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Cover image: The mudskipper *Periophthalmus argentilineatus* on the mangrove of Ulo Beach, Cabo Delgado, North Mozambique. © José Paula, 2006

Growth, mortality, exploitation rate and recruitment pattern of *Octopus cyanea* (Mollusca: Cephalopoda) in the WIO region: A case study from the Mafia Archipelago, Tanzania

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Abstract

Octopus cyanea is a commercially important cephalopod in the Western Indian Ocean (WIO) region, but scientific information to inform management strategies for the species is limited. A study was conducted in 2014, 2015, 2017 and 2018 to investigate biological parameters including growth, mortality, exploitation rates and recruitment patterns in the sea around Mafia Archipelago, Tanzania. Virtual population analysis (VPA) indicated differential mortality between two sampling sites; the lowest and highest fishing mortality of $F = 1.5yr^{-1}$ and $F = 2.7yr^{-1}$ were observed in Bwejuu (Dorsal mantle length, DMT = 18-20 cm) and Jibondo (DMT = 8-12 cm) fishing villages, respectively. The maximum exploitation rate (E_{max}), which gives the maximum relative yield per recruit, was estimated at 0.380 and 0.379 for Jibondo and Bwejuu, respectively. The exploitation rates $E_{0.5}$, which corresponded to 50% of the unexploited stock relative biomass per recruit, were estimated at 0.248 for Jibondo and 0.247 for Bwejuu. These values differ greatly from the exploitation rates of 0.53 and 0.41 for Jibondo and Bwejuu, respectively, suggesting that the stock of *O. cyanea* is probably being overfished both in terms of yield per recruit and biomass per recruit. The stock-recruit pattern was observed to be continuous year-round, with the peak being between May and July. Since the peak in recruitment of both areas coincides with the south-east monsoon (SE Monsoon) and the level of maximum sustainable yield has been overshot, it is recommended that management plans are implemented that will reduce effort while increasing biomass, for example, implementing temporal octopus fishery closures at a village level.

Keywords: *Octopus cyanea*, growth, mortality, exploitation rate, recruitment, Western Indian Ocean Reserve, small-scale fisheries, spatial mapping

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Introduction

Octopus is an important food item among local coastal communities in tropical and temperate regions. The small scale fishery for *Octopus cyanea* is among the important commercial cephalopod fisheries and contributes to foreign currency earnings in the Western Indian Ocean (WIO) (Rocliffe and Harris, 2014). This fishery is an important economic activity for local coastal communities in the WIO and Tanzania, where *O. cyanea* dominates landed catches (Guard and Mgaya, 2002; TAFIRI, 2017). For instance, in the Mafia Archipelago of Tanzania mainland (Fig.1), the octopus fishery serves as an important economic activity for the local people on the island. Octopus also plays an essential ecological role in the marine ecosystem where they act as predators and potential prey to larger fishes such as sharks and some neritic tuna (Forsythe and Hanlon, 1997; Guard, 2009). Despite the importance of octopus catches in providing food and income to the people of the region, and their ecological function, this species has recently experienced alarming over-exploitation. Most previous studies indicate that the mean harvestable sizes and weights of the landed catches of octopuses in the region has declined (Rocliffe and Harris, 2014; Sauer *et al.*, 2011; TAFIRI, 2017; Guard, 2003; Guard and Mgaya, 2002).

The reported declines in octopus catches have been linked to several factors, including over-exploitation, seasonal change in sea temperatures, habitat degradation, disease outbreaks, pollution and predation (Katsanevakis and Verriopoulos, 2006; Heukelem, 1973; Sparre, 1998). To further understand the observed decline in octopus catches, it is necessary to obtain information on mortality, recruitment and exploitation patterns, particularly in data-poor fisheries (Hordyk *et al.*, 2014). To address this information gap in the *O. cyanea* fishery, a comprehensive study was designed to: (i) understand factors that cause octopus demise; whether natural or as a result of fishing pressure; (ii) understand octopus exploitation ratios (E) to better describe octopus stock status; and (iii) determine octopus recruitment periods, and/or age at which the octopus can recruit as a critical factor triggering catch fluctuations.

