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Revealing the role of crab as bait in octopus fishery: An ecological and fishing approach to support management decisions

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ABSTRACT

In southern Portugal, artisanal octopus fisheries play an important socioeconomic role. Live crab bait in traps was used up to 2010 and banned in 2012. Such regulation, based on co-management advice, was not established under a scientific fundament. As a result, a long-standing controversy ensued with some fishing associations claiming that live crab bait increased fishing effort and exploitation rates and therefore risked the octopus stock status, while other fishers denied all these alleged impacts. The issue has not been resolved so far due to lack of scientific studies. In this study, we resolve the controversy conducting experimental fishing to determine bycatch and octopus catch rates using live crab bait versus other types of baits based on fish and assess the stock status of octopus over-time with constant parameters (hypothesis of no effect of the use of live crab bait) versus time-varying parameters (hypothesis of raised exploitation rates and riskier stock status). Bycatch was very low regardless of bait type. Our experimental fishing trials showed that fish-based baits increase bycatch and octopus catch rates. Stock assessment models showed that exploitation rates and stock status do not worsen in years of use of crab bait. We conclude that the use of crab bait in octopus fishery does not lead to increased exploitation rate or risks for stock sustainability status. Other considerations involving fishing costs and fishing operations further highlight the advantages of lifting the ban on the use of live crab bait in the Algarve octopus fishery.

1. Introduction

Octopus fisheries worldwide contribute around 10% of cephalopods landings with an increasing trend in recent decades due to high prices, increasing market demand and possibly less opportunities in finfish stocks [44]. This raised output has been brought about by increasing fishing effort directed to octopus stocks [4,21,39]. Higher demand for octopus and correspondingly higher fishing effort without studies of the impact of raised effort on stocks' status may threaten the development of those fisheries and deteriorate their sustainability [11,40,44]. One such example of the risks of raising fishing effort on octopus stocks occurred in the Algarve, southern Portugal, where the introduction of traps with live crab bait has been blamed for a rise in fishing effort potentially leading to overfishing. This in turn led to interventions by authorities without the necessary scientific basis to support such interventions [21].

The importance of octopus in Portugal is aligned with the significance of other cephalopod fisheries, which are also socio-economically important in European and Mediterranean waters [13,28,30,33,46], north [16,18] and south African countries [32,51,53], Latin American countries [11,34,39], Australia and New Zealand [23], and Asian countries [44,52]. In those regions, methods to catch octopus include clay pots [16,43,45], baited traps [6,13,21], baited drifting rod, gleaning and spear [32], wooden sticks to which hanging lines are fixed and baited [5,11,17], trawling [16] and diving [34].

Landings of octopus are mostly from artisanal fisheries [21,39] although there are large industrial fisheries in Western Africa [16,38]. The artisanal fleet in the south coast of Portugal, specifically in the Algarve region, is highly dependent on the *Octopus vulgaris* species. It is responsible for 52% of the national octopus landings in 2021, which amounted to approximately 3800 tons. These landings reached an

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average value of €7.59 per kilogram at auction sites making it a high-value fishery. In this region of Portugal, pots and traps are the most commonly used gears while trawlers contribute to octopus bycatch in low proportions (<5% per year; DGRM, Direção Geral dos Recursos Marinhos). Traps baited with live crab were used from the 80s to 2009. Due to controversies in local communities [21], a regulation was enforced in 2010 to ban the use of live crab bait (*Carcinus maenas*) in Portuguese octopus trap fisheries, with the purpose to reduce fishing effort and thus the risk of overfishing. The ban was lifted in 2011 and reinstated in 2012 in the Algarve but not in the remaining Portuguese coast. The Common Fisheries Policy (CFP) established that cephalopod fisheries in EU member states should have local/national management plans that apply a top-down system based on expert opinions and research. Consequently, efforts have been made to involve fishers in the decision-making process in octopus fisheries [29]. The regulation banning crab usage was imposed as a result of decisions taken by the Algarve octopus co-management task force, composed of fishers' associations and organization, scientists, and policy makers, but it lacked robust scientific evidence to support it. It occurred at a time of relatively poor landings of octopus and it sought to reduce fishing effort as it was thought that the use of live crab bait increased effort because traps could remain submerged with crabs for several days. In 2017, a meeting was held between scientists, fishing associations and organizations as part of the CRUSTAPANHA project. The purpose of this meeting was to conduct a study that would address the objectives outlined in the present study. These are:

