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Seascape configuration influences big blue octopus (*Octopus cyanea*) catches: Implications for a sustainable fishery

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ABSTRACT

Seascape configuration is known to influence fish distribution and abundance in coastal waters. However, there is little information regarding how the shape of the coastal seascape influences catches of landed fisheries species, particularly so in the understudied western Indian Ocean (WIO). With focus on big blue octopus (*Octopus cyanea*), which is a widely found cephalopod species in the WIO, we compared landed catches (biomass, catch rate, and density) in submerged and exposed reefs, and explored the influence of proximity to fishing villages and reef habitat size on octopus landings. We used fishery-dependent data collected between 2018 and 2020 from eight landing sites spread across the Tanzanian coast. We found a strong relationship between biomass of octopus catch and distance from fished reefs to fishing villages, with higher fished biomass on reefs farther away. Octopus densities were higher, while catch rates were lower, on reefs very close to (within one km distance from) fishing villages compared to more distant reefs. In general, submerged reefs provided higher catches than exposed reefs. The low octopus catches on the exposed reefs were attributed to high fishing pressure, while submerged reefs that are only accessible through diving provide optimal areas for octopuses to grow. Octopus catches were, however, not significantly affected by reef size. The findings suggest that management policies should proportionate fishing efforts to ensure sustainable exploitation of reefs and associated fishery resources.

1. Introduction

Climate and geographical features influence the abundance and distribution of organisms worldwide. Critical from a landscape perspective, the number of habitats, habitat patches, and microhabitats in an area is of significant importance in determining species diversity and variability (Borland et al., 2021; Chittaro, 2004; Consoli et al., 2016; Ferrari et al., 2018; Samoilys et al., 2019). An area rich in microhabitats typically sustains more species, which may affect the resilience against climate change and other stressors such as fishing (Franco-Gordo et al., 2002). Since the early 1960s, terrestrial ecologists have developed substantial knowledge that illustrates the influence of pattern-oriented landscape metrics on animal distribution and abundance. In marine environments, the field of seascape ecology gained attention more recently (Pittman, 2018), and is today an emerging science for biodiversity conservation and sustainable development (Pittman et al., 2021). An important reason for this is that landscape index metrics developed for terrestrial environments were simple and could be based on visual inspection and interpretation (Dolný et al., 2021; Krummel et al., 1987). In contrast, to apply landscape ecology in the marine environment more advanced tools are needed. For example, the influence of seascape elements and underwater passages for fish movement is difficult to comprehend (Harris and Baker, 2012; McKenzie et al., 2012). Nevertheless, the recent advancements in marine remote sensing, application of high-tech underwater robotics and cameras, and increased accessibility of high-resolution satellite images, have widen our understanding

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of seascape ecology and allowed for more advanced development of seascape metrics (Harris and Baker, 2012; Pittman et al., 2011; Qiu and Jones, 2013; Staveley et al., 2017). There is generally a growing understanding of how seascape configuration influences fish community composition (Perry et al., 2018; Pittman et al., 2011; Qiu and Jones, 2013; Staveley et al., 2017), ecological connectivity (Berkström et al., 2013; Gullström et al., 2011) and ecosystem resilience (Olds et al., 2012). There is, however, a major knowledge gap regarding how fisheries' efficiency is affected by the seascape structure (Borland et al., 2021).

We used big blue octopus (*Octopus cyanea*) as a model fishery species to investigate the influence of seascape configuration on landed catches. This species was chosen because it is the most-traded mollusc in the WIO region, which is supported by the diverse tropical coastal seascape (Rocliffe and Harris, 2014). Octopuses prefer reefs as they contain many holes (dens) providing refuges or shelter against predators. Fishers generally capture octopuses in dens using spears (Guard, 2009; Silas et al., 2021; Silas et al., 2022). The distribution of reefs throughout the Tanzanian coastal landmass from north to south provides an opportunity for coastal inhabitants to participate in this fishery. In addition, as the demand for octopus has grown globally, with increased economic benefits, men have entered this fishery sector (Guard and Mgaya, 2002; Sauer et al., 2020; TAFIRI, 2021), which was previously dominated by women and children. Women dominated this fishery for over four decades as it was a relatively easy way to get food and some income to the family. During this period, women and children exploited shallow areas, which small octopuses prefer as their niche and where large-sized octopuses are uncommon. In fact, juvenile octopuses have their fastest growth in shallow areas, with a daily gain of about 5 % of their body weight daily, and once matured, adult octopuses migrate to deep waters to reproduce (Guard and Mgaya, 2002).

