Aquat. Living Resour. 2024, 37, 13
© D. Raberinary and A. Andrisoa, Published by EDP Sciences 2024
https://doi.org/10.1051/alr/2024011

Aquatic
Living
Resources
Available online at:
www.alr-journal.org

RESEARCH ARTICLE OPEN ACCESS

Assessing stock of reef octopus *Octopus cyanea* in southwest Madagascar using age-based population modelling

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Received 20 October 2023 / Accepted 21 August 2024

Handling Editor: *François Le Loc'h*

Abstract – The reef octopus *Octopus cyanea* fishery is the most economically important fishery in southwest Madagascar. The substantial increase of octopus exploitation in the region has raised concerns over the sustainability of this fishery. While a growing number of measures have been implemented to sustainably manage the octopus stock, there is a lack of information on the status of this octopus stock. In this study, we analyse the status of octopus stock in southwest Madagascar by investigating the interannual and seasonal variability in recruitment and fishing mortality using virtual population analysis (VPA) performed on monthly basis from 2020 to 2022. Yield per recruit is also predicted using a Thomson and Bell model. Our results indicate that octopus fishery national closures (December 15 to January 31 each year) result overall in increase of catches and stock biomass, evidencing the positive impacts of the implemented fisheries regulations in the region. Recruitment exhibits high interannual and seasonal variability with a peak observed between October and December. The simulation model suggests that yield per recruit remains almost unchanged from one year to the next and not exceeding the maximum yield per recruit. Overall, this study shows the importance of understanding the status of octopus stock for sustainable octopus fisheries in southwest Madagascar.

Keywords: Fishery / *Octopus cyanea* / Madagascar / stock assessment / virtual population analysis / recruitment

1 Introduction

Octopus fishery is the major economically important fishery in Madagascar, particularly in the southwest region. It accounts for ca. 70% of the value of the marine resources purchased by commercial fishery and export companies in southwest Madagascar (Benbow and Harris, 2011). Since 1995, there has been substantial increase of octopus fishing activities related to the establishment of seafood collection companies in the region (Langley, 2006; L'Haridon, 2006). From 1996 to 1999, the octopus catches fluctuated around 700 t and jumped to around 1400 t from 2000 to 2003 (Tantely, 2009). In southwest Madagascar, octopus is captured from intertidal reef flats and subtidal inner reefs chiefly during spring tides for local consumption and increasingly for export to European and Asian Markets (L'Haridon, 2006; Guard, 2009). Octopus fisheries have been historically assigned to women and children but men have become increasingly involved due to a rise in demand and greater income opportunities (Oliver et al., 2015). Whilst the octopus fishery is the major source of fishing-derived revenue for the coastal communities, there is a growing evidence suggesting the decline of octopus catches as a result of increased fishing effort (Tantely, 2009; Benbow et al., 2014; Rocliffe and Harris, 2016; Zafimamatrapehy, 2019). Fishing pressure has considerably increased during the last decades due to the arrival of export markets. Previous studies showed evidence of octopus overfishing since 2002 in southwest Madagascar (e.g. Iida, 2005; Humbert, 2006; Tantely, 2009), and the need for initiatives to manage the octopus fishery has become obvious. In 2004, pilot short-term octopus fishery closures were trialled in the region to boost fishery yield to local communities. The success of this temporary closure (e.g. Benbow et al., 2014; Oliver et al., 2015) has led to the implementation of new national fisheries regulations on octopus fishery in 2005, including a minimum catch size limit of 350 g and a national closure season between December 15 and January 31 each year corresponding to the spawning period.

The reef octopus *Octopus cyanea* Gray, 1849 is the most common octopus species on reef worldwide (Van Heukelem, 1976; Guard, 2009). *Octopus cyanea* is the most landed octopus species in Madagascar (Humbert, 2006; Andrisoa, 2011).

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It resides in holes and crevices in coral reefs and rocky shores. Like other cephalopods, *O. cyanea* is a key opportunistic predator with foraging usually occurring during dawn and dusk (Guard, 2009). It has rapid growth and can increase in size by as much as 200 g in only 15 days and up to 13 kg in weight (Wells and Wells, 1970; Guard, 2003). *Octopus cyanea* has a short lifespan between 9 and 18 months (e.g. Van Heukelem, 1983; Herwig et al., 2012) and maturity occurs at body size of ca. 2200 g for females and 600 g for males (Raberinary and Benbow, 2012). Mature female individuals often migrate from shallow reef flats into deeper subtidal areas for spawning (Whitaker et al., 1991; Oosthuizen and Smale, 2003). Upon hatching, planktonic larvae migrate into the water column for one to two months, and travel up to several hundred kilometres in the ocean currents (Chande et al., 2021).