Material and methods

The study area

This study was conducted in the Mafia Archipelago, which is located between longitudes 39.33°E and 39.95°E and latitudes 7.60°S and 8.15°S (Fig. 1). The island has an estimated land area of 435 km^2 and is home to around 46,850 people (NBS, 2012). About 60 % of the inhabitants are fishermen (NBS, 2012). The village on Jibondo Island represents a typical fishing village of the WIO (McClanahan and Cinner, 2012; Cinner *et al.*, 2012). The weather and climate are both influenced by the monsoon trade winds, which reverse on an annual basis to form two alternating seasons: the northeast (NE) and southeast (SE) monsoons. The SE monsoon season occurs between May and September and is dominated by southerly trade winds of relatively high speeds (Semba *et al.,* 2019). This season affects mostly the southern part of the Mafia Archipelago. The reverse of the trade winds forms a NE monsoon, which occurs from November to March and is dominated by winds of relatively low magnitude blowing from the north. The NE monsoon season mostly affects the northern side (windward side) of the Mafia Archipelago. The change in monsoon seasons affects sea surface temperature (SST) and rainfall patterns on the island (Bryceson *et al.*, 2006), which also affects catches of major marine fish (McClanahan and Cinner, 2012; Meynecke *et al.,* 2006). The two islands of Bwejuu and Jibondo in the Mafia Archipelago were selected as sites (Fig.1). These islands were selected because of the high number of active octopus fishers. The number of fishers in the villages on these two islands differs greatly with around 94 active fishers on Bwejuu Island and 500 on Jibondo Island. The study sites fall within the boundary of the Mafia Marine Protected Area (MPA), where fishers are required to abide by Fisheries Regulation of 59 (l) d (MLFD, 2009) and capture octopuses that are above half a kilogram (0.5 kg). The sites also have local government by-laws limiting fishing activities during spring tides (Fisheries officer, personal communication).

Data collection

Octopus samples for morphometric data were obtained from the artisanal fishers at the selected landing sites between August 2014 and July 2015, and between November 2017 and March 2018. Data were collected from foot fishers and those using vessels. The two study sites had permanent localised fishers, who ensured availability and consistency of data. Sampling and measurement of the length and weight of individual octopus was done for 15 days during the low tide period. Data collection was conducted during spring tides (low tides) because octopus fishing occurs when the water is low in the intertidal reefs, and reefs are exposed, thus leaving a total of 16 fishing days a month. The morphometric data collected included the total length (TL, cm), dorsal mantle length (DML, cm) and weights (kg) of

O. *cyanea* individuals per site per day. DML and TL of individuals were measured to the nearest 1 mm using a 100 cm measuring board, and the individual weights of octopuses were measured using a 50 kg digital scale to the nearest 100 g. The data records were kept on paper forms. The information recorded in these forms was later entered into an electronic Catch Assessment Survey (eCas) system using a mobile phone application. This *(eCas)* is hosted by the Tanzania Fisheries Research Institute (TAFIRI). It is a server system that facilitates data entry and access in a consistent way for fisheries management.

Where 'W' represents wet weight, 'L' is the DML in centimetres, 'b' is the slope of the regression line and 'q' is the intercept of the y-axis. The parameter 'b' is used to determine the growth pattern of octopus. When the 'b' value of the length-weight relationship at 95 % confidence level is 3, it indicates that the octopus population has an isometric growth. When the value is less or greater than 3, it means an allometric growth pattern.