This study examined whether landed catches of big blue octopus are influenced by the seascape configuration in coastal waters of Tanzania in the WIO. Specifically, we aimed to assess how octopus catches (biomass, catch rate and density) differ (*i*) between submerged and exposed reefs, (*ii*) with distance between fished reefs and fishing villages, and (*iii*) with reef area size. We hypothesised that (a) reefs adjacent to fishing villages and exposed reefs have lower octopus catches by weight and number than distant and submerged reefs due to heavy fishing pressure in the former environments, and (b) smaller reefs will have lower octopus catches than larger reefs based on biogeography theory. According to the theory of island biogeography, a larger island will contain more abundant species than a smaller one (Gray et al., 2021; MacArthur and Wilson, 1967). The information of seascape characteristics and their influence on octopus catches could assist decision makers in the strategic intervention of this important coastal resource.

2. Method

2.1. Study area

Between August 2018 and February 2020, we mapped reefs used for octopus fishing and collected data on octopus catch in four coastal regions of Tanzania, covering a total of eight landing sites, including Kwale and Mtambwe (Tanga), Bwejuu, Jibondo, and Jojo (Mafia Archipelago), Songosongo (Kilwa), and Mgao and Msanga Mkuu (Mtwara) (Fig. 1). These eight sites—one core site in each coastal district—represent important octopus fishing villages along the coast. The selected fishing villages are situated approximately between the latitudes 4.8-10.5° S and the longitudes 38.5-40.5° E (Fig. 1) . The study region is rich in fisheries-supporting habitats such as mangroves, seagrass meadows, and coral reefs (Kimirei et al., 2016). Most coastal reefs are fringing reefs, with some exposed at low tide and others permanently submerged. Msangamkuu and Mgao (far south) are dominated by submerged reefs, whereas the other sites have both submerged and exposed reefs that vary in size. In the study region, fishers catch octopuses using iron and wooden sticks on both exposed and submerged reefs.

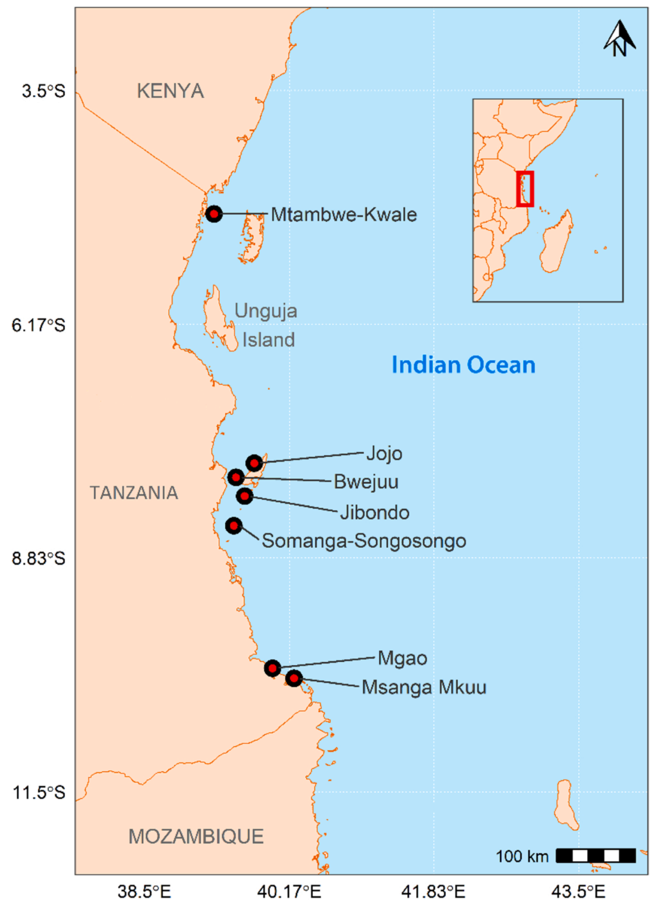

Fig. 1. Map of the coastal areas of Tanzania showing study sites. The inserted map shows the position of Tanzania in the western Indian Ocean.

