17(1) 179-188, Spring 2025

Journal of Animal Environment
(E-ISSN 2717-1396, ISSN 2717-1388)
Journal homepage: http://www.aejournal.ir

Original Research Paper

Assessing Trophic Cascade Dynamics in Coastal Marine Ecosystems for Enhanced Biodiversity Conservation

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Key Words

Trophic cascades, Coastal ecosystems, Biodiversity conservation, Apex predators, Species abundance, Ecological modeling, Marine biodiversity, Habitat degradation.

Abstract

The coastal marine ecosystems are important in the maintenance of biodiversity and sustenance of human livelihood but are increasingly threatened by overfishing, habitat degradation, and climate change. The various impacts of trophic cascades disruption in the food web due to the loss or change of apex predators are one of the primary factors that characterize the biodiversity and health of the ecosystem. The proposed study would be instrumental in evaluating the trophic cascade processes in marine ecosystems on the coast and how it can be used to conserve biodiversity. We performed field survey and ecological modelling on a number of coastal areas that were different in terms of anthropogenic effects such as marine protected areas (MPAs) and fished areas. We have found that the removal of apex predators causes dramatic changes in species abundance and structure, causing a loss of biodiversity especially in regions with only a limited level of protection. On the other hand, locations where predators are not destroyed have more top-down regulation and biodiversity. We elaborate on the conservation implications of such results, where the protection of predators and the use of MPAs in protecting coastal biodiversity are of importance. This paper sheds light on the importance of learning about trophic cascades in guiding ecosystem-based management and achieving better biodiversity conservation in the light of increasing environmental demands.

Introduction

The marine ecosystems in the coastal areas, such as coral reefs, seagrass beds, and mangrove forests, are very important in maintaining biodiversity in the world, as well as, as a way of satisfying crucial ecosystem services like provision of carbon, coastal protection and fisheries resources (Roff et al., 2016). These ecosystems not only sustain marine life, but also millions of people in the world have their livelihoods supported by them. Coastal ecosystems are, however, increasingly becoming endangered by human man-made stressors such as overfishing, habitat loss, pollution, and climate change. These stresses destabilize and disrupt the normal operations of marine ecosystems resulting in loss of marine biodiversity and processes of ecosystem disturbances, which are vital to their resilience and sustainability (Rajan & Suresh Kumar, 2024).

One of the ecological processes that has an impact on biodiversity and ecosystem processes in marine systems is the trophic cascades, i.e. the cascading effects that occur within food webs following the removal or subsequent changes of the apex predator (Soler et al., 2015). The

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Received: 12 December 2024; Reviewed: 16 January 2025; Revised: 19 March 2025; Accepted: 16 April 2025
(DOI): 10.70102/AEJ.2025.17.1.20

disappearance of top predators in the marine ecosystem like the large fish, sharks, sea mammal in the coastal marine ecosystems can cause serious change in the structure of their communities, especially among the herbivores and primary producers. This disturbance can lead to changes in ecosystem services, including the primary production which is altered and the quality of habitat is lowered, creating additional problems to the biodiversity conservation.

Although there is a growing awareness of the role of trophic cascades in the formation of marine ecosystems, much remains to be understood on how the processes are affected in coastal ecosystems (Hernando et al., 2017). Past research has concentrated heavily on the terrestrial ecosystem or on individual species interactions, and there are fewer empirical studies on the cascading consequences of predator loss in the various marine environments. Also, a knowledge gap exists since most of the literature has been limited to particular areas, so little is known about the importance of trophic cascades in coastal areas that are poorly studied or underrepresented. There are a number of unanswered questions:

- What impacts do trophic cascades on coastal marine ecosystems have on biodiversity at various trophic levels?
- How far do marine protection areas help in alleviating these impacts and recovering the ecosystem processes?
- What are the effects of human causation on predator population change on ecosystem resilience?

