaridae. Fish assemblage structure was characterized using the Shannon-Wiener diversity index (H′) and Pielou's evenness index (J′). All statistical analyses were conducted using MS Excel, SPSS (IBM Version 27), and XLSTATS Version 2023.3.0 (Lumivero 2024). Next, to investigate the associations between Acanthuridae and Scaridae fish families and benthic variables across survey sites, a Canonical Correspondence Analysis (CCA) was generated using XLSTAT Version

2023.3.0 (Lumivero 2024). The CCA was chosen for its suitability in examining the relationships between multivariate ecological data and environmental gradients, particularly when working with count or proportion data.

RESULTS AND DISCUSSION

Benthic composition

The benthic cover varied among the different surveyed sites around Rodrigues Island. A significant difference was observed in live coral cover (p=0.04), dead coral (p=0.037), algae (p=0.02), and red coralline algae (p=0.039) and across the sites (p<0.05), with live coral cover ranging from 64.03±9.55% to 7.3±1.32% (Figure 2). Couzoupa displayed the highest live coral cover, while Plateau Bénitier had the lowest live coral cover, nearly 9-fold lower than at Couzoupa. Dead coral cover ranged from 1.93±1.33% to 33±20.56%. The highest dead coral cover was recorded at the Aquarium, while the lowest was at Couzoupa. Rubble cover varied across sites, with Ti Trou exhibiting the highest rubble cover (40.6±13.16%), while Plateau Bénitier had the lowest rubble cover (16.8±1.78 %). Algal cover was highest at Plateau Bénitier (61.47±8.76 %), and red coralline algae was highest at Antonio's Finger, which had 23.53±17.71% cover. A significant difference was observed in live coral cover, algae, and red coralline algae between the coral-dominated and non-coral-dominated habitats.

The biomass of the Acanthuridae and Scaridae families, expressed in kg/ha, exhibited notable variation across the study sites; however, statistical analysis indicated significant differences in biomass of the Acanthuridae family only among the sites (p=0.03). Couzoupa recorded the highest biomass for both families, with Acanthuridae at 1,040.15±348.33 kg/ha and Scaridae at 798.96±304.15 kg/ha (Figure 3). Antonio's Finger also displayed relatively high biomass values, with Acanthuridae at 795.44±104.74 kg/ha and Scaridae at 289.21±115.10 kg/ha. In contrast, Plateau Bénitier exhibited the lowest biomass for both families, with Acanthuridae at 346.65±87.15 kg/ha and Scaridae at 139.61±121.51 kg/ha.

A total of 13 herbivorous fish species were identified across two habitats. Seven of these belong to the family Acanthuridae (surgeonfishes) and six to the family Scaridae (parrotfishes) (Figure 4). Of all the species, 12 were recorded in the non-coral-dominated (Figure 4.A) habitat and 10 in the coral-dominated (Figure 4B). The highest biomass was recorded for the species *Acanthurus mata* for the non-coral dominated habitats (358.23±194.13 kg/ha). In contrast, for the coral-dominated habitat, the *Chlororus sordidus* exhibited the highest biomass (388.09±361.34 kg/ha). The total biomass was higher in the coral-dominated habitats compared to non-coral-dominated habitats. However, the total biomass of individuals (kg/ha) showed no significant difference in the coral-dominated (1,028.54±847.78 kg/ha) and the non-coral-dominated (728.34±229.36 kg/ha) habitats. Moreover, no significant differences (p>0.05) were observed in the biomass of Acanthuridae and Scaridae between coral-dominated (641.7±494.3 kg/ha and 486.90±399.2 kg/ha, respectively) and non-coral-dominated habitats (538±218 kg/ha and 190.30±148.10 kg/ha, respectively). Shannon-Wiener diversity index was higher in coral-dominated habitats, with a value of 1.47, compared to 1.38 in non-coral-dominated habitats. Evenness was also greater in coral-dominated areas, reaching 0.64, while non-coral-dominated areas had a lower evenness of 0.56.