While some studies have investigated the biology, ecology, and fishery information of *O. cyanea* in southwest Madagascar (Andrisoa, 2011; Raberinary and Benbow, 2012; Benbow et al., 2014), there is a lack of information on the status of octopus stock in the region. Stock assessment is a key bio-mathematical tool in the understanding of the population dynamics of fished stocks, estimation of their productivity and establishment of management programs for sustainable exploitation (Roa-Ureta, 2022). In addition, effective management of fisheries that sustain viable fishing communities require knowledge to maintain exploited populations at levels that can produce sustainable yield (Martell and Froese, 2013). Fishing according to biologically sustainable rates may help fishermen to obtain better economic gains because well managed fisheries could achieve better market access and more consistent yields (Oliver et al., 2015; Roa-Ureta, 2020). Octopus fisheries are special case as octopus stocks are short-lived, with fast dynamics, and their exploitation is usually carried out by small scale fisheries. Data collection tends thus to be deficient and often making them data-poor fisheries that require specializes tools for their assessment (Roa-Ureta, 2022). While conventional stock assessment methods have been developed for large-scale fisheries, there has been a tremendous effort in the fishery science community to develop stock assessment methods applicable for small-scale fisheries (Thiaw et al., 2011; Roa-Ureta, 2020, 2022). Among these methods adapted for small-scale fisheries, virtual population analysis (VPA) and yield-per-recruit analysis (Y/R) models have been shown to be applicable and useful for the management of octopus fisheries (Pope, 1972; Jouffre et al., 2002a,b; Jouffre and Caverivière, 2005; Thiaw et al., 2011).

In this study, we (i) estimate the recruitment and fishing mortality of *O. cyanea* in southwest Madagascar using VPA on monthly basis from 2020 to 2022 and (ii) provide diagnosis of the current status of octopus stock for a sustainable fishery management. Octopus fishery data from 22 fishing villages along the southwest coast of Madagascar are studied to contribute to the understanding of octopus fishery biology and provide suitable information for the management of octopus population to decision makers and stakeholders.

2 Materials and methods

2.1 Study area and data sources

The study area is located in the Mozambique Channel on the southwest coast of Madagascar (Fig. 1). The region is characterized by an important biological production driven by an active coastal upwelling (Houart and Virginie, 2013; Ramanantsoa et al., 2018). Coastal upwelling in this region is thought to be driven by coastal winds (DiMarco et al., 2000) and the interactions between the East Madagascar Current (Lutjeharms and Machu, 2000). The southwest Madagascar is also characterized by strong southerly wind called "*Tioky antimo*", regularly exceeding $10\,\mathrm{m\,s^{-1}}$.

Octopus catch data in this study originates from 22 fishing villages along approximate 500 km of coastline from Morombe in the north and Androka in the south (Fig. 1). Blue Venture (BV), a marine conservation NGO, started to work with coastal communities in southwest Madagascar in 2003 and by the first half of 2010s, BV started building a database of fishery operations to help local coastal communities improve their octopus fishing practices and achieve sustainable exploitation of their resource through scientific studies (Roa-Ureta, 2022). BV octopus fishery data is collected by trained data collectors who recorded landings in fishing village at the point of sale. This study used the octopus fishery data collected by BV from 2020 to 2022 to assess the status of octopus stock in southwest of Madagascar.

2.2 Virtual population analyses (VPA)

VPA is a widely used technique in fishery science for reconstructing the historical population structure by age using information on the deaths of individuals in each time step. The advantage of VPA is that once the history is known it becomes easier to predict the future catches, which is usually among the most important tasks of fishery scientists. In this study, VPA was used to model the past stock dynamics and calculate the number of octopus alive in each cohort. Calculations were computed using R software, and three basics equations were used: catch, survival and Pope approximate of the survival equations (see below). VPA is defined as virtual in the sense that the population size is not observed or measured directly but is inferred or backcalculated to have been a certain size in the past. Since VPA methods require age-structured data, the catches-at-weight data was converted to catches-at-age following a weight-age relationships obtained for a *O. cyanea* population in Australia (Herwig et al., 2012):

$$W_t = a * t^b \tag{1}$$

where $a = 2\times 10^{-5}$, $b = 2.042$, W is the weight (in kg) and t is the age (in days). Fifteen age groups 2–16+ months were used, where the 16+ age group encompasses catches of the 16-month-old and older individuals. The catches-at-age, expressed as the number of individuals (abundance) for each age group was used for the VPA.