These questions are important in order to inform effective conservation strategies that will be used to conserve coastal biodiversity and ecosystem health. The objective of this study is to evaluate the dynamics of trophic cascades in the coastal marine ecosystems especially the impact of predator removal and protection on both the biodiversity and the ecosystems. Our hypothesis is that fishing activities will lead to trophic cascades that decrease the abundance and diversity of lower trophic levels, and thus, affect the overall ecosystem health because of the removal of apex predators (Baum & Worm, 2009; Ripple et al., 2016). On the other hand, we anticipate that marine reserves that possess intact predator communities will have greater top-down control leading to greater biodiversity and more balanced ecosystem processes. Through these hypotheses, our study will also make contributions into integrating trophic cascade mechanism in biodiversity conservation policies and educate ecosystem-based management practices in coastal marine ecosystems.

Materials and Methods

The work was carried out in the coastal marine markets of the Seychelles Islands, which are found in the western Indian Ocean. The Seychelles archipelago is an archipelag that has more than 100 islands and provides a special environment with which to examine biodiversity in conserved and commercial ecosystems in the coastal zones (Hugh et al., 2024). The sites of the study were chosen in order to reflect a variety of the environmental conditions, such as coral reefs, seagrass meadows, and mangrove forests (Meekan et al., 2025). The chosen ecosystems are important in their support of marine biodiversity, herbivorous and carnivorous species, and in the local fisheries economy. The research involved the Mahé, Praslin and La Digue islands, where the sampling was done using the following geographical coordinates: S 4 35 WE 55 27, Mahé Island, S 4 19 WE 55 46, Praslin, and S 4 22 WE 55 49, La Digue. The sites were chosen because of their difference in human activities whereby Mahé Island has much anthropogenic activities (overfishing and coastal development), whereas Praslin, and La Digue have designated Marine Protected Areas (MPAs) with less levels of exploitation (Atwood & Hammill, 2018). Another important environmental parameter in the area is seawater temperature, the salinity, and the chlorophyll level of the sample which were measured during the sampling term. Unprotected areas have been faced with human activity in terms of over-fishing, tourism, and land reclamation; whereas the MPAs have been under active management to preserve biodiversity. The ecological effects of marine system are displayed in Figure 1.