2.2. Octopus landing data

Each of the eight landing sites had two enumerators trained to collect octopus catch and effort data. In each of the landing sites, catch data from 10 to 16 randomly selected local fishers (mostly males and a few females) were recorded each day during the sampling period. Enumerators used a 100 kg digital scale to weigh the octopuses and counted the number of octopuses caught by each fisher. The practice was repeated for 12–14 days a month, depending on the length of the spring tide, which determined the number of fishable days. All catch data were based on octopus fishing efforts for an average of three hours per day during low tide (where most fishers leave and return to the landing site synchronously). As SCUBA is not permitted on the reefs, the fishing is only conducted in relatively shallow waters by free-diving using iron and wooden sticks. Because some fishers migrate depending on the season, we sought to obtain octopus catch data from permanent local fishers to guarantee that catch and effort data were available for the whole study period. Data on catch and effort were first recorded in the prescribed forms and then the records were entered into an electronic catch assessment platform (e-CAS). The e-CAS allows selected enumerators in the landing sites to enter fisheries data using a mobile phone application.

2.3. Reef digitisation and boundary area determination

Selected reefs that fishers exploit for octopus fishing were mapped to identify their geographical locations, estimate their distances from the fishing community, and determine the reef areas (in km^2). First, a GPS was used to mark the locations of the reefs. The polygons of marked regions were transformed into simple features (Pebesma, 2018). Subsequently, point features were created and superimposed on a map using an online mapview package in the R Environment (Team, 2013). After determining the different areas' geographical limits, the perimeter of each reef was digitised by tracing the margins of the different reefs with the mapedit package (Appelhans et al., 2017). For reefs that were not captured in the survey, the boundary features created were superimposed on a base map in the mapview package and digitized . The accuracy of the digitised reefs was checked and verified in the Open Chart Plotter Navigator CPN (https://opencpn.org/OpenCPN/info/about.html), which contains nautical vector charts used for navigation. Then the polygons were projected from the geographical coordinate system (measured in degrees) to the projected coordinate system (measured in metric), and the total area of the reef (reef size) computed. For each reef polygon, the Euclidian distance was used to determine the distance between the centre of the polygon to the fish landing site, later referred to as the distance between the fishing village and the fished reef. In this survey, 183 reefs were digitised, though octopus fishers utilize only 86 reefs (see Supplementary Table 1).

2.4. Statistical analysis

Correlation analyses were carried out to compare normalised octopus weight, estimated as total catch per frequency of encounter (i.e. number of trips made) at each reef and Euclidian distance between the fish landing site or village and reef location. All reefs were pooled in the analysis to better understand the influence of seascape configuration on normalised landed weights. Linear regression analysis was used to explored the link between reef distance and landed biomass (i.e. the landed octopus weight per square kilometre reef). We also used non-parametric multidimensional scaling (MDS) bubble plots to depict a three-dimensional link between octopus density (measured as the total number of octopuses caught per square kilometre) and catch rate (measured as weight of landed octopuses per fishers involved in fishing), reef size, and distance between village and fished reef segregated by reef type. Furthermore, submerged and exposed reef catches were analysed with a Wilcoxson rank-sum test by comparing the median catch with the median octopus weight at each landing site for each reef type. Prior to all analysis, the Shapiro-Wilk test was used to test whether the octopus catch data were normally distributed.

3. Results

3.1. Influence of distance between fished reef and fishing village on fished octopus biomass

The farthest distance from the fish landing locations where an octopus was caught was 19 km (see Fig. 2). Within the 19 km distance window, a fitted regression line shows a strong relationship between biomass of octopus catch and distance between fished reef and fishing village, with reefs near the fish landing site providing lower fished octopus biomass (weight per reef area) compared to the sites further away from the fishing village (Fig. 2). The biomass increased from roughly 10 kg per km^2 in reefs located near a fishing village to approximately 40 kg per km^2 at 15 kilometres distance. The factor distance explained 50–97 % of the octopus biomass caught on most reefs. In general, reefs in the Jibondo site appear to provide more fished biomass than in the other investigated communities, whilst Jojo and Mgao deliver less. Surprisingly, the farthest reef (Nyuni) had low fished biomass, which was comparable to reefs at 2.5 km distance from fishing village. The mid-distance site Kitutia had the largest biomass, averaging more than 80 kg per km^2 (Fig. 2).