The total mortality (Z) defines the rate of decrease of the population size and is decomposed into fisheries mortality (F) and natural mortality (M) (Lassen et al., 2001):

$$Z = F + M. \tag{2}$$

Fishing mortality depends on fishing effort while natural mortality is a biological parameter. We used 0.25 per month for natural mortality as estimated by previous studies (Jouffre et al., 2002a; Thiaw et al., 2011). This estimation is based on

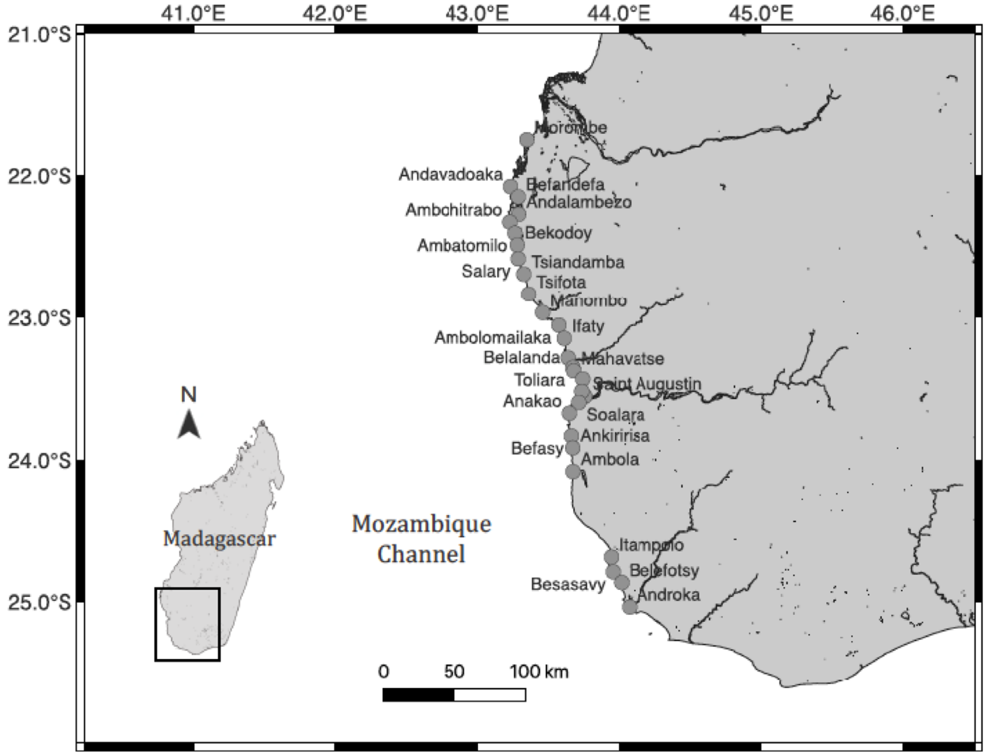

Fig. 1. Map showing the study location and fishing villages in southwest Madagascar. Black lines represent rivers in the region.

the assumption that the average fecundity ranges between 300 000 and 500 000 eggs per laying (Caddy, 1996; Jouffre et al., 2002a). This natural mortality value is comparable to the values reported for *O. cyanea* in southwest Madagascar using intra-annual generalized depletion models between 0.05 and 0.25 month^{-1} (Roa-Ureta, 2022). To calculate the fishing mortality for each age group, terminal fishing mortality for the last age group must be determined (see below).

Three basics equations were used for our analysis (Hilborn and Walters, 1992; Thiaw et al., 2011):

(i) Catch equation:

$$C_{t,i} = \left(\frac{F_{t,i}}{F_{t,i} + M}\right) * N_{t,i} * \left(1 - e^{-\left(F_{t,i}+M\right)}\right). \tag{3}$$

(ii) Survival equation:

$$N_{t+1,i+1} = N_{t,i} * e^{-\left(F_{t,i}+M\right)}. \tag{4}$$

(iii) Pope approximate of the survival equation (Pope, 1972):

$$N_{t,i} = N_{t+1,i+1} * e^{-M_{t,i}} + C_{t,i} * e^{-\left(M_{t,i}/2\right)}. \tag{5}$$

where N denotes the number of individuals, t the age group, i the month and C the total catch (in number). Fifteen age groups (2–16+) were used for our analysis, and the 16+ age group represents catches of the 16-month-old and older individuals.