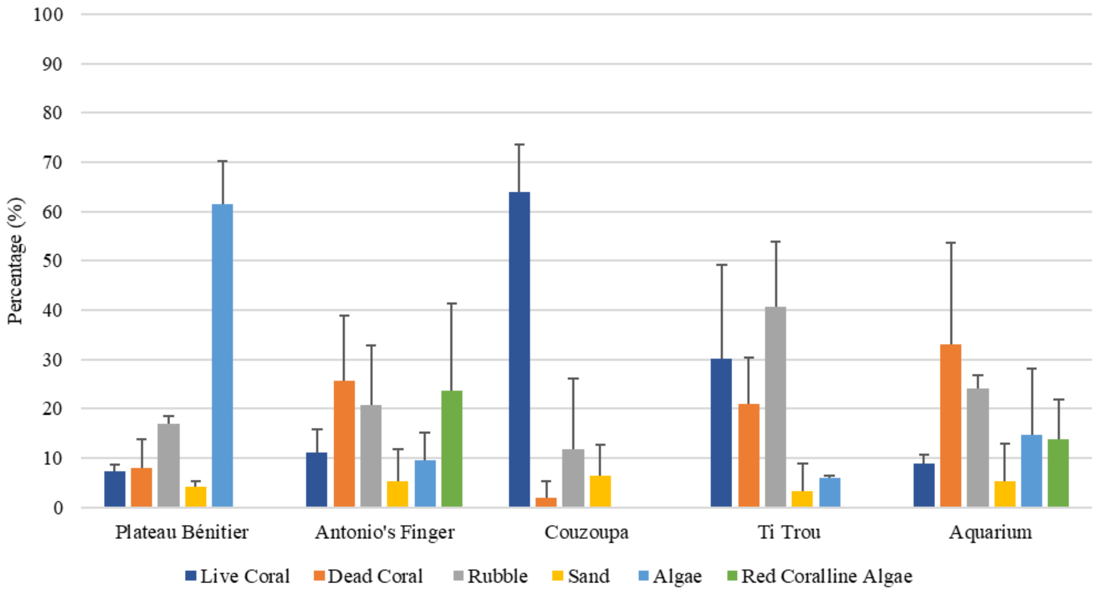

Figure 2. Benthic cover at the five surveyed sites around Rodrigues Island (bars represent mean ± standard deviation)

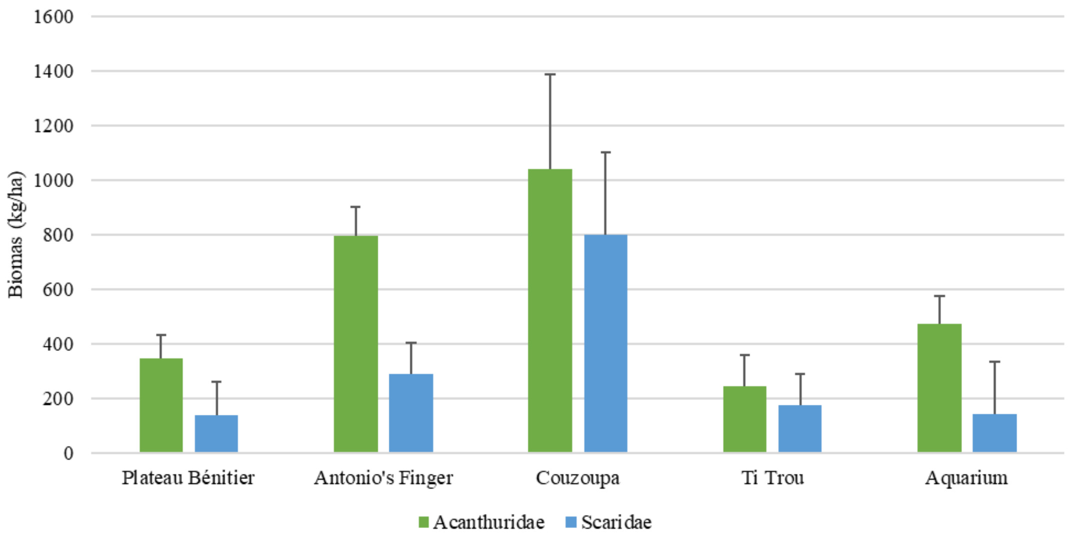

Figure 3. Biomass of the Acanthuridae and Scaridae at five studied sites around Rodrigues (bars represent mean ± standard deviation)