1) If the ban on using crabs as bait is lifted, concerns about the indirect role of live bait in accidental catches (bycatch) may arise. We conducted a comparative bycatch assessment of traps baited with live crabs versus fish.
2) Do catch rates differ when traps have live crab bait versus fish bait? We fitted generalized linear models considering various bait type and gear/fishing characteristics to test the hypothesis that live crab bait increases octopus catch rates.
3) Is the octopus stock closer to overfishing in years of no ban of live crab bait versus years of banned live crab bait? The current status of the octopus stock in the Algarve region has not been determined by stock assessment studies so we assessed the stock with a model with time-varying parameters that explicitly accounted for potential effects of the introduction and removal of the ban on live crab bait.

2. Methods

2.1. Study site

The Algarve, in the south coast of Portugal, includes eleven main ports where the artisanal octopus fleet lands its catches: Sagres, Lagos, Portimão, Albufeira, Faro, Quarteira, Olhão, Tavira, Fuzeta, Manta Rota, Vila Real de Santo António (Fig. 1).

The continental shelf off Algarve is narrow, extending 7 km in the narrowest parts, with weak wind-driven drift currents predominating over tidal currents, although the latter are predominant when winds are mild. Wind-driven drift currents tend to run along the shore, from east to west or vice-versa, to 30 m depth or more [25].

2.2. Experimental design/protocol

2.2.1. Octopus bycatch

Bycatch strategies that result in reduced catch of species caught incidentally in fishing operations can be broadly applied to environmental protection of living habitats and to marine biodiversity conservation in general, so they are part of the ecosystem approach to fisheries [48]. Bait type may impact on bycatch of trap gears yet the bycatch composition of the Algarve octopus fishery is poorly known. Generally, the perception exists that the trap discard rate is low in total biomass [2] so little attention has been given to species composition and diversity of the bycatch [42].

All field bycatch surveys were conducted in a single octopus fishing boat (length=8 m, gross tonnage=2.36 tonnes, power=37 KW) from the artisanal fleet with a two fishermen crew and typical trap gear, granted a special license to use the banned live crab bait for scientific purposes. These traps were deployed following fishermen's local knowledge on traditional fishing grounds on sandy bottoms between 20 and 40 m