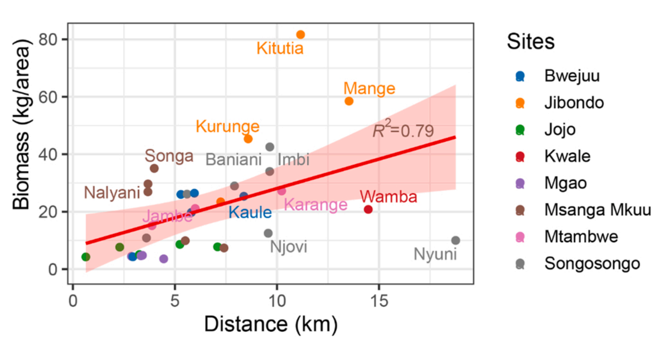

Fig. 2. Biomass of octopus catch per fishing trip and reef location.

3.2. Influence of reef size and distance between fished reef and fishing village on octopus catch rate

The mean catch rate (catch per fisher and trip) varied depending on the distance from village to reef, reef size and type of reef (Fig. 3). The mean catch rates from the smallest reefs, i.e. those less than 1 km^2, irrespective of the distance from the fishing village, provided octopus landings below 10 kg per fisher and trip. Submerged reefs with reef areas of up to 5 km^2 located near the fishing village (at less than 5 km distance) gave at least two times higher mean catch rates (around 30 kg per fisher and trip) than exposed reefs larger than 15 km^2 in size (less than 15 kg per fisher and trip). Moreover, exposed reefs with a size range between 5 and 7.5 km^2 and submerged reefs with a size range between 7.5 and 12.5 km^2 have comparable catch rates irrespective of the distance.

3.3. Influence of reef size and distance between fished reef and fishing village on octopus density

Octopus densities varied among the studied reefs (Fig. 4). In general, smaller reefs (< 2.5 km^2) that were located close (< 7.5 km) to the fishing villages had more octopus individuals per km^2 (i.e. a higher density) than reefs over 7.5 km^2 in size and located 10 km away (Fig. 4). In addition, all exposed reefs had less than 1600 individual octopuses per km^2, while some submerged reefs had a density of up to 2400 individuals per km^2.

3.4. Influence of reef type on each fishing community's total weight of octopus catch

Fishers caught an average (based on median values) of about 17 kg of

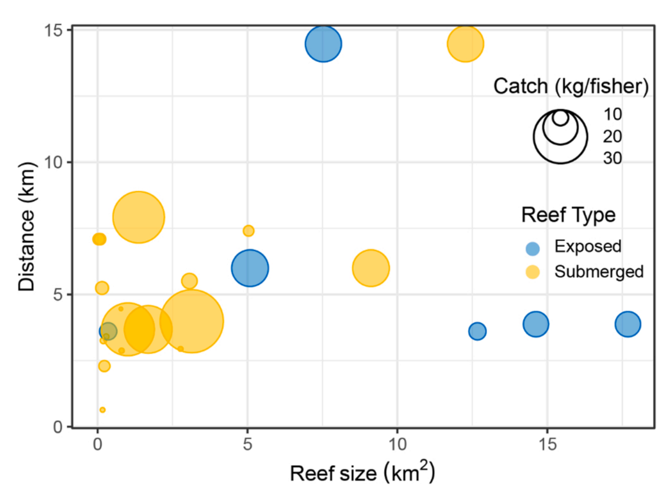

Fig. 3. MDS bubble plot showing octopus catch rate (kg per fisher) in relation to (i) the distance between fishing village and fished reef, and (ii) reef size separated into reef types.

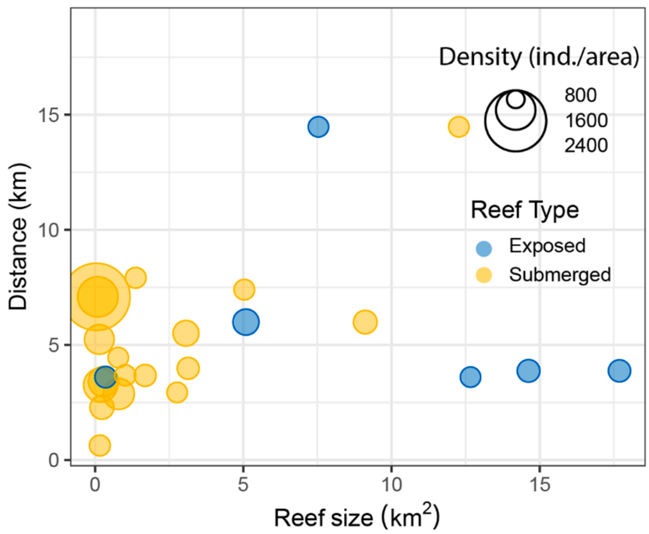

Fig. 4. MDS bubble plot showing octopus density (individuals per area) in relation to (i) the distance between fishing village and fished reef, and (ii) reef size separated into reef types.