Total mortality coefficient (Z)

The annual total mortality coefficient (Z) was estimated by the length-converted catch curve using

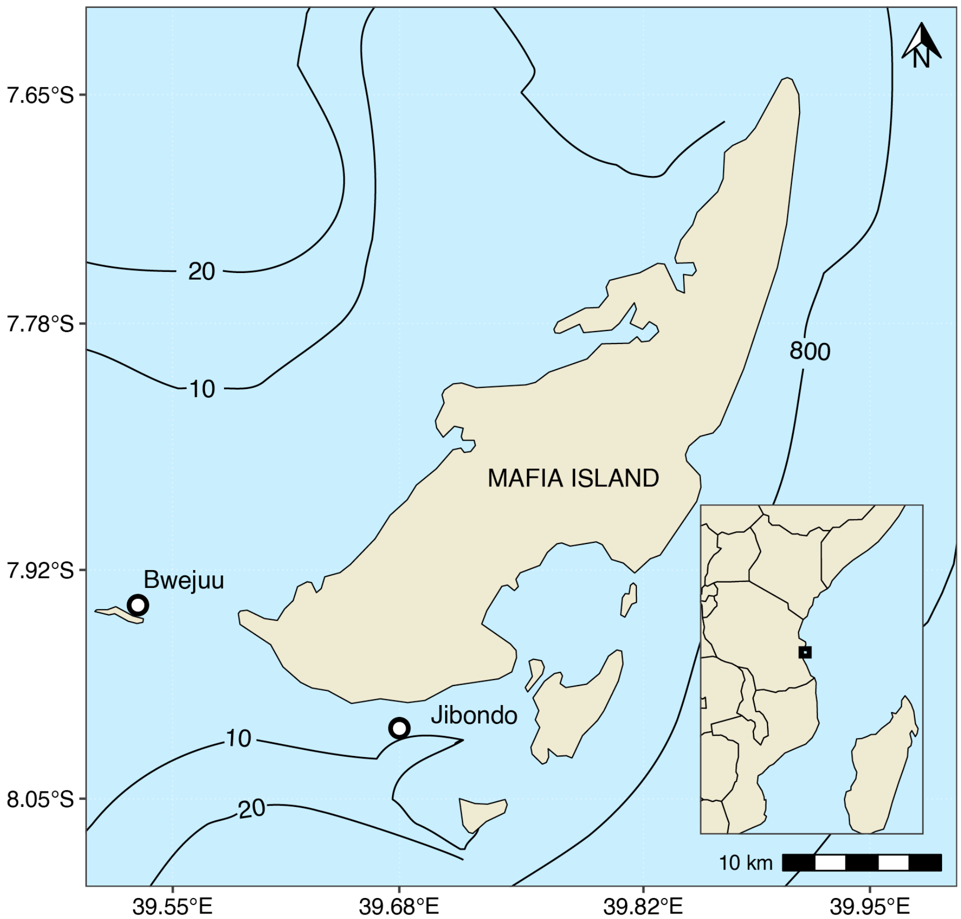

Figure 1. Map of Mafia Archipelago with the location of the study sites. An inset map of the western Indian Ocean locating the position of Mafia in the region. The label lines are depth isobars.

Data analysis

Length-weight relationships

The individual DML and weights of the octopuses were grouped according to each site and analysed with the power curve equation:

$$W = qL^b$$

the ELEFAN package as fitted in the FiSAT II programme (Gayanilo Jr *et al.*, 1996; Pauly, 1980; Sparre and Venema, 1992). In this analysis, the percentage of samples in length classes were grouped to mimic a steady-state population. The data for the catch curve was obtained by grouping monthly length frequencies.

Instantaneous natural mortality' and fishing mortality 'F'

The instantaneous natural mortality of octopuses (M) was estimated with the empirical formula of Pauly (1980, 1983).

$$Log_{10}M = 0.0066 - 0.279Log_{10}L + 0.654Log_{10} + 0.4634\log_{10}T$$

Where L and K were derived from the Von Bertalanffy Growth function and T is the average sea surface temperature (SST) for the study area. Fishing mortality (F) was then calculated from the function $F = Z - F$

Exploitation ratio

The state of exploitation of *O. cyanea* (E) was calculated from the equation F/Z (Appeldoorn, 1988), which is the fraction of the total mortality (Z) caused by fishing mortality (F).