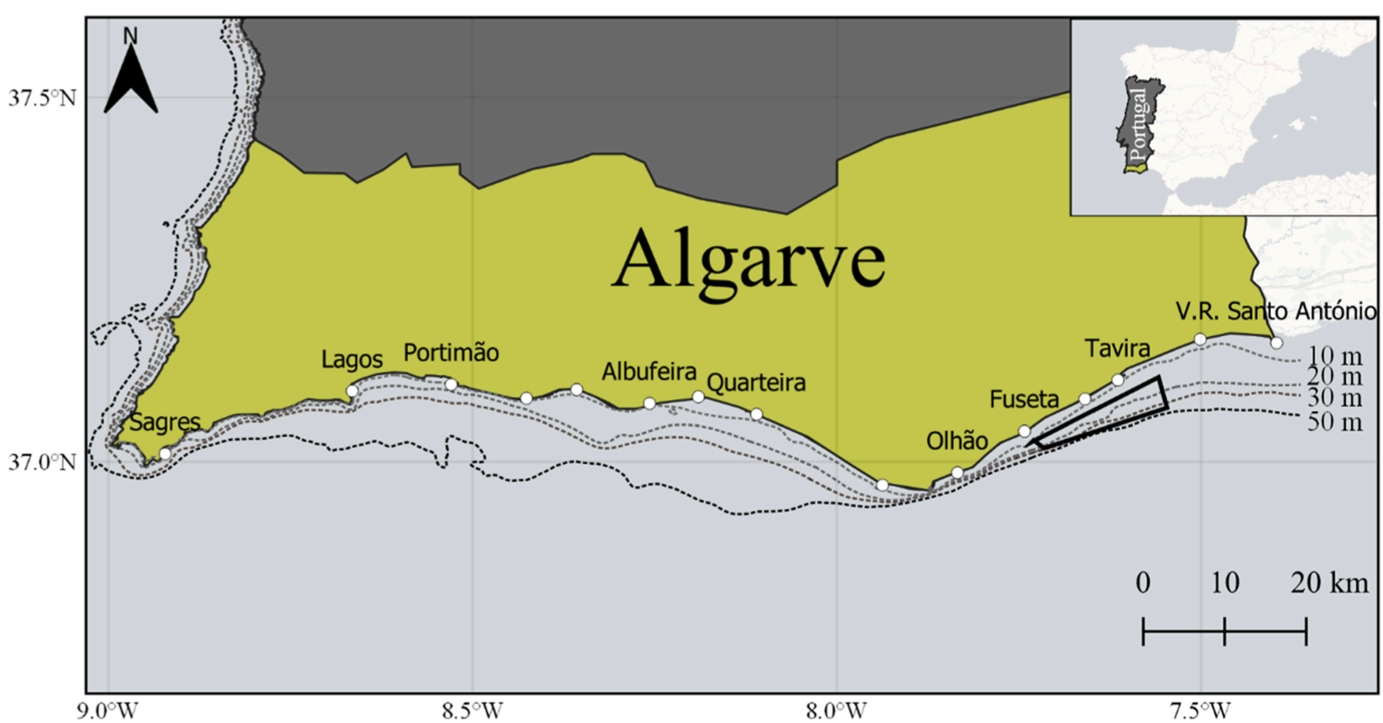

Fig. 1. Algarve coast with fishing ports and the fishing areas where the bycatch study was conducted (square).

depth with an average of 35 ± 6 m and 31 ± 4 m for crabs and fish, respectively. Non statistical differences were observed between depths for traps deployed with different bait types (Mann-Whitney: $z = 1.8861$; $p < 0.05$). Following fishermen's common practices traps remained deployed at sea one day for fish bait type and 2–3 days for live crab bait type. A total of 8 and 13 surveys were completed for fish and crabs bait types corresponding to 3395 and 5610 traps sampled, respectively. The average number of traps used per set was 340 ± 118 with the maximum 1000 and minimum 160.

Upon hauling all catch was removed from traps and sorted into target and bycatch species following fishers' commonly onboard sorting practices. Total number of octopus were recorded together with total weight. Further following fishers' discard practices each taxon was classified into a bycatch category as follows. Landed bycatch (BL) were taxa that are sold at auction, discarded bycatch (BD) were taxa discarded at sea, and trapped bycatch (BT) were taxa that were of no commercial value but that could not be discarded because it took too much work to dislodge them from the trap's structure or it was too dangerous to manipulate them (e.g. small scorpion fish and sea urchins). BT is usually re-deployed thus possibly acting as extra bait in octopus fishery. All taxa were taken to the laboratory for identification to the lowest possible taxonomic level, weighting and length measurement. Epiphytic sessile fauna (e.g. *Anomia ephippium*) were included in the sampling.

Similar to the use of fish as bait, the octopus trap fishery that utilizes crabs operates as a manual fishery. The crabs are positioned and contained within small cylindrical compartments made from polypropylene netting, which are securely attached and sewn into the main trap structure. The live crabs are held in place by an upper door that can be opened and closed using elastic bands, facilitating the loading and reloading of crabs.

2.2.2. Octopus catch rates

Catch per unit effort (CPUE), or catch rates, from commercial fisheries are widely used to derive indices of relative abundance. These indices are derived from approximate linear models that remove the effect of factors other than the factor of interest, usually annual abundance [8,19]. In our studies, a three-year monthly survey was conducted between January 2020 and December 2022, aimed at collecting demographic data on octopus population (weight composition) and estimate catch rates in the trap octopus fishery. The selection of the boats for this study was made by administrative authorities (the DGRM, *Direção Geral dos Recursos Marinhos*). The criteria for boat selection included landings statistic of the boats (higher landings records were the first to be selected for the study) and onboard conditions suitable for the work of the scientific observer. Boats complying with the above criteria were granted a temporary license to use crabs as bait for both, scientific and commercial purposes. The main role of the scientific observer was to sort the octopus catches by bait type, either fish, live crab bait, or a mixture of fish and live crab bait types. Once in land and before auctioning, the observer counted and weighted all octopus by bait type. A total of 1050 records/sets were obtained from these bait type comparison experiments.