Fishing mortality was used in the catch equation to generate the abundance of the terminal age group, which, in turn, was used to in Pope's equation to estimate the number of individuals in the preceding age group of the same cohort. Fishing mortality in each age group was estimated from abundance estimates using the reverse form of the survival equation and terminal fishing mortality for the last group and the last month was estimated by repeating the calculation until stabilisation (Thiaw et al., 2011). The fishing mortality is expressed as:

$$F_{t,i} = \ln\left(\frac{N_{t,i}}{N_{t+1,i+1}}\right) - M_{t,i}. \tag{6}$$

2.3 Yield-per-recruit analysis (Y/R)

A classical yield per recruit model was used to estimate the stock size and to analyse the fishing impact on the octopus stock (Thiaw et al., 2011). Thompson and Bell model is widely used as a prediction model for assessing the optimum factor for increasing or decreasing of fishing effort to achieve maximum sustainable and economic yield of commercially exploited species (Thompson and Bell, 1934). This builds on the output of age-based VPA model (Jouffre et al., 2004). In this study, Thompson and Bell model was used using R software and the input data included the fishing mortality (F), the weight (W) and the abundance (N). The yield per recruit (Y/R) was estimated using the following equation:

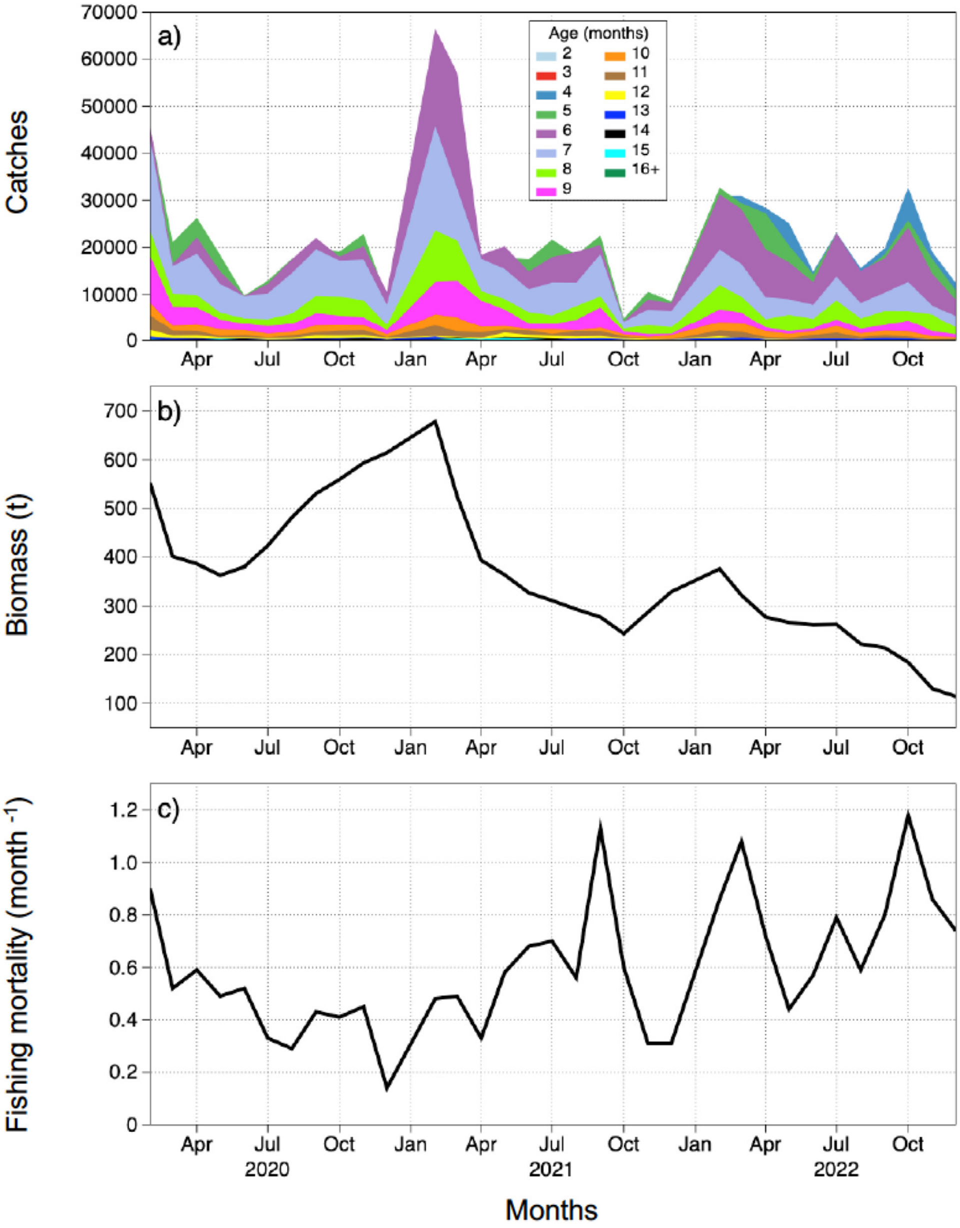

Fig. 2. Monthly catches of *O. cyanea* (a), biomass (b) and mean fishing mortality for all age groups (c) from age 2 to 15 months between February 2020 and December 2022. Catches correspond to the monthly number of octopus caught and colours represent the age groups.