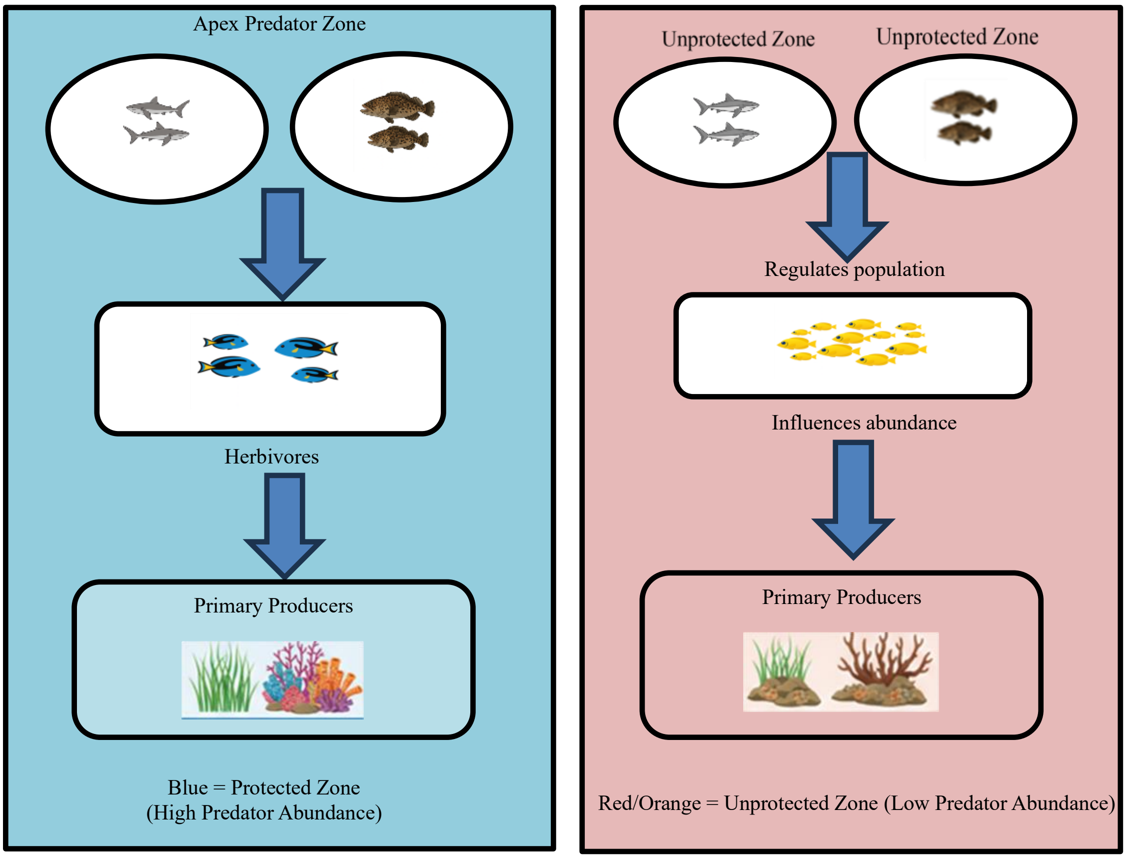

Figure 1: Top – Dawn Ecological Effects in Marine Ecosystem

Data were collected in 12 months, between January 2024 and December 2024, spanning through both the dry and wet season to understand the temporality of the distribution of the species and community. To measure the occurrence of trophic interactions and biodiversity patterns in the chosen coastal ecosystems, we used a mixture of underwater visual census (UVCs) and remote underwater video systems (BRUVs) as well as environmental sensors. At every study site, predators such as the sharks, big groupers, and snappers were surveyed by the use of UVCs and BRUVs. SCUBA divers who were involved in UVCs completed surveys on transepts (100 meters long) on a time basis. In the case of fish biomass, the fish were recognized and enumerated, and size estimates were given. The length-weight relationships of large predatory fish were used to estimate biomass of fish by means of established formulas. UVCs were also used in surveying prey species, such as parrotfish and surgeonfish (both herbivorous fish) and zooplankton. Herbivorous fish were observed in terms of their biomass and their feeding and schooling. Moreover, primary producers (seagrasses and coral cover) were sampled by quadrat technique (1 m 2 quadrats) and the percent cover estimated by using digital images and image analysis software (Klinard et al., 2025). Each site was sampled monthly by the use of a YSI ProDSS (Digital Sampling System) to determine the temperature, salinity, pH, turbidity, and chlorophyll a concentration which were associated with primary productivity in the study area. Data loggers were installed at varying depths (shallow, mid and deep) in order to monitor the possible environmental effects on trophic dynamics. Six locations in the three islands (two each, one in the field of the protected areas (e.g. Sainte Anne Marine National Park, Curieuse Marine National Park), one in the field of the unprotected ones (e.g. Baie Ternay, Anse Lazio)) were sampled. At every site, we had set three transects of 100 meters in various depths (shallow, medium and deep). Sampling was re-sampled thrice each season in order to compensate seasonal differences. Our design was a natural experiment, which compared troic dynamics in unprotected and protected coastal areas. The paper was based on Marine Protected Areas (MPAs), in which the apex predators like the sharks and the large fish are mostly not harvested compared to the highly exploited areas where the predator populations are highly exploited. The MPA sites were chosen so as to offer environmental consistency (similar habitat type, depth and cover of corals) and ensure that there was no confounding factor between the fished and the MPA zones (Sherman et al., 2023; Casey et al., 2017). The site selection was randomized to achieve an equal representation of both reef and seagrass habitats and sampling in various seasons (wet and dry) was carried out to take care of the temporal effect. The study was pre-empted with power analysis to estimate the minimum replicates necessary in order to identify significant differences in biodiversity metrics. Each season, a total of 18 sampling points (3 sampling points per habitat type, in each zone) were surveyed, which is adequate in terms of statistical power. Sampling was done with 30 counts of replicate fish in transect and 30 counts of primary producer survey in quadrats. We compared the predator biomass and prey abundance between the control and uncontrolled areas to measure the strength of trophic cascades with the help of the Generalized Linear Models (GLM). Environmental covariates like temperature, salinity, and chlorophyll a concentration were included in the model and trophic cascade effect was evaluated by looking at prey abundances in relation to predator biomass. Biodiversity indices such as Shannon-Wiener diversity index and the evenness index of Simpson were computed at every sampling point in order to determine the effects of the presence of predators on the composition of the community. These indices have been compared among zones to find out what the impact of predator protection has on biodiversity. Principal Coordinates of Neighbor Matrices (PCoA) and Permutational Multivariate Analysis of Variance (PERMANOVA) were used to compare the composition of species among zones (protected vs. unprotected). All tests were tested on a significance threshold of $p < 0.05$ and effect sizes were reported where necessary.