With the data from these surveys, the hypotheses of no effect of bait type was tested using two different response variables. In the first analysis the response variable were the catches of octopus in numbers per trap deployed, so CPUE was defined as octopus/trap. In the second analysis the response variable was additionally standardized by days of soaking time, so that CPUE was defined as octopus/(trap,day). Using the first response variable (octopus/trap) is equivalent to interpreting fishing effort in soaking days as a random effect while the second response variable removes the effect of soaking days by using it as a standardizing variable.

2.2.3. Octopus stock assessment

A recent review of stock assessment methods for cephalopods recommended the use of innovative depletion models because these models are better suited to cephalopod life history and to data typically collected from their fisheries, as well as being flexible to adapt to specific situations [4].

The question around the bait type effect before and after the ban on live crab bait is centred on the hypothesis that the use of the live crab ultimately increases the risk of overfishing via more fishing effort or more effective fishing effort. We designed a test of this hypothesis by conducting stock assessments with multi-annual generalized depletion models (MAGD, [36]) that (1) ignored any impact of the live crab bait by assuming that relevant parameters in the model did not change from years of live crab bait banning to years of free use (null hypothesis) or (2) that had time-varying parameters that changed depending on the status of the ban (alternative hypothesis). The null hypothesis represent the view that the use of live crab bait does not increase octopus exploitation rates.

Additional advantages of using the stock assessment approach to analyse the effect of the use of live crab bait are the usual use of stock assessment results in supporting management actions, in this case for the implementation of a co-management system in the Algarve octopus fishery as proposed in 2022–2023 [27]. Furthermore, having stock assessment results may support Marine Stewardship Council certification for this fishery, having previously failed to achieve it [7].

2.2.4. Bait consumption and cost

Data on the amount of bait required by boat for the Algarve fishery was also estimated for both fish and live crab type baits, in weight and in value. The collection of the consumption and expenses with bait was obtained by providing a logbook to boat captains where they noted the information regarding the price fishers pay for bait acquisition and amount of bait used in the fishery. Bait monthly consumed by the fleet was estimated accordingly by boat size category and over an average of 12 days fishing per month. Statistical differences between bait types in amount of bait required and expenses per month were compared using the Mann-Whitney U test.

2.3. Data analyses

2.3.1. Bycatch

The data (abundance and weight of bycatch) was standardized by 100traps/day. Species richness and Shannon-whinner (H based on log) diversity ecological indexes were estimated for each gear set and by bait type using abundance data. Comparison between bait types in abundance, weight and ecological indexes were made by means of ANOVA or Kruskal–Wallis one-way analysis of variance whenever ANOVA assumptions were not fulfilled (Past4.01 software: [15]).

As the size of the trap and fishing area (depth) were invariant between bait types we can assume that differences in taxa retained in traps, if any, are due to the bait type effect. Bycatch composition and abundance data (individuals per 100 traps per day) were analysed with multivariate methods to compare bait types. The non-parametric Permutational Analysis of Variance (PERMANOVA) test was performed to identify statistical differences in bycatch composition between bait types. The non-metric multidimensional (MDS) ordination analyses was used to plot bycatch composition data. Finally, SIMPER analysis (similarity percentage – species contribution) was undertaken in order to highlight the taxa that most contributed to the dissimilarity found between bait types. All above multivariate analyses were based on the Bray-Curtis similarity coefficient matrix with PRIMER v5.0 [9].

For the estimation of the likely number of bycatch taxa in the BT category that would die due to not being discarded for the overall fleet on a yearly basis, the following assumptions were made:

i) A fishing boat would fish for 3 days a week and throughout the entire year.
ii) Fleet size was 592 boats, which was the number of the Algarve fleet that landed octopus in 2021.

iii) Octopus boats would maximize their catch by using the maximum number of traps allowed by regulation (Regulation No. 1127-B/2019). Specifically, it was assumed that each boat would use 750 traps per trip for boats with a length less than 9 m, 1000 traps per trip for boats with a length between 9 and 12 m, and 1250 traps per trip for boats longer than 12 m.
iv) The composition of the fleet in terms of boat size was the same as in 2021, namely: 79% in the size category of 9 m, 13% in the 9–12 m category, and 8% in the category of boats longer than 12 m.