Octopus recruitment pattern

The octopus relative yield-per-recruit (Y/R) and relative biomass-per-recruit (B/R) was determined by the knife-edge recruitment method, which is described as a yield-per-recruit by Beverton and Holt (1959) and has been integrated into the FiSAT programme to assess recruitment (Pauly, 1983; Gayanilo Jr *et al.*, 1996). Analysis of the recruitment patterns was carried out in FiSAT using the maximum likelihood approach of the separation of the normally distributed components of the sampled length-frequency (NORSMSEP) to fit the Gaussian assumptions for the length-frequency data for the years grouped (Pauly, 1983; Gayanilo Jr *et al.*, 1996).

Results

Length-weight relationships

The regression analysis of the *O. cyanea* length-weight relationship at Jibondo and Bwejuu sites, respectively, were computed by the equations: $W = 0.0032DML^{2.2809}$ ($r^2 = 0.7615$); and $W = 0.0058DML^{2.1623}$ ($r^2 = 0.6838$). The value of b at Jibondo was 2.28 compared to that of Bwejuu, which was 2.16, and both sites had relatively lower b values compared to a typical value of 3.

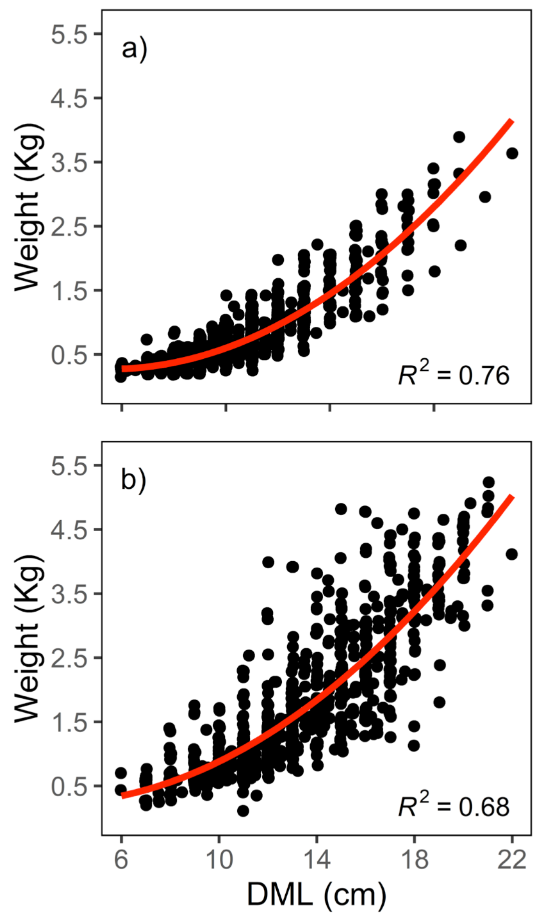

Figure 2. Length-weight relationship of *Octopus cyanea* sampled at a) Jibondo and b) Bwejuu islands in Mafia Archipelago.

The lower b value suggests an increase in the size of different organs or parts of the octopus at various rates during growth (Fig. 2).

Mortality coefficient (Z, M and F) and exploitation rate (E)

The result of the mortality (Z, M, and F) and exploitation rate (E) of *O. cyanea* at Jibondo and Bwejuu is presented in Table 1. Total mortality, natural mortality, fishing mortality and exploitation rate are all higher at Jibondo than Bwejuu. In addition, this study showed higher fishing mortality at Jibondo at a relative smaller

Table 1. Estimated mortality parameters for *Octopus cyanea* in Mafia Archipelago.

Site	Z	M	F	E	F – Class (DML)
Jibondo	5.24	2.48	2.76	0.53	08 - 12
Bwejuu	3.63	2.14	1.49	0.41	18 - 20

Z = Coefficient of total mortality, M = Coefficient of natural mortality, F = Coefficient of fishing mortality and E = Exploitation ratio. F – Class = Octopus size class with higher fishing mortality