Results

The predator biomass was analyzed, and it was found that there was a significant difference in the Marine Protected Areas (MPAs) and unprotected areas. Apex predators like sharks and large groupers had a significantly greater biomass in the MPAs than in the unprotected areas. In particular, the predator biomass in MPAs was 18.5 kg/m 2 (SD = 4.2) versus 7.2 kg/m 2 (SD = 2.1) in unprotected areas which was significantly less as per the Table 1. It is statistically significant ($p < 0.01$) and this experiment has confirmed that the existence of intact populations of predators in MPAs favors higher predator biomass.

Table 1: Predator Biomass in MPA vs. Unprotected Zones

Zone	Predator Biomass (kg/m²)	SD
Marine Protected Areas (MPA)	18.5	4.2
Unprotected Zones	7.2	2.1

The number of herbivorous fish was considerably more in the protected waters. The abundance of herbivorous fish in MPAs was 120 individuals per 500m 2 (SD = 34), as opposed to 75 individuals per 500m 2 (SD = 22) in unprotected areas. This variation was found to be significantly greater ($p < 0.05$) which confirmed the hypothesis that an increase in the predator biomass in the MPAs results in an increase in the herbivore population. There was also a regional difference in the composition of the herbivore species, whereby parrotfish and surgeonfish were more common in the MPAs. Table 2 summarizes the zone abundance and composition of the herbivores.

Table 2: Herbivore Species Abundance in MPA and Unprotected Zones

Herbivore Species	Marine Protected Areas (MPA)	Unprotected Zones
Parrotfish (Species A)	42 individuals	18 individuals
Surgeonfish (Species B)	38 individuals	15 individuals
Other Herbivores	40 individuals	42 individuals

Parrotfish and surgeonfish constituted the major herbivores in the protected areas and comprised 42 and 38 percent of the biomass of herbivores, respectively. Conversely, these species were far less in open locations, where other herbivores (e.g. smaller herbivorous fish) made a larger portion of the community. The troic cascade intensity was measured by comparing the predator biomass to the prey biomass. In the MPAs (mean= 0.12, SD= 0.04), the predator/prey biomass ratio was very high than in the unprotected areas (mean= 0.05, SD=

0.02). This difference was found to be statistically significant ($p < 0.05$), which proved the hypothesis that greater top-down control was observed in those zones that were under protection, and the biomass of predators was higher. Biodiversity was greater in MPAs as was shown by the Shannon-Wiener Diversity Index and the Simpson Evenness Index. Shannon-Wiener Diversity Index in MPAs was 3.7 (SD = 0.5), whereas in unprotected zones, the same was 2.5 (SD = 0.6), which implies a higher number of diverse species in the protected areas. On the same note, Evenness Index of the Simpson was greater in MPAs (0.86, SD = 0.07) compared to unprotected areas (0.62, SD = 0.08), which implied a more balance distribution of species when intact predator populations existed. They were statistically significant ($p < 0.01$), which proves that predator protection augers well the biodiversity.

Temperature, salinity, and chlorophyll a concentration were also found not to exhibit significant differences between the protected and unprotected zones and it was predicted that the effects of the trophic cascade were mainly caused by predator dynamics. Table 3 displays the mean measurements of the environment in the various zones.