2.3.2. *Bait type effect on catch rates*

We fitted generalized linear models (glm) to response variables octopus/trap and octopus/(trap.day) with the following explanatory variables as factors: type of bait (three levels: crab, fish and mixed), trap size (three levels: small, medium and large), year (three levels: 2020, 2021, 2022); as well as soaking days and depth as continuous covariates in some models. The mesh size of the three different sizes of traps used was the same (3.5 cm), as it is a mandatory mesh size established in octopus fishing regulation for traps (Regulation No. 1127-B/2019). Although trap size is not the focus of this test we recognized the existence of three trap size categories. Small traps are 40 cm length, 35 cm width and 17 cm height, medium traps are 55 cm length, 46 cm width, and 23 cm height, and large traps are 75 cm length, 60 cm width, and 37 cm height. Several models were considered and tested for evaluating different postulated hypotheses about the significance of co-variables though the main purpose remained the same: to extract the effect of bait type (three levels: fish, mixed and live crab) to determine whether live crab bait increases catch rates. The selection of the best model was based on the Akaike information criterion (AIC).

2.3.3. *Stock assessment modelling*

Unlike the studies of bycatch and catch rates, that were conducted using sample data collected by us during execution of the CRUSTAPANHA project, total effort and total catch data for stock assessment were compiled from official archives of the DGRM that covered the entire fishing activity for octopus in the Algarve. Fishing effort was measured as the number of days fishing per month and the catch was measured in kg of octopus.

The effort-catch database covered the period of January 2006 to December 2020 (180 months) and contained monthly boat-by-boat totals of fishing effort and catch for three classes of boats (in order of increasing size): local, coastal and long distance; and three classes of gears: artisanal, seine and trawl. Long distance boats and the seine gear contributed a negligible catch (less than 0.1%) and were not further considered. The gear called artisanal corresponded to baited traps and pots which accounted for close to 95% of the total catch over the 15-yr long period of data, while the trawl contributed the remaining 5%. Although the data from trawls was much less it contributed to make the stock assessment results valid for a larger region, because trawlers operate offshore and the artisanal fleet operates in near shore areas. Thus, data from trawlers were included in the assessment. This raises the issue whether the MAGD stock assessment model should be a two-fleets model. Effort and catch data are shown in Fig. 1 of Suppl. Mat. 1. It is apparent that the effort-catch relationship is very similar for both fleets and therefore a two-fleet model would not yield different fishing operations parameters for each fleet. Thus, we fitted one-fleet MAGD models to the pooled data from artisanal (baited trap and pots) and trawl boats.

MAGD models fit the catch data in numbers rather than weight. Thus, it is necessary to have a parallel time series of mean monthly weight in the catch alongside the effort and catch in weight data, to convert catch in weight to catch in numbers. We used the data from the three-year sampling program used to test for different catch rates, to sample mean octopus weight in the catch from May 2020 to May 2022.

A total of 41,479 octopus, evenly distributed over the months, was collected for this purpose. To apply these data to create the parallel time series of mean monthly weight in the catch over the 15 years of effort and catch data, we used the method described in Roa-Ureta [36]. We fitted an accessory model of mean weight versus month ignoring the year of the sample data (Fig. 2 of Suppl. Mat. 1). For this we used a cubic spline in *loess* function of the R statistical programming language [31]. Subsequently we used the mean and the standard deviation of the spline model at each month to produce a random realization of mean monthly weight from January 2006 to December 2020. For this purpose, we used the Runuran R package [24], resampling at every month from truncated normal distributions. These were defined within the bounds of six standard deviations above and below the mean at each month. In this manner, we built a time series of mean monthly weight that mostly followed the monthly trend but that retained some sampling variation. This time series is then used to convert from total catch in weight to total catch in numbers at every month of the effort and catch time series.

MAGD models are premised on the concept that the catch in numbers at every time step (C_t) is the result of two causes: fishing effort (E) and stock abundance (N). They produce maximum likelihood estimates of initial abundance (N_0, December 2005), average natural mortality over the period covered by the data (M), one distinct pulse of recruitment at every year (R_j) that enters the vulnerable stock at a specific time step p_j, and three fishing operations parameters. These latter parameters include a generalized catchability coefficient k, called the scaling, and two power parameters that allow for nonlinear connection between catch and effort, the effort response α, and between catch and stock abundance, the abundance response β. These models are apt for testing the hypothesis of increased exploitation rates on octopus due to the use of live crab baits because these hypothesized higher exploitation rates would be reflected in changes in the three fishing operational parameters depending on whether a given year is in the set of years in which the ban is non-implemented or implemented.