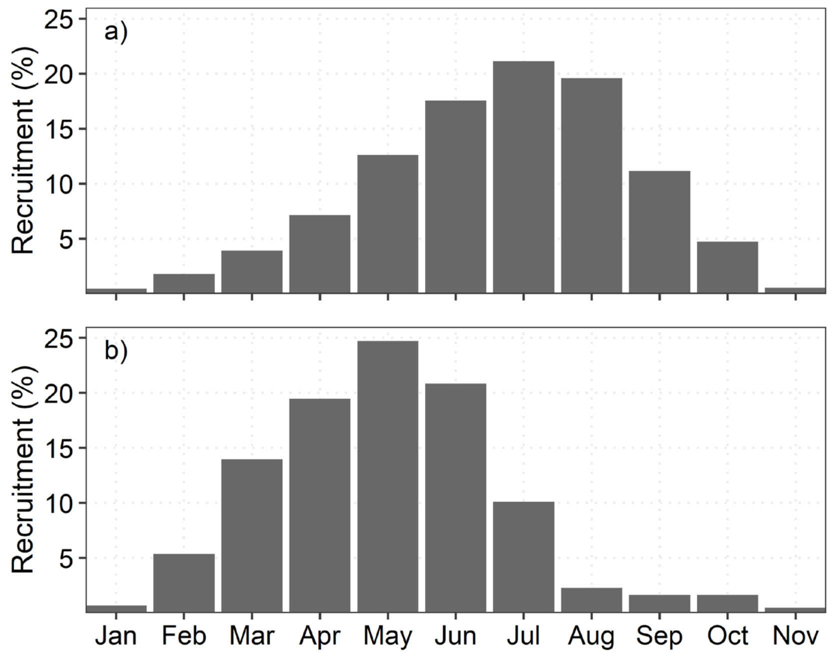

Figure 3. Relative yield-per- recruit and relative biomass-per-recruit of *Octopus cyanea* using the knife-edge recruitment method for Jibondo (a) and Bwejuu (b) fishing areas in the Mafia Archipelago (Green = $E_{0.1}$, Red = $E_{0.5}$ and Yellow = E_{max}).

octopus size class (8-12 cm, DML) while lower fishing mortality at Bwejuu at a relative higher size class (18-20 cm, DML).

Exploitation rate and relative coefficient rates

The estimated optimum exploitation rates from relative yield-per-recruit (Y/R) and related coefficient rates from relative biomass-per-recruit (B/R) analysis by the knife-edge selection for Jibondo and Bwejuu are presented in Figure 3. The exploitation rate 'E_{max}' that provides maximum relative yield-per-recruit was 0.380 and 0.379 for Jibondo and Bwejuu, respectively. The exploitation rate at which marginal increase occurred in the relative yield-per-recruit was similar for both sites, where $E_{0.1}$ was at 0.307. The exploitation rate $E_{0.5}$, which corresponded to 50 % of the unexploited stock relative biomass-per-recruit, was almost the same for Jibondo and Bwejuu; 0.248 and 0.247, respectively. The mean ratio of length at first capture L_c and asymptotic length L_∞ was 0.41 for Jibondo and Bwejuu, while that of natural mortality and growth rate was 2.06 and 1.42 K yr^1 for Jibondo and Bwejuu, respectively (Table 2).

Octopus recruitment pattern

The recruitment pattern of *O. cyanea* for Jibondo and Bwejuu is presented in Figure 4. Recruitment was year-round with one major peak. Length at infinity (L∞) was 23.1 for both sites, while the K values were 1.2 and 1.5 for Jibondo and Bwejuu, respectively. In the analysis, C = 0, WP = 0, and t_o = 0, were set similarly for both sites. The percentage recruitment values for Jibondo and Bwejuu respectively for the different months were: January (0.67 and 0.27 %); February (5.17 and 1.61 %), March (13.74 and 3.93 %); April (19.47 and 6.99 %); May (24.67 and 12.57 %); June (20.92 and 17.60 %); July (9.98 and 21.09 %); August (2.12 and 19.73 %); September (1.49 and 11.04 %); October (1.37 and 4.72 %); November (0.39 and 0.44 %); and December (0.00 and 0.00 %), as shown in the Figure 4.