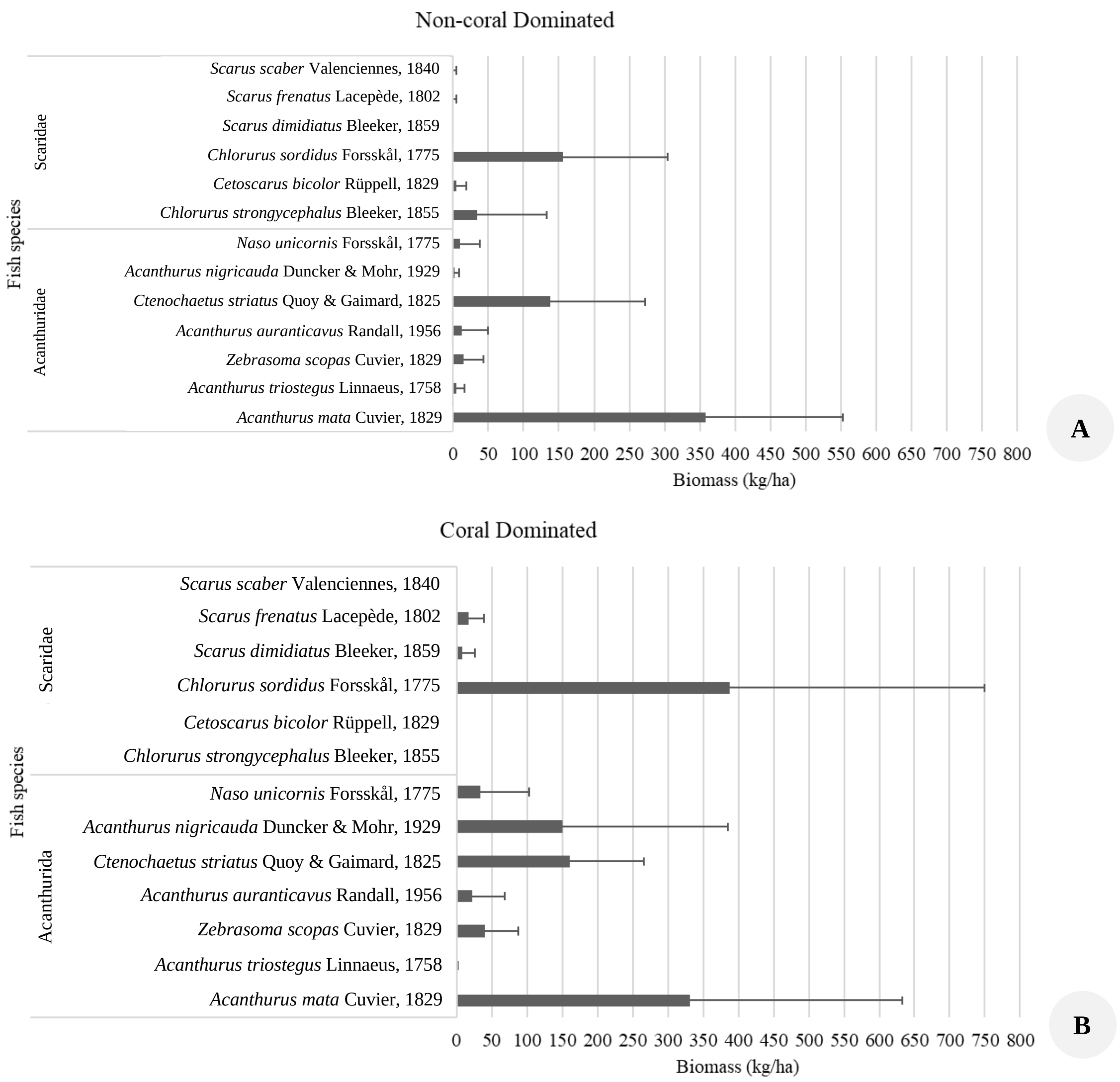

Figure 4. Biomass (kg/ha) of herbivorous fish species surveyed in A. The non-coral-dominated habitats, B. The coral-dominated habitats (bars represent mean ± standard deviation)

The effects of protection, live coral, and their interaction on the biomass of Acanthuridae and Scaridae revealed no significant main effects for protection or live coral on the biomass of either family (Table 3). Specifically, protection did not significantly influence the biomass of Acanthuridae (F=3.918, *p*=0.105) or Scaridae (F=4.289, *p*=0.093), nor did live coral cover have a significant effect on Acanthuridae (F=0.636, *p*=0.461) or Scaridae (F=0.525, *p*=0.501). However, a significant interaction effect was observed for Acanthuridae (F=11.074, *p*=0.021) and Scaridae (F=6.193, *p*=0.045), indicating that the combined influence of protection status and live coral cover levels significantly affected the biomass of these fish families.