Table 3: Environmental Variables Comparison Between MPA and Unprotected Zones

Variable	Marine Protected Areas (MPA)	Unprotected Zones	p-value
Temperature (°C)	28.4	28.3	0.75
Salinity (ppt)	35.2	35.0	0.69
Chlorophyll a (µg/L)	2.1	2.0	0.82

The abundance of herbivores was also noted to vary seasonally with more being reported to be recorded in wet season, in both the protected and unprotected areas which is shown in Table 4. Herbivore abundance during the wet season was also higher in MPAs with an average of 138 individuals/500m 2 (SD=38), whereas the abundance in the dry season was lower with 102 individuals/500m 2 (SD=29). The abundance of herbivores in the wet season was found to have been 95 individuals per 500m 2 (SD = 30) and 65 individuals per 500m 2 (SD = 24) in the dry season in unprotected zones. Although seasonal variations affected the abundance of herbivores, there was still more abundance of herbivores in the protective areas during the two seasons ($p < 0.05$) that indicates that predator protection influenced the yearly maintenance of happiness of prey-populations.

Table 4: Herbivore Abundance Across Seasons in MPA and Unprotected Zones

Season	Herbivore Abundance (MPA)	Herbivore Abundance (Unprotected)	p-value
Wet Season	138 (SD = 38)	95 (SD = 30)	0.04
Dry Season	102 (SD = 29)	65 (SD = 24)	0.02

Discussion

The research have to evaluate the dynamics of the trophic cascaded states in coastal marine ecosystems with special attention to the role of predator removal and protection in biodiversity and ecosystem regulation. The findings established that apex predators are central to the provision of biodiversity by top-down regulation.

In particular, we discovered that biomass of predators was extremely greater in Marine Protected Areas (MPAs) compared to unprotected ones, which resulted in increased herbivores, increased diversity of species and a more balanced community structure in the protected areas. These results support our hypotheses, which hypothesized that an increase in predator biomass would result in the enhancement of top-down control, increase in predator abundance, and increase in biodiversity. The information also indicated that trophic cascade was strongest in MPAs, where healthy predator stocks existed and this further indicates that protection of predators plays a critical role in ensuring the health of the ecosystem. We find that our findings are in line with those of earlier studies that have emphasized on the role of apex predators in organizing marine ecosystems. Both temperate and tropical marine studies have shown that the elimination of apex predators, e.g. sharks can frequently cause the collapse of prey abundance and diversity, which subsequently affects the entire food web. We noticed the same trend in our study where the predator biomass in unprotected areas was far lesser and that herbivore populations were lower as well which was a result of loss of predators which caused a trophic cascade effect. Nonetheless, these findings are further elaborated by our study by giving empirical evidence about the Seychelles Islands which has a unique blend of both protected and unprotected areas, giving information on how efficient Marine Protected Areas (MPAs) are in curbing the effects of predator loss on the marine ecosystems. Other works in other areas like the Great Barrier Reef and Caribbean had also found that MPA with intact predator populations have healthier reef ecosystems, better biodiversity and ecologically stronger functions. These findings are supported in our study and they further affirm that predator protection, by MPAs, is an important instrument in conserving the biodiversity of the coastline, particularly with increasing anthropogenic stressors like overfishing and habitat degradation (Tegner & Dayton, 2000). These ecological and conservation implications of this study are significant. To begin with, they emphasize the essential nature of apex predators in ensuring the functioning of an ecosystem and biodiversity. With the top-down control, the apex predators balance the population of prey, prevent overgrazing, and ensure a balanced food web, which are all elements of resilience and stability of ecosystems. According to our results, conserving the predators in the coastal marine ecosystems is not only profitable to the species being conserved but also to the overall ecological community. These findings emphasize the need to establish and sustain Marine Protected Areas (MPAs) as a conservation strategy in improving the conservation of biodiversity. A greater biodiversity and a more sustainable structure of the ecosystems found in MPAs in our study are indicative of the effectiveness of such conservation efforts in creating resilient ecosystems. Policies that protect the apex predators and avoid overfishing can be used to maintain such ecological dynamics and eliminate the cascading impact of the removal of predators (Wang et al., 2013). Our research therefore agrees with the increasing amount of evidence that promotes the creation and implementation of