$$Y/R = \sum\nolimits_{t=t_r}^{T}\left[\overline{W_t} * F_t * e^{\left(-\sum\nolimits_{i=t_r}^{t-1}(F_i+M_i)\right)} * \frac{1-e^{-(F_t+M_t)}}{F_t+M_t}\right]. \tag{7}$$

The biomass was estimated using the following equation:

$$B_{t,i} = N_{t,i} * W_t. \tag{8}$$

3 Results

3.1 Octopus population dynamics

The catches of *O. cyanea* varied between months for different age groups (Fig. 2a). There was no clear trend in the catches, but a clear seasonal pattern was observed with higher catches recorded from January to April and lower catches from October to December.

The monthly average number of *O. cyanea* caught from February 2020 to December 2022 was 6585, with a minimum observed in December 2022 (3402) and maximum in February 2021 (17 679). In addition, catches of age groups 5–6 months were more abundant in comparison to other age groups and varied considerably between months (Fig. 2a). In contrast, older age groups were less abundant and nearly constant during the study period.

The biomass showed also important variation between years (Fig. 2b) with lower biomass observed during 2022 (mean = 239 t) in comparison to that of 2020 (mean = 480 t) and 2021 (mean = 366 t). Biomass showed also strong seasonal pattern with higher values recorded in February–March and

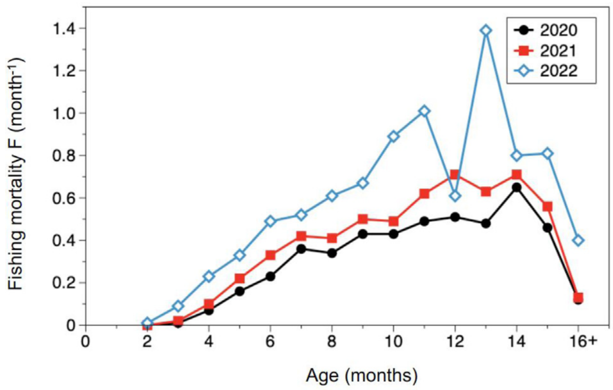

Fig. 3. Annual average exploitation patterns for *O. cyanea* in southwest Madagascar for 2020, 2021 and 2022.

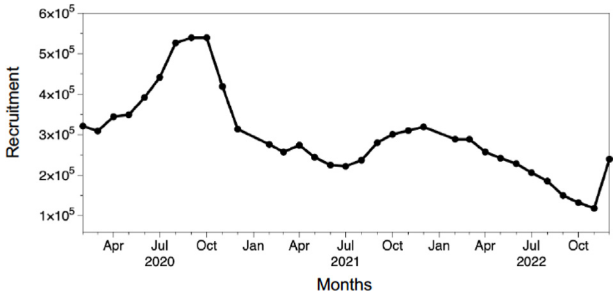

Fig. 4. Monthly octopus recruitment as number of individuals (for age group 2 months) from February 2020 to December 2022.

lower values in October–November and in May (Fig. 2b). The maximum biomass was observed in February 2021 (678 t) and the minimum in December 2022 (114 t).

In southwest Madagascar, the octopus fishery is marked by interannual and seasonal exploitation (Figs. 2c and 3). Fishing mortality varied from 0.14 to 1.18 month^{-1} and the lowest values were observed in December while the highest values in February–March and September–October. Figure 3 shows that fishing mortality increased progressively throughout the lifespan of individuals within a cohort and reached a maximum for older octopuses (age groups 13–14 months) and decreased again for age groups 15–16+ months. The exploitation of *O. cyanea* followed a relatively similar pattern for 2020, 2021 and 2022 with different intensity according to the age group (Fig. 3).

3.2 Recruitment

Our results showed that recruitment, which is the number of individuals at age 2 months, varied considerably between years and months (Fig. 4). The average number of recruits was 296 396 recruits per month and fluctuated between 212 620 (cohort 2022) and 408 664 (cohort 2020) per year. The recruitment exhibited peak in September–November 2020 (maximum = 539 360 in October 2022) and declined until July 2021. A second peak was observed in December 2021, but less pronounced compared to the first peak (319 231). The recruitment decreased from December 2021 and reached a minimum in November 2022 (minimum = 118 362).