The CCA biplot (Figure 5) illustrates the relationships between benthic habitat types and reef fish communities, with the first two principal components explaining 79.10% of the total variance (F1: 53.31%, F2: 25.79%). The active variables (red vectors) represent benthic habitat types and reef fish families, while the active observations (blue points) indicate sampling sites.

Live coral and sand are positively correlated with F1, alongside fish families such as Scaridae and Acanthuridae, while rubble, red coralline algae, and dead coral are associated with F2. Sampling sites such as Couzoupa are strongly aligned with live coral and Scaridae, whereas sites like Aquarium and Antonio's Finger are associated with dead coral, red coralline algae, and rubble. Ti Trou and Plateau Bénitier exhibit alignment with rubble and algae.

Table 3. Effects of protection, live coral cover, and their interaction on the biomass of Acanthuridae and Scaridae

Source	Dependent variable	F	Sig.
Protection	Acanthuridae	3.918	0.105
	Scaridae	4.289	0.093
Live coral cover	Acanthuridae	0.636	0.461
	Scaridae	0.525	0.501
Protection * Live coral cover	Acanthuridae	11.074	0.021
	Scaridae	6.193	0.045

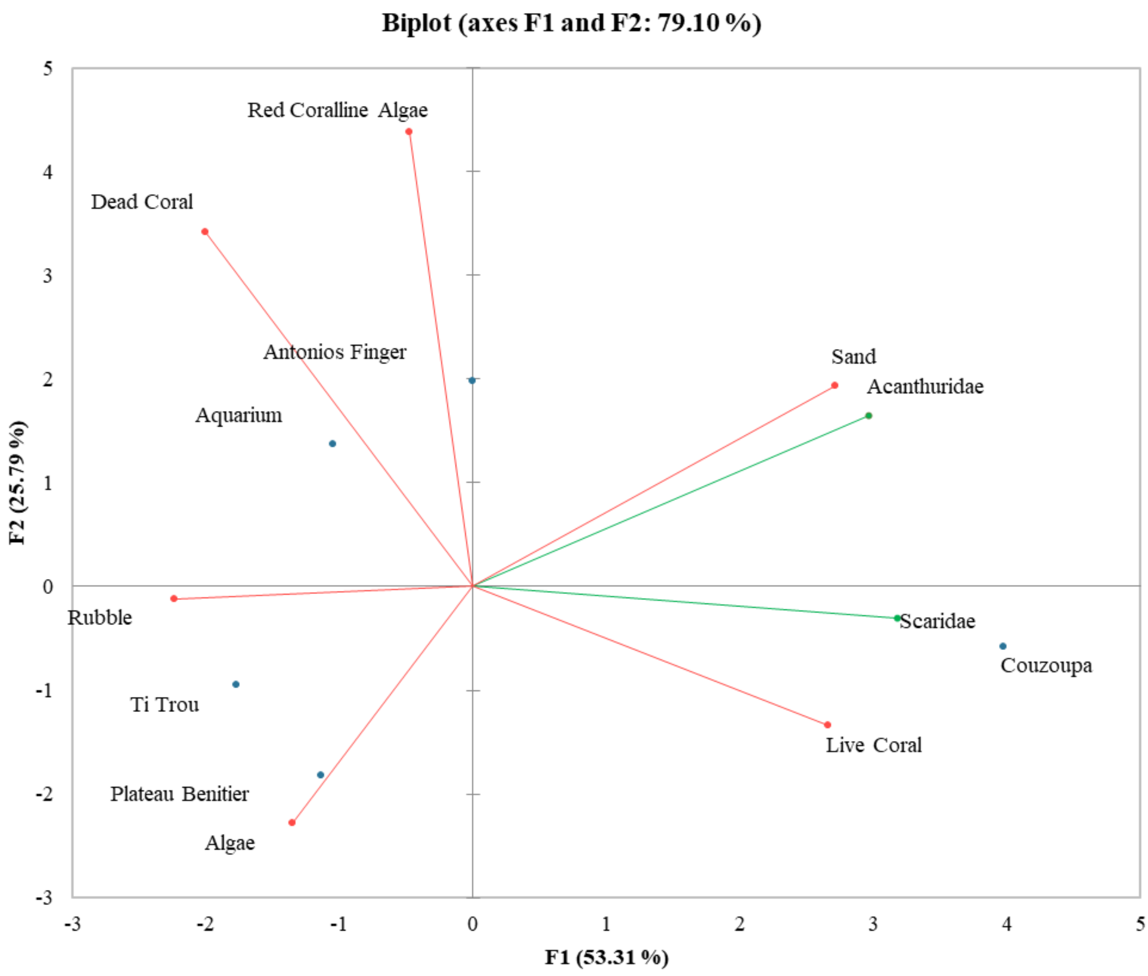

Figure 5. CCA biplot showing the relationships between benthic habitat types (red), reef fish families - Acanthuridae and Scaridae (green), and sampling sites (blue)

Discussion

In coral-dominated habitats, the highest biomass, diversity, and evenness of herbivorous fish were recorded. This suggests that coral-dominated habitats (sites with more than 20% live coral cover), could thus be providing essential habitat and dietary resources for an assemblage of herbivorous fish with higher species diversity. The positive association between live coral cover, benthic complexity, and fish community structure has been widely documented, with previous studies highlighting the role of structurally complex reef environments in sustaining high fish abundance and biomass (Jones et al. 2004; Messmer et al. 2011; Pratchett et al. 2011; Chong-Seng et al. 2012; Graham et al. 2015; Holbrook et al. 2015; Darling et al. 2017; Richardson et al. 2017, 2020; Russ et al. 2021; Helder et al. 2022; Fisher 2023).