Table 2. Estimated optimum exploitation rates and relative coefficient rates of *Octopus cyanea* at Mafia Archipelago.

Site	E_{max}	$E_{0.1}$	$E_{0.5}$	L_C	L∞	L_C /L∞	K	M/K
Jibondo	0.38	0.307	0.248	9.54	23.1	0.41	1.2	2.06
Bwejuu	0.379	0.307	0.247	9.5	23.1	0.41	1.5	1.42

E_{max} = Exploitation rate that gives maximum yield-per-recruit, $E_{0.1}$ = Exploitation rate at which relative yield-per-recruit was 10 %, $E_{0.5}$ = 50 % of unexploited stock, L_c = Length-at-first capture, L_∞ = asymptotic length, M/K = Ratio of natural mortality (m) and growth rate (K)

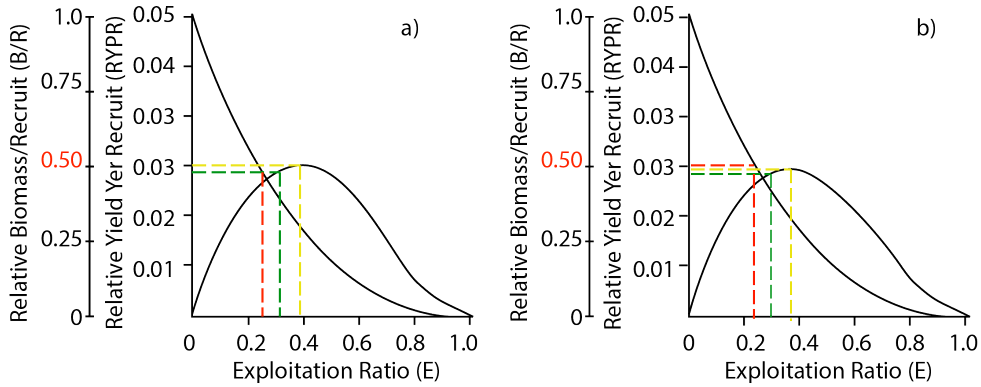

Figure 4. Recruitment pattern of *Octopus cyanea* of Mafia Archipelago. Jibondo L_{α} = 23.1, K = 1.5, WP = 0, t0 = 0 (a) and Bwejuu (b) L_{α} = 23.1, K = 1.2, WP = 0, t0 = 0.

Discussion

The octopus fishery in the Mafia Archipelago is an important economic and subsistence activity for local coastal communities. Octopus fishing dominates small-scale fishing effort at the islands which have a shallow continental shelf with coral reefs, and is a particularly important economic activity for women as well as men. Octopus provides food and income that support livelihoods for the local communities and forms an important element of the local ecology. However, despite its economic and ecological importance, exploitation ratios and recruitment periods of octopus in the Mafia Archipelago is poorly understood. This study is the first to reveal important information on the exploitation and recruitment patterns of octopuses at Bwejuu and Jibondo islands.

This study found that exploitation of octopus as expressed by yield-per-recruit and biomass-per-recruit has increased in the study area in recent years. The increased fishing pressure has resulted in the landed catches of octopus being dominated by small size classes. The maximum exploitation rate (Emax), which is expected to contribute to the maximum relative yield-per- recruit, was estimated at 0.380 and 0.379 for Jibondo and Bwejuu, respectively (Fig. 3 and Table. 2). Interestingly, these estimated exploitation values were lower compared to 0.53 for Jibondo and 0.41 for Bwejuu found in this study (Table. 1). The high exploitation values suggest that the *O. cyanea* stocks are overfished in terms of both yield- and biomass-per-recruit, as described by Gulland (1971).

On the other hand, the exploitation rate for Jibondo, which is characteristic of numerous fishing villages with many fishers in Tanzania (McClanahan and Cinner, 2012), was higher with E = 0.53. The high values of 'E' indicate a high fishing rate. Furthermore, the higher 'E' value corresponded with a relatively small size class 8-12 cm DML. In comparison, the exploitation rate at Bwejuu was lower (0.41), and the octopus were of a much larger size-class of18-20 cm DML. Based on the assumption that in an optimally exploited stock, natural mortality (M) and fishing mortality (F) should balance ('E' = 0.5 (E = F/Z = 0.5)) as suggested by Gulland (1971), then it is evident that small-sized octopus at Jibondo are exposed to high fishing pressure.