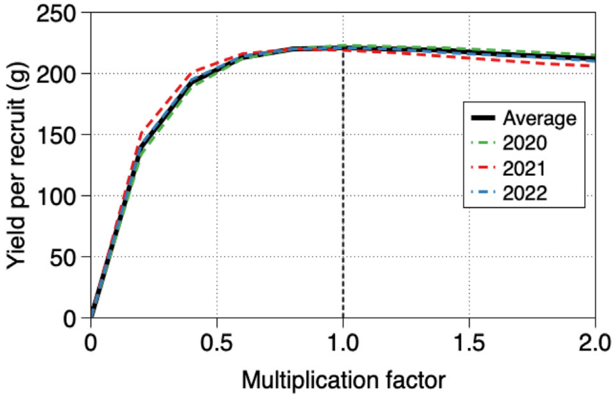

Fig. 5. Yield per recruit as a function of multiplier factor. The actual status corresponds to multiplication factor 1.

3.3 Exploitation diagnosis

The yield per recruit curves for the study period indicate that there is only slight change from one year to the next and the increasing current fishing effort would solely cause a slight decrease in yield per recruit (Fig. 5). Inversely, decreasing fishing efforts would not result in a considerable increase in yield per recruit. In addition, the current fishing effort still corresponds to the maximum yield per recruit, thus not exceeding the critical threshold. The multiplier factor corresponding to the maximum yield per recruit was close to 1, which is the actual situation.

4 Discussion

4.1 Age-based modelling approach

Size-based approach (or weight-based) implies modelling on pseudo-cohorts but not on true cohorts, and using pseudo-cohorts has two major constraints. Firstly, it assumes constant recruitment and unchanged levels of exploitation for all cohorts in the pseudo-cohorts (Jouffre and Caverivière, 2005). It is impossible to assume a constant exploitation in the present situation as octopus exploitation in southwest Madagascar varies seasonally and the recruitment is known to follow strong seasonal pattern (e.g. Raberinary and Benbow, 2012). Our findings confirm this seasonal variation of recruitment, especially at the inter-monthly scale defined by the model temporal step of calculation (Fig. 4). Secondly, the model must be able to simulate monthly changes in exploitation to evaluate the impacts of fishing efforts under various scenarios (e.g. impacts of periodic octopus fishery closures). Such simulation is impossible by assuming constant exploitation. Therefore, a modelling option based on true cohorts, thus on age, is more appropriate for this study. However, for age-model approach, the conversion of initial catch data from weight to age is always a delicate operation because it introduces additional uncertainties in the estimations. Overall, a lack of biological knowledge of octopus, the interannual variability of recruitment, and their rapid growth make octopus stock assessment a difficult undertaking. Most stock assessment tools are designed for finfish (on a yearly basis) and are often not directly applicable for short-lived animal like octopus. The first stock assessment of *O. cyanea* in southwest Madagascar used intra-annual generalized depletion models (Roa-Ureta, 2022). This study estimated natural and fishing mortality, stock's total abundance and the magnitude of pulses of recruitment. This approach appears to be useful for data-limited fisheries such as the octopus fishery in southwest Madagascar as they do not use biological composition data (e.g. age, length frequencies).

4.2 Effects of fishing closure on octopus stock

In this study, the period of lower octopus catches coincides with the national closure season (between December 15 and January 31) and the peaks of octopus biomass in February-March occur just after the closure (Figs. 2a and 2b), indicating marine closures implemented in the region reduces fishing pressure and increases biomass of octopus stock. Marine closures such as marine reserves or marine protected areas have been widely used to manage octopus fishery around the world (Pipitone et al., 2000; Halpern, 2003; Narvarte et al., 2006; Storero et al., 2013). A study of octopus artisanal fishery in Senegal showed that temporary fishing closures lead to enhanced octopus stock biomass (Jouffre et al., 2002b). In southwest Madagascar, this national closure season coincides with the peak of spawning periods of *O. cyanea* in the region and thus allows the protection of spawning females (Raberinary and Benbow, 2012). In addition to the national closure, local periodic closures have also been implemented, in which fishers temporarily refrain from harvesting in specific fishing sites (20–25% of the overall fishing grounds). Periodic closures have long been a part of traditional fishing cultures across the Indo-pacific (Johannes, 2003; Cinner et al., 2005; Bartlett et al., 2009) and several studies have demonstrated the positive impacts of periodic closures in southwest Madagascar (Humbert, 2006; Benbow et al., 2014; Oliver et al., 2015). Results from fishing villages in southwest of Madagascar showed that median octopus landing increases from 49.5 (±22.8) kg in 30 days before closures to 404.8 (±119.9) kg in the 30 days after the reopening accounting for 718% increase (Oliver et al., 2015). Furthermore, villages implementing closures observe a doubling of octopus fishery income after re-opening and notice no significant decline of income during closures (Oliver et al., 2015). Due to short time frame of socially acceptable closure periods, there is an important need to understand the life cycle of the target species to maximize fisheries benefits from the closure. For instance, the identification of recruitment peaks has important management implications for the octopus fishery as it could significantly increase the size of octopus caught once a closed fishing site is reopened.