The higher evenness observed in coral-dominated habitats indicates a more balanced distribution of ecological traits among herbivorous species compared to non-coral-dominated areas. In contrast, herbivorous fish in non-coral-dominated habitats exhibited lower biomass, species diversity, and evenness. Notably, parrotfish (Scaridae) species, which play a crucial role in removing turf algae and sediments (Adam et al. 2018; Abu-Taweel et al. 2023; Randazzo-Eisemann et al. 2024), had the lowest biomass in the non-coral dominated habitats. Similarly, apart from *A. mata*, most of the surgeonfish species that contribute to sediment removal, turf clearance, and crevice cleaning were less abundant, resulting in a functional decline within the herbivorous assemblage. The reduced structural complexity and limited live coral cover in non-coral-dominated habitats likely constrain niche availability and diminish protection from predators. Shelter from predators is an important resource in coral reef environments (Catano et al. 2016; Kerry and Bellwood 2016) and ultimately shapes the observed differences in herbivorous fish assemblages. While the ecological roles of herbivorous fish can differ depending on the habitat preference, the total biomass of herbivorous fish which presented no significant difference between coral-dominated and non-coral-dominated habitats remained an essential ecological component across all habitats, with their role in maintaining ecosystem balance being ecologically significant even in non-coral systems (Hardman et al. 2010). This is further reinforced by the knowledge that, even in severely damaged coral reef systems, fish herbivory is an essential ecological function (Plass-Johnson et al. 2015).