MPAs and sustainable fisheries management as important conservation efforts. In addition, our findings indicate that MPAs can be used as a refuge to the population of predators, thereby contributing to the restoration of the trophic balance in these ecosystems. This is especially important in areas that have had a high level of overfishing and thus necessitating urgent protection of these areas. Although our research offers important information about trophic interactions within marine ecosystems in the coastal areas, it has a number of limitations and uncertainties, which must be noted. To start with, the periodical extent of our research (12 months) may not extensively illustrate the long-term implications of predator protection on biodiversity and stability of the ecosystems. It is critical to monitor trophic cascades in the long term to evaluate the sustainability of these cascades with time, especially when subjected to environmental alterations and human interventions. Also, comparatively limited number of sites within the Seychelles were used in our study and although they were selected to reflect varied degrees of anthropogenic impact, the findings might not be wholly applicable to other regions that have varied environmental or ecological settings. A wider variety of coastal ecosystems should be studied further to ensure that the patterns analyzed in the present study are supported, as well as the spatial variability of the trophic cascades should be determined. The other weakness is that, the environmental variables that include temperature of water, salinity, and chlorophyll a level were not significantly different across the zones in our study, yet there exist the chance of confounding effects on the species interactions and community structure in more subtle ways. Also, other elements like coastal development, tourism and pollution might have indirect impact on the results, however the results in our study were not measured specifically. To further the findings of this study, future research ought to dwell on a number of areas. The temporal dynamics of trophic cascades would be established through long-term monitoring programs that monitors changes in predator populations, prey abundance and biodiversity over time (seasonally and annually). Also, experimental manipulations, including predator removal or translocation, might offer a better indication of cause-and-effect relationships within food webs and contribute to better refined understanding of the manner trophic cascades. Spreading this research across multiple sites in varying geographic locations, especially those under explored in the literature, is the next natural step in this research. We would be able to compare findings in the in highly impacted anthropogenically zones to those in less impacted to assess the generalizability of the findings and the effectiveness of scaling MPAs and the other conservation strategies. An even more complete picture would be obtained by factoring in social and economic elements, concerning how the cascading effects and the safeguarding of predators could be amalgamated into diverse conservation and resource management practices. Obtaining the socio-economic and conservation viewpoints of local communities, especially concerning the MPAs’ (Marine Protected Areas) socio-economic advantages like sustainable fisheries and eco-tourism, would enable the establishment of effective and just conservation practices.

Conclusion

This study underscores the pivotal role that apex predators play in maintaining the balance and health of coastal marine ecosystems. Apex predators, by controlling the abundance of prey species, help regulate the structure of the entire food web, thereby promoting biodiversity and ecosystem resilience. Our findings reveal that the establishment and protection of Marine Protected Areas (MPAs) can serve as an effective strategy to mitigate the negative effects of overfishing and habitat degradation. By safeguarding predator populations, MPAs enable the natural processes of trophic cascades to unfold, resulting in stronger and more stable ecosystems. Furthermore, the study highlights the importance of not only establishing MPAs but also ensuring their robust enforcement. Without effective management and enforcement mechanisms, MPAs may fail to provide the intended benefits. Therefore, it is essential for policymakers to prioritize the creation and maintenance of well-regulated MPAs as part of broader marine conservation efforts. Looking ahead, future research should focus on long-term monitoring of ecosystems within MPAs to better understand the dynamics of predator-prey relationships and their broader ecological impacts. Experimental manipulations could also provide deeper insights into how changes in predator populations influence ecosystem functions over time. Additionally, exploring the role of MPAs in the face of other anthropogenic pressures, such as climate change and pollution, will be crucial for developing adaptive management strategies. In conclusion, protecting apex predators through MPAs is a fundamental strategy for sustaining marine biodiversity. The conservation of these species should be a cornerstone of ecosystem-based management, particularly as coastal ecosystems face increasing human impacts. Enhanced predator protection will not only contribute to the preservation of individual species but will also support the resilience and health of entire marine ecosystems.

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