4.3 *Octopus cyanea* stock dynamics

This study shows high seasonal variability in octopus recruitment, similar to recruitment patterns observed for octopus stocks in other areas such as Senegal (Thiaw et al., 2011), Mauritania (Gascuel et al., 2007) and Gambia (Caverivière, 1990). This study indicates that there is a 5-fold difference between the maximum and the minimum monthly recruitment values estimated throughout the 3-year study period (Fig. 2c) and recruitment peak occurs mainly in October-December, although the length of the peak period varied annually (Fig. 4). Similar findings have been documented for *O. cyanea* in southwest of Madagascar based on gonadosomatic index (Raberinary and Benbow, 2012) and in Rodrigues, western Indian Ocean (Sauer et al., 2011). However, the intra-annual generalized depletion models were not able to detect the recruitment peaks due irregular distribution across the season (Roa-Ureta, 2022). Previous studies suggested that the octopus seasonal spawning patterns generally drive recruitment peaks and a delay of five to six months are expected between peak spawning and recruitment period (Caverivière et al., 2002; Raberinary and Benbow, 2012). Changes in recruitment among years were mainly attributable to fluctuations in environmental conditions. Generally, octopus growth is mainly influenced by food availability and water temperature (van Heukelem, 1976; Cortez et al., 1999), suggesting that these parameters may have been more suitable for 2020 (higher recruitment), but less suitable for 2021 and 2022 (lower recruitment) (Fig. 4). It has been well recognized that high primary production supports octopus growth and thus enhances spawning and recruitment (Otero et al., 2008; Faure et al., 2008; Vargas-Yáñez et al., 2009). In southwest Madagascar, high primary productivity is attributed to coastal upwelling (Ramanantsoa et al., 2018). This high primary productivity provides food to octopus larvae which feed on zooplankton including larval stages of crabs and shrimps (van Heukelem, 1976). In addition, coastal upwelling which drives the fluctuation of environmental conditions, is probably the source of interannual variation in recruitment in this region, as previously reported in the recruitment of *O. vulgaris* along the coast of Senegal (Demarcq and Faure, 2000), Mauritania (Faure et al., 2008) and Spain (Otero et al., 2008). Strong wind in southwest Madagascar could also act as a key factor for octopus larval abundance and distribution because it facilitates the mixing of water, which brings bottom nutrient rich water to the euphotic zone (Chande et al., 2021), favouring biological production and thus high octopus growth rate (Jabeur et al., 2009). Wind-driven turbulence has also been reported to affect the early life stage of *O. vulgaris* in northeast Atlantic Ocean, contributing to 85% of the annual variability of adult octopus catch (Otero et al., 2008).

Adverse environmental conditions enhanced by natural phenomenon may lead to increased natural mortality. This indicates the uncertainty associated with the estimation of the natural mortality parameter in the model. For *Octopus cyanea*, an additional difficulty lies in the fact there are very few studies on the estimate of this natural mortality parameter. It has been shown in previous study that variation in octopus population size could result from changing environmental condition (Katsanevakis and Verriopoulos, 2006). Nevertheless, octopus stocks are considered resilient populations because of their biological characteristics such as fast-growing rates, their reproductive strategies, and the female reproduction behaviour (Silva et al., 2002; Kivengea et al., 2014). Therefore, it is necessary to take into account such behaviour in population and the potential impact when studying octopus population dynamics.