Habitat characteristics that benefit herbivorous fish in one environment may not have the same influence in another, as different environmental factors drive variations in fish abundance and biomass across habitat types. The close association observed between live coral cover and the Scaridae family may be attributed to the structural complexity associated with this benthic category (Friedlander and Parrish 1998). This aligns with broader trends indicating that higher biomass of larger reef fish, including Scaridae, is often correlated with structurally complex coral colonies (Roos et al. 2019; Fisher 2023; Sheppard et al. 2023). In contrast, Acanthuridae were more strongly associated with the benthic variable sand, consistent with findings from Hoey and Bellwood (2011) from the Great Barrier Reef, where herbivorous fish demonstrated a preference for open substrates over dense macroalgal stands. Herbivore habitat selection may also be influenced by top-down processes, particularly if refuge availability or the capacity to detect and evade predators is linked to habitat structure (Hoey and Bellwood 2011). In marine ecosystems, structural complexity is widely recognized as a key factor in mitigating predation pressure (Hensel et al. 2019; Santano et al. 2021; Chang and Todd 2023). Increased habitat complexity, provided by corals in tropical environments, has been shown to reduce fish mortality by offering spatial refuge from predators (Anderson 2001; Holbrook and Schmitt 2002). The apparent avoidance of structurally complex patches by certain herbivorous fish species may reflect an aversion to habitats where predator presence is likely rather than a direct response to predation itself (Verdolin 2006). Additionally, coral-dominated habitats by exhibiting increased structural complexity, also support a greater diversity of foraging niches, which collectively contribute to sustaining higher biomass levels of herbivorous fish, particularly within grazing guilds (Brooker et al. 2013; Wen et al. 2013). In contrast, habitats with low coral cover generally possess lower structural heterogeneity, thereby reducing both the availability of shelter and the quality of feeding substrates, ultimately limiting their capacity to support dense herbivorous fish populations (Sánchez-Caballero et al. 2016; Ho et al. 2018).

Marine Protected Areas (MPAs) serve as an essential management tool for conserving marine resources and habitats by restricting activities that contribute to habitat degradation (Cortés-Useche et al. 2021). Our findings indicate that the coral-dominated site Couzoupa, located within an MPA and exhibiting the highest live coral cover among the studied sites, together with the significant interaction effect observed for herbivorous fish families Acanthuridae and Scaridae suggests that both protection status and coral cover levels play a key role in shaping their biomass. These results align with previous studies demonstrating that effective MPA management enhances reef fish communities, leading to increased fish density and biomass (Halpern and Warner 2002; Muallil et al. 2015; Chirico et al. 2017; Cabral et al. 2020; McClure et al. 2020; Thiaw et al. 2021; Ziegler et al. 2022; Frid et al. 2023).

The ecological significance of coral reefs within MPAs further underscores the need for targeted conservation measures. In Rodrigues, corals are considered the most well-developed and substantial in the Mascarene region (Montaggioni and Faure 1980; Bhagooli and Kaullysing 2019) and play a crucial role in ecosystem functioning, including carbon cycling (Fenner et al. 2004; Payet and Agricole 2006). The association of the coral-dominated site Couzoupa with live coral cover, shown by the results and the significant interaction effect for the herbivorous fish Acanthuridae and Scaridae, highlights the importance of protecting these foundational habitats to sustain reef fish populations. Given the small size of Rodrigues Island and the pressures on its coastal resources (Heemstra et al. 2004; Turner and Klaus 2005; Klaus 2017; Bhagooli and Kaullysing 2019; Bhagooli et al. 2021), MPAs provide a valuable framework for safeguarding reef ecosystems while supporting sustainable fisheries management as part of an integrated coastal zone management strategy (Bunce et al. 2008; Costello and Ballantine 2015; Cortés-Useche et al. 2021; Grorud-Colvert et al. 2021; Horta e Costa et al. 2022; Masud et al. 2022; Nowakowski et al. 2023). These findings emphasize the critical role of habitat structure in shaping herbivorous fish assemblages and highlight the need for continued monitoring and adaptive management strategies to ensure the long-term sustainability of coral reef ecosystems on Rodrigues Island.

In conclusion, the results of this study highlight the critical role of live coral cover in sustaining herbivorous fish biomass around Rodrigues Island. While no significant differences were observed in the biomass of the Acanthuridae and Scaridae fish families between coral-dominated and non-coral-dominated sites, the significant interaction between protection status and live coral cover indicates that the combination of effective management and habitat restoration may play a crucial role in supporting herbivorous fish populations. Future research should focus on investigating temporal variations in herbivorous fish biomass and benthic composition to understand the long-term stability of these communities better. Furthermore, incorporating additional environmental variables such as ocean currents, temperature, and nutrient availability would provide a more refined understanding of the factors driving the observed ecological patterns. The limitations of this study, including the relatively small number of transects and the spatial scale, should be acknowledged. Larger-scale, long-term studies are necessary to obtain more robust and generalizable data, enabling a more comprehensive understanding of the complex interactions between benthic habitats, fish populations, seasonal variability, and conservation management. Such research will be essential for informing more effective, evidence-based conservation strategies aimed at preserving the integrity and function of coral reef ecosystems.

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