The link between high exploitation pressure and smaller fish sizes has been reported for the crab *Callinectes amnicola* in West Africa (Abowei *et al.,* 2010), the garfish *Belone euxini* in the Black Sea (Ceyhan *et al.,* 2019) and *O. cyanea* in the Indian Ocean (Guard and Mgaya, 2002; Jhangeer-Khan *et al.,* 2015). In the Fernando de Noronha Archipelago (tropical oceanic island of Brazil), however, the variation of the octopus size was caused by depth gradient between sites rather than fishing pressure. Small-sized octopuses preferred shallow habitats, and large-sized octopus were likely to be found in deeper water habitats (Leite *et al.,* 2009). This was not the case for the two sites accessed by fishers in the Mafia Archipelago where the depth difference between them was negligible.

Despite estimates made in this study, additional scientific information is needed to adjust the mortality values since the method used (length at age) assumed natural mortality of the octopus is constant throughout its life span. It is however known that adult females die after spawning, which results in changes from a female-dominated sex ratio in all seasons to equally represented sex rations after spawning has occurred (Herwig *et al.,* 2012; Arreguín-Sánchez *et al.,* 2000). However, mortality values obtained give a better understanding of how fishing pressure is likely to define octopus sizes that are caught, which has been found to be important for the management of the fishery.

Like previous studies which found that octopus spawn throughout the year, this study also found that *O. cyanea* recruits all year round at Mafia, but with a peak between May and July. This peak coincides with the SE monsoon that occurs between May and September (Semba *et al.,* 2019). The low sea surface temperature and high magnitude of wind with nutrient enrichment from the land after the long rain season during the SE monsoon season provides the ideal conditions for octopus spawning, growth and recruitment. These findings are similar to those from previous studies conducted in Rodrigues Island (Sauer *et al.,* 2011) and Madagascar (Raberinary and Benbow, 2012) in the WIO, where recruitment peaks occurred around May and July. In Madagascar, the recruits of octopus showed an additional lower peak in October and November (Raberinary and Benbow, 2012). The peaks of octopus recruitment in Madagascar are contrary to the findings of this study where only one peak was evident. In general, year-round recruitment is perhaps a compensation for the high octopus mortalities found in this and some other studies (O'Dor, 1998; Raberinary and Benbow, 2012).

This study also used the M/K ratio to examine the accuracy of growth parameter indices, which are constant for a group of species or closely related families of taxa (Chakraborty, 2001; Charnov *et al.,* 1993). The M/K ratio for the octopus in this study was 1.42 for Bwejuu and 2.06 for Jibondo, and the values are within the recommended range indicating good environmental state (Beverton and Holt, 1959; Silas *et al.,* 1985; Mohamed, 1996). In addition, the 'b' value from the fitted power equation suggested an increase in the size of different organs or parts of the octopus at various rates, as has been described previously for the WIO octopus (Guard and Mgaya, 2002).

During this study, *O. cyanea* was found to be overexploited, which was evident from the higher exploitation levels found in areas where there are many fishers. This suggests that fishing mortality could be controlled to attain the maximum yield and biomass per recruit that has already been overshot. However, fishing mortality estimated in the study needs to be adjusted based on additional information because larvae and post-spawning mortalities are higher than for the adult octopuses. This analysis assumed octopus mortality to be constant across age. Recruitment was found to be occurring all year round, with one major peak in the SE monsoon season. However, further research is needed to confirm the recruitment pattern, as in some other parts of WIO, recruitment peaks occur twice a year. Management measures could include better control over the issue of fishing licences, spatial rotation of fishing activities and voluntary octopus fishing closures to address the current excessive fishing pressure which has resulted in the small-sized octopuses that are landed.

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