4.4 Octopus biology and fishery management implications

The cohort exploitation patterns at each relative age shows that older octopuses are overall subject to the highest fishing mortality (Fig. 3). The increase in fishing mortality among adults may be attributed to the higher prices of older individuals compared to younger ones and the increased demand from octopus fishery companies. This could also be explained by a seasonal change in the behaviour of fishers. Larger octopus may be preferred target when they spawn along the coast. Two spawning peaks are suggested for *O. cyanea* in southwest Madagascar: one in January–February and another in April–June (Raberinary and Benbow, 2012). Indeed, the first spawning period (January–February) coincides with the period of higher catches (January to April), suggesting that spawning females are likely fished during this period. Similar spawning periods are documented for *O. vulgaris* in May and December in Greece (Katsanevakis and Verriopoulos, 2006), in April and May in the canary Islands (Hernández-García et al., 1998), and in April–May in Spain (Otero et al., 2007). However, the study by Raberinary and Benbow (2012) in southwest Madagascar reported the scarcity of fully mature female caught during their study, suggesting that fishers are only able to exploit octopus residing on the shallow reef flats exposed at low tide and there is likely a deep stock of subtidal octopus beyond the reach of fishers. Such "deep refuge" phenomenon has been reported for *O. vulgaris* in South Africa (Oosthuizen and Smale, 2003) and in Spain (González et al., 2011) and brooding female octopus have been observed at depths of up to 150 m (Silva et al., 2002). Therefore, the introduction of deeper water fishing gears for the exploitation of *O. cyanea* in southwest Madagascar may have ecologically detrimental impacts on octopus population and requires careful management to prevent over-exploitation of mature females prior to spawning (Raberinary and Benbow, 2012). However, it should be noted that octopus fishery is specific because animals are caught before reproduction and spawning as they tend to die immediately reproduction (Arreguín-Sánchez et al., 2000; Hernández-García et al., 2002). The lack of information on post-hatching mortality of females to adjust fishing mortality computation remains a challenge in octopus stock assessment from VPA analysis (Arreguín-Sánchez et al., 2000).

Our cohort model shows that the octopus stock in southwest Madagascar is fished at sustainable rates, although very close to the maximum yield per recruit (Fig. 4). From 2020, there is an increase of the fishing effort, leading to important fishing mortality in 2022, particularly for older animals. The study by Roa-Ureta (2022) using intra-annual generalized depletion models reported similar results for 2017, 2018 and 2019. Previous studies in octopus fishery showed that under fishing pressure, octopus population dynamics may be dominated by cycles of abundances, with high abundance years followed by low abundance years (Thiaw et al., 2011; Duarte et al., 2018; Roa-Ureta, 2022). In such situation, excessive exploitation rates may lead the stock to collapse in years of low biomass in the cycle (Roa-Ureta, 2022). These cycles are likely associated with a highly unstable relationship between spawning and recruitment and enhanced by fishing activities. Raberinary and Benbow (2012) documented likely unstable relationship between the spawning and recruitment peaks for *O. cyanea* in southwest Madagascar caused by temperature and prey availability during pelagic larval phase, likely driven by coastal upwelling in the region. Lower abundance in 2022 compared to that of 2021 and 2020, suggests thus that the octopus stock in southwest Madagascar may enter a population dynamics cycle marked by high abundances years followed by low abundance years. Therefore, it would be necessary to reduce fishing effort so that annual catches remain under the lower point of biomass fluctuations. In addition, our results indicate that octopus fishery in southwest Madagascar is still in full exploitation and the current octopus stock corresponds to the F_{MSY} (Fig. 5). However, to ensure the sustainability of the resource, a precautionary approach should be considered by introducing a reference point. In the present situation, the reference point should be equal to F_{MSY} multiplied by the three quarters, denoted as $F_{0.75}$. This would result in a reduction of the current effort up to 25% and likely lead to higher abundance, thereby increasing the global resilience of the stock.

5 Conclusion

This study shows the high interannual and seasonal variability in catch, biomass and recruitment of *O. cyanea* in southwest Madagascar. The variations in recruitment and fishing mortality are estimated using VPA performed on monthly basis while yield per recruit is estimated using a Thomson and Bell model. Our results show that reduced catch and increased biomass of octopus observed during the study period coincide with the annual closure season, suggesting the positive impacts of the regulations implemented to manage octopus resources in the region. The VPA shows a recruitment peak in October–December with an annual variation of peak length period. This interannual variation in recruitment is likely attributed to coastal upwelling in the region which drives the fluctuation of environmental conditions such as primary productivity and temperature. Strong wind in the region may also enhance this interannual variation. Our simulation model shows that the octopus stock is fished at sustainable rates, but very close to the maximum yield per recruit. Precautionary approach should be therefore considered by reducing fishing effort. Overall, this study allows to elucidate the stock dynamics of *O. cyanea* in southwest Madagascar and provides insights on the management of octopus fishery in the region.

Acknowledgments

This study was made possible by the data provided by Blue Ventures. We thank Thomas Stieglitz for his generous support. Aladin Andrisoa acknowledges support from the French Institute for Sustainable Development (IRD) and the IRD community of knowledge (CoSav Leo).

Data availability statement

Data will be made available on request.

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Cite this article as: Raberinary D, Andrisoa A. 2024. Assessing stock of reef octopus *Octopus cyanea* in southwest Madagascar using age-based population modelling. *Aquat. Living Resour.* 37: 13