octopuses daily from the exposed reefs along the coast (Fig. 5). The reefs outside Kwale provided the largest landings of about 21 kg per fisher and day, while the exposed reefs at Songosongo provided the lowest landings of about 11 kg per fisher and day. The observed differences were however not significant. For submerged reefs, the median weight was estimated to be almost 21 kg (Fig. 5). Songosongo had the highest median weight, while Msanga Mkuu, Mtambwe, and Kwale had weights close to the median value, and Jojo, Bwejuu, and Mgao had the smallest median weights, ranging from 4 to 7.5 kg. The differences observed between median values for submerged reefs were significant (Wilcoxson test; $p < 0.05$). At the landing sites (receiving landed catches from both exposed and submerged reefs), the median weight of landed octopuses was similar, except that the exposed reefs had a significantly lower median octopus weight than submerged reefs in Songosongo.

4. Discussion

Our findings showed that reefs near fishing villages, and hence accessible by foot fishers, tend to have higher densities of octopus but lower catch rates than distant and submerged reefs that only a few divers with boats can reach. Consequently, the accessibility of the reefs influences octopus yield, which is an important criterion in determining a fishery's long-term viability. Because submerged and distant reefs are less visited by fishers, larger octopuses are more likely to be found on these reefs, and the few fishers who reach them have reported greater landings than on reefs with broader access. However, these reef habitats (submerged and distant reefs) have comparably low octopus densities. Fishers prefer larger octopuses because they fetch higher prices. They also lay larger eggs (with sufficient yolk-sac), which is responsible for faster growth (Boyle and Chevis, 1992). Small eggs result in offspring that grow slower, exposing young individuals to prolonged predation, which might affect recruitment. It should be noted that even octopuses predate on young octopuses; therefore, juvenile octopuses need to grow fast (Morrongiello et al., 2012). In that regard, the benefits of submerged and distant reefs in harbouring large octopuses are equivalent to the benefits of temporally closed reefs (Oliver et al., 2015; Silas et al., 2022). They both ensure the existence of larger individuals that are important for recruitment. Therefore, in locations with more difficult-to-reach reefs, such as submerged or remote reefs, accessed reefs may function as octopus sinks, where exploitation is conducted. In contrast, inaccessible or less reached reefs may act as octopus sources equivalent to a function provided by marine protected areas (Raycraft, 2018; Robinson et al., 2014). With respect to this, for the sustainability of the fishery, less accessible reefs are critical for long-term resilience.

Differences in density and biomass of octopus catches between near and distant reefs were observed in this study. Octopuses on near reefs were found in higher density than at distant reefs. We expected reefs with higher density of octopus to contribute more to octopus biomass than reefs with lower density. However, nearshore reefs were found to have low biomass of caught octopus. Several factors, including variation in fishing intensity, may explain these patterns (Silas et al., 2021). Women and children dominate the adjacent reefs because they cannot dive and are limited by their traditions and customs to stay in the nearshore environment (Bradford and Katikiro, 2019). Their fishing practice comprises walking to the most accessible reefs. Since they make up the majority of octopus fishers, their fishing efforts can cause nearshore overexploitation (Cosgrove, 2020; TAFIRI, 2021). In such a situation, octopuses have no time to grow. As a result, smaller octopuses dominate nearshore reefs, while larger octopuses dominate less frequented reefs (Silas et al., 2022). In this aspect, bigger octopuses—like the specimens in Kitutia—dominate less exploited reefs, contributing greater biomass because they get enough time to grow.