Consequently, hypothesis testing through the MAGD assessment models was accomplished by fitting a null hypothesis model of no change in parameter values of the MAGD model,

$$C_t = kE_t^{\alpha}N_t^{\beta} = kE_t^{\alpha}\left(N0e^{-Mt} - e^{-M/2}\left(\Sigma C_i e^{-M(t-i-1)} + \Sigma R_j e^{-M(t-pj)}\right)^{\beta} e^{-M/2},\right.$$
$$t \in [1,180], i \in (t), j \in [2006,2020], C \geq 0, k > 0, E \geq 0, \alpha > 0, N > 0, \beta > 0, p \subset t$$

representing the view that live crab bait does not increase octopus exploitation rates, versus an alternative hypothesis where the MAGD model had different values of k, α and β depending on whether the ban on using live crab bait was effective,

$$C_t = k_1 E_t^{\alpha_1}\left(N_0 e^{-Mt} - e^{-M/2}\left(\sum C_i e^{-M(t-i-1)}\right) + \sum R_j e^{-M(t-p_j)}\right)^{\beta_1} e^{-M/2}, t \in [1,48](2006-2009)$$
$$C_t = k_2 E_t^{\alpha_2}\left(N_0 e^{-Mt} - e^{-M/2}\left(\sum C_i e^{-M(t-i-1)}\right) + \sum R_j e^{-M(t-p_j)}\right)^{\beta_2} e^{-M/2}, t \in [49,60](2010)$$
$$C_t = k_1 E_t^{\alpha_1}\left(N_0 e^{-Mt} - e^{-M/2}\left(\sum C_i e^{-M(t-i-1)}\right) + \sum R_j e^{-M(t-p_j)}\right)^{\beta_1} e^{-M/2}, t \in [61,72](2011)$$
$$C_t = k_2 E_t^{\alpha_2}\left(N_0 e^{-Mt} - e^{-M/2}\left(\sum C_i e^{-M(t-i-1)}\right) + \sum R_j e^{-M(t-p_j)}\right)^{\beta_2} e^{-M/2}, t \in [73,180](2012-2020)$$

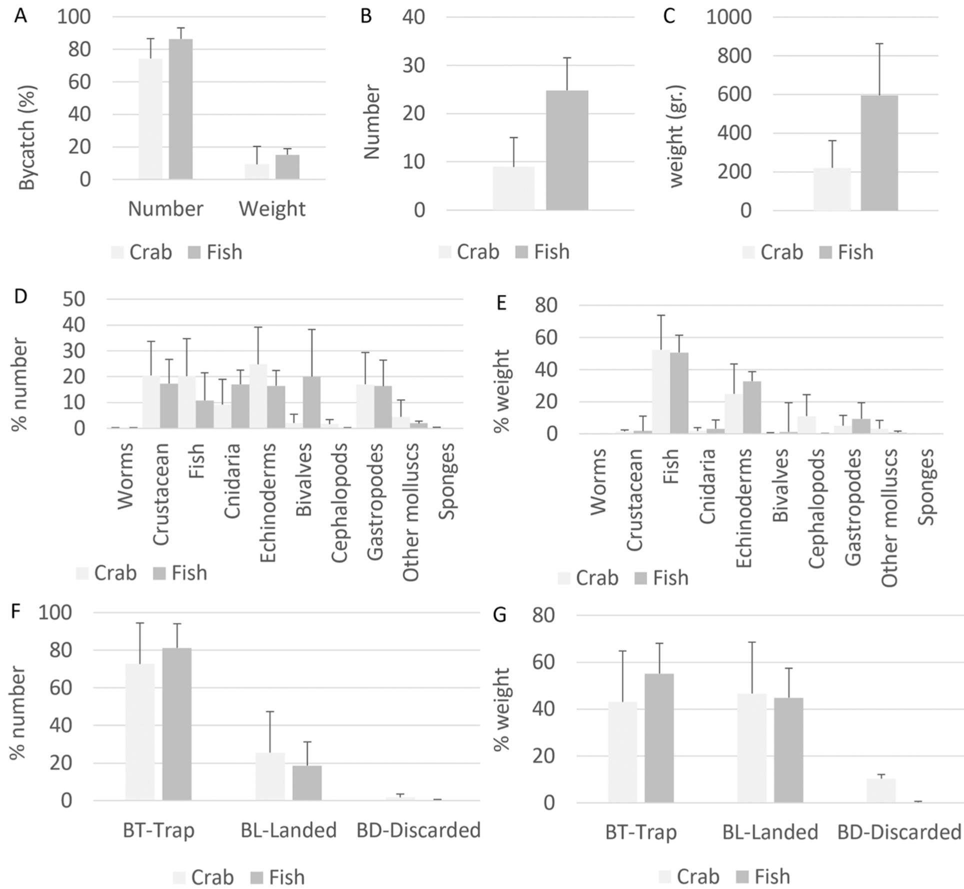

Fig. 2. Average values and standard deviation (bars) for A) percentage of bycatch; B) average bycatch number caught by 100/traps.day; C) average bycatch number caught by 100/traps.day; D) percentage in number by commercial group; E) percentage in weight by commercial group; F) percentage in number by bycatch category; G) percentage in weight by bycatch category. For commercial group information (Worms, Crustacean, Fish, Cnidaria, Echinoderms, Bivalves, Cephalopods, Gastropods, Other molluscs, Sponges) and bycatch categories: BT-Trap, BL-Landed, BD-Discarded.

and which represented the view that hat live crab bait increases octopus exploitation rates,

The null hypothesis model had 20 parameters to estimate: N_0, M, 15 annual recruitments R_j, k, α, β; while the model for the alternative hypothesis with time-varying parameters had 23 parameters to estimate: N_0, M, 15 annual recruitments R_j, k_1 (scaling with no ban), k_2 (scaling with banning), α_1 (effort response with no ban), α_2 (effort response with banning), β_1 (abundance response with no ban), β_2 (abundance response with no ban). Live crab bait was allowed from the 80s to 2009, then it was banned in 2010, the prohibition was retracted in 2011, and then imposed again from 2012 onward [21]. Further details of hypothesis testing through MAGD stock assessment models are provided in the Supplementary Material 1 (SM1).

3. Results

3.1. Bycatch

A total of 90 bycatch taxa were identified with 81 and 48 taxa for crabs and fish respectively. If we considered taxa that are caught more than once (frequency occurrence >1) then 59 and 48 taxa were caught for crabs and fish respectively (Table 1, Suppl. Mat. 2). A total of 41 taxa identified for crabs were not observed in traps with fish. This includes one polychaete, 8 crustacea, 9 fish, 6 cnidaria, 7 echinoderms, 4 bivalves, 1 Cephalopoda, 5 gastropods and 1 sponge. A total of 7 taxa caught with fish were not observed in crab traps. This includes 1 polychaete, 1 crustacean, 3 fish and 4 bivalves' taxon with fish as bait. The mean number of species (K-W: H= 0.13, P = 0.71; 23.38 ± 5.27 and 24 ± 4.93 for crab and bait) and ecological diversity (K-W: H= 0.005, P = 0.94; 2.45 ± 0.22 and 2.47 ± 0.3 for crab and bait) did not vary among bait types.

Bycatch account for 9.3 ± 11% and 15.09 ± 3.8% in number 74 ± 12% and 86 ± 7% of total weight catch, for crab and fish type baits, respectively. The mean number and weight bycatch varied between 9 and 25 ind./(100 traps, day) and 220–590 gr./(100 traps, day) for fish and crabs tpe baits, respectively (Table 1; Fig. 1). Both bycatch in number (K-W: H= 6.78, P = <0.01) and weigh (K-W: H= 6.20, P = <0.01) were statistical higher for fish traps (Table 1, Fig. 2). The bycatch percentage was also statistically higher in number (K-W: H= 6.25, P = <0.05) for fish bait but did not differ in weight between bait types (K-W: H= 3.70, P = 0.05) (Table 2, Suppl. Mat. 2). All fish species recorded come onboard alive.