In areas with high fishing pressure, there is a tendence that different targeted organisms adapt by increasing reproduction efforts and

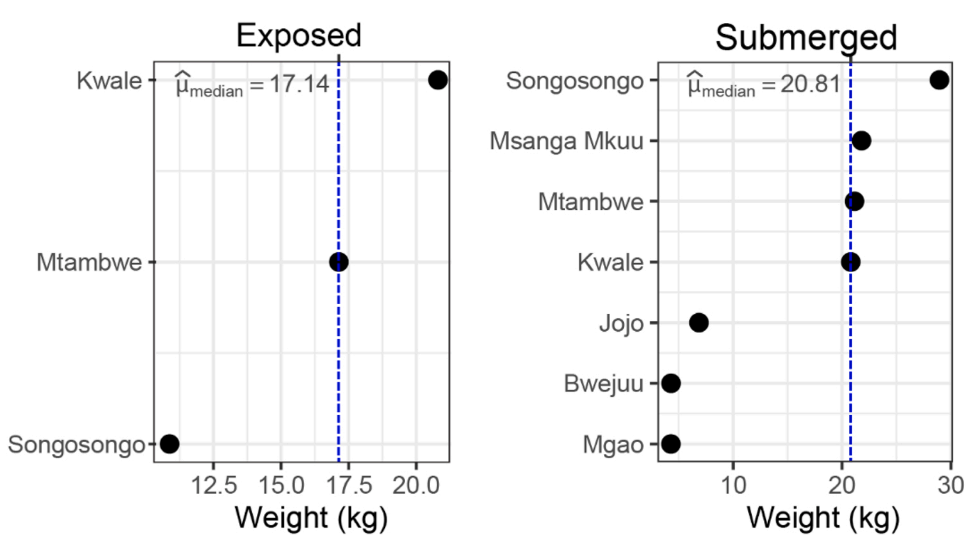

Fig. 5. Median octopus catch rates from exposed and submerged reefs of different fish landing sites across Tanzania.

optimising reproductive timing rather than investing in growth (Planque et al., 2010). This might also be true for the octopuses living on reefs near fishing villages that are visited more regularly (by fishers), which might explain why we found smaller octopuses in these locations. This adaptation has also been observed in the southmost region of Tanzania (at Mgao and Msangamkuu) and at Jibondo, an island in the Mafia Archipelago (TAFIRI, 2021). The influence of fishing pressure from easily accessed reefs, in our case, exposed reefs and reefs near fishing villages, enlightens our understanding of what would happen if un-accessed reefs (like submerged reefs) were fully utilised. We found that while reefs near fishing villages are overharvested, some protected reefs, such as Kitutia, have fewer but larger octopuses that can produce more offspring, enabling increased production of the surrounding reefs. Though the Kitutia reef is located within a marine protected area, it is also located distant from the fishing village. Based on the advantages of remote and protected reefs, it is essential to protect reefs like Kitutia. One example of a reef in the WIO that is partially protected, and provide similar benefits as if fully protected, is the Songosongo reef which provides the highest octopus yield in Tanzania. All protection measures that aim to lessen fishing pressure will aid in improving octopus productivity by reducing overexploitation of smaller individuals. Although distant reefs generally contribute more than reefs adjacent to fishing villages in terms of catch, not all distant reefs are equally valuable. For example, the furthest reef (Nyuni) had low fished biomass, which is comparable to reefs located within a 2.5 km distance from fishing communities. Because Nyuli is an exposed and extended reef, migratory fishers frequently use this reef as 'dago', which describes a local fishing camp, likely transforming Nyuli into a fishing village. As a result, this remote reef comprises similar features to a reef near a fishing village. Fishers come to these places in quest of favourable fishing conditions, particularly for fish supply, as explained by Wanyonyi et al. (2017).

When we evaluated the influence of reef size on octopus catch, there were no clear patterns for either density or landed weight (biomass and catch rate), which is contrary to our hypothesis and similar to research previously conducted on land (Lawrence et al., 2018) and on aquatic ecosystems (Staveley et al., 2017), which showed that reef size matters. Our results also violate the theory of island biogeography (Jonathan and Robert, 2010; MacArthur and Wilson, 1967), where habitat size determines organism density and variability. For example, Lawrence et al. (2018) found that mammals and reptiles are more numerous in more extensive habitat patches than in small patches of terrestrial habitats in California, which aligns with our hypothesis and other findings (Pettersson and Nilsson Jacobi, 2021), but contradicts our findings. Large and heterogeneous habitats are expected to provide more extensive home ranges that facilitates animals getting prey and finding appropriate foraging grounds. Given this knowledge, we expected more extensive reefs to provide larger octopuses than smaller reefs. The lack of such a relationship in our study suggests that some larger reef areas have been subject to overfishing, which in combination with other factors may have removed most octopuses, leaving few and smaller individuals which are less in numbers than the natural carrying capacity.

According to our findings, a more sustainable fishery in heavily fished areas, such as nearby reefs and exposed reefs, could be achieved by (*i*) reducing fishing pressure on overfished reefs, (*ii*) instituting temporary fishing closures, and (*iii*) increasing diversification among fishing communities, for instance by involving fishers in alternative livelihoods (e.g. mariculture), as a means of coping with and lowering fishing stress, as detailed by Silas et al. (2020). Such actions might allow octopuses to grow and achieve larger sizes and, at the same time, improve landings, as has been shown from temporally closed reefs in varying regions of the world (Benbow et al., 2014; Berrío-Martínez, 2022; Jhangeer-Khan et al., 2015; Silas et al., 2022), including Tanzania (Silas et al., 2022). Shifting fishing pressure to less exposed areas where more fished biomass is found, like submerged or distant reefs in this case, should not be considered an alternative as it would encourage increased exploitation. It would also result in increased costs due to the advancement of boats and gears required to withstand bad weather in distant environments, though such community adaptation is seen among small-scale fishers all over the world (Saldaña et al., 2016; Torres-Guevara et al., 2016), including ringnet fishers found along the coast of East Africa (Silas et al., 2020).

Gender is a key factor in determining which reef is fished. Although the sampling protocol took gender into account, data were not desegregated by gender because records only included the total number of fishers by gender and were not linked to octopus catch data, as detailed in Westerman and Benbow (2013). Mostly women and children exploit exposed reefs, while males exploit submerged reefs. Even though there are differences, this study did not distinguish between male and female fishers. If the aim was to link octopus catch with gender, the analysis would have been done at a much higher resolution. In addition, all data utilised are fisheries-dependent, even for the estimations of fished biomass, limiting our interpretations because fishers' behaviour could, in some ways, affect the observed patterns.

5. Conclusion and recommendation

This study aimed to examine if seascape configuration influences catches of landed octopus in terms of landed biomass, catch rate, and density. We found that the distance between fishing villages and fished reef, the type of reef (submerged or exposed), and to some degree reef size influence the catches of landed octopus, which are also assumed to be influenced by fishing intensity and frequency. In general, compared to remote reefs, more accessible reefs have lower fished biomass, and smaller individuals, and therefore are contributing less to the total landings of octopus. On the other hand, the remoteness of some reefs provides a refuge for octopuses, limiting the overfishing of the brooding population that constitutes such reefs and guaranteeing that overfished areas continue to benefit from new octopus recruitment. Thus, any management action that discourages excessive fishing in exploited and unexploited areas, e.g. short-term closures, will increase the sustainability of the fisheries. This would lessen the fishing pressure in already over-exploited locations and allow overexploited areas to recuperate.

Animal ethics

With permission from TAFIRI, the Tanzanian body in charge of fisheries research, information about fish catch was obtained from fishers. Before data collection, all the targeted groups—including village leaders, beach management unit (BMU) members, fishers, and the fisheries officers—were explicitly informed of the visits' objectives. With full knowledge of the benefits, risks, and rights to privacy and confidentiality, it was intended that participants would voluntarily choose to take part in the study. No live animal was used in this study.

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CRediT authorship contribution statement

Mathew O. Silas: Conceptualization, Methodology, Formal analysis, Investigation, Visualization, Writing – original draft, Writing – review & editing. **Mary A. Kishe:** Methodology, Investigation, Writing – review & editing. **Masumbuko L. Semba:** Methodology, Formal analysis, Investigation, Writing – review & editing. **Bigeyo N. Kuboja:** Methodology, Investigation, Writing – review & editing. **Benjamin Ngatunga:** Methodology, Investigation, Writing – review & editing. **Said S. Mgeleka:**

Methodology, Investigation, Writing – review & editing. **Hans W. Linderholm:** Writing – review & editing. **Martin Dahl:** Writing – review & editing. **Martin Gullström:** Conceptualization, Methodology, Writing – original draft, Writing – review & editing, Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this article.

Data Availability

Data will be made available on request.

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Data

Data is only available upon request owing to privacy and ethical concerns.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.fishres.2023.106716.

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