In numbers, the commercial groups with higher bycatch percentage were crustaceans (20%), fish (20%), echinoderms (25%) and gastropods (17%), while in weight groups that contributed the most to bycatch were crustaceans (52%), echinoderms (25%), and cephalopods (11%). The bycatch in weight of crustaceans, fish, cnidarians, echinoderms, bivalves, cephalopods and gastropods were statistically higher in fish bait type traps (Table 1). In numbers cephalopods were statistical higher in crab bait type traps while the fish bait type traps caught more bivalves (Table 1, Fig. 2).

Most of the bycatch in number and weight belongs to the BT category (Table 1, Fig. 2). This means an average of 7 and 22 ind./(100 trap, day) remain inside the trap and are not sorted and discarded in octopus fishery for crab and fish bait types. In weight the percentage amount of bycatch landed was 47% and 45% for crab and fish bait types,

Table 1
Catch summary with bycatch by commercial groups and predefined bycatch categories: BT-Trap, BL-Landed, BD-Discarded. * Not compared statistically among bait types due to low Frequency of Occurrence (F.O); bold means statistical bycatch differences among bait and crab. Values are mean number and weight (± standard deviation) by 100/traps.day of taxa species caught with crabs and fish in octopus fishery. Statistical details in Table 2 Supplementary Material 2 (SM2).

	FO		Number		Weight (gr.)	
	Crab	Fish	Crab	Fish	Crab	Fish
Total catch	100	100	11.49 ± 6.446	27.588 ± 21.757	3370.5 ± 1388.9	4160.4 ± 2367.6
Total octopus	100	100	2.568 ± 1.055	2.824 ± 1.016	3150.8 ± 1449.2	3565.1 ± 2127.1
Bycatch	100	100	**8.922 ± 6.083**	**24.765 ± 21.036**	**219.7 ± 142**	**595.3 ± 267**
Worms*	8	29	0.005 ± 0.017	0.02 ± 0.044	0 ± 0.1	0.2 ± 0.4
Crustacea	100	100	1.824 ± 1.749	5.735 ± 8.561	2.6 ± 2.2	13.7 ± 16.8
Fish	100	100	1.582 ± 1.184	1.554 ± 0.923	122.1 ± 106.3	265.3 ± 32.8
Cnidaria	69	100	**0.673 ± 0.778**	**4.013 ± 3.029**	**3 ± 4.1**	**18.2 ± 13.7**
Echinoderms	100	100	2.232 ± 2.075	3.98 ± 3.293	**51.7 ± 54.3**	**219.4 ± 159.4**
Bivalves	62	100	**0.212 ± 0.42**	**4.682 ± 6.49**	**1.1 ± 1.9**	**7.9 ± 9.6**
Cephalopods	69	29	**0.104 ± 0.09**	**0.015 ± 0.028**	**19 ± 23.5**	**0.4 ± 0.7**
Gastropodes	100	100	1.614 ± 1.491	4.329 ± 6.156	**12.8 ± 18.9**	**64.3 ± 79.6**
Other molluscs	62	100	0.672 ± 1.324	0.437 ± 0.398	7.4 ± 14.5	5.9 ± 7.7
Sponges*	8	0	0.009 ± 0.031	0 ± 0	0.1 ± 0.3	0 ± 0
BT-Trap	100	100	**6.86 ± 5.88**	**21.52 ± 20.11**	84.07 ± 58.8	386.83 ± 321.32
BL-Landed	100	100	1.94 ± 1.71	3.21 ± 1.84	119.29 ± 119.83	207.82 ± 81.29
BD-Discarded	77	57	**0.12 ± 0.09**	**0.04 ± 0.05**	16.33 ± 19.72	0.62 ± 0.74
			Number (%)		Weight (%)	
Bycatch (%)			Crab	Fish	Crab	Fish
Bycatch (%)			**74.33 ± 12.19**	**86.4 ± 6.79**	**9.3 ± 11.07**	**15.09 ± 3.84**
Worms*			0.06 ± 0.22	0.07 ± 0.14	0.01 ± 0.05	0.03 ± 0.05
Crustacea			20.49 ± 13.16	17.35 ± 9.29	1.44 ± 0.97	1.83 ± 1.67
Fish			20.2 ± 14.46	10.75 ± 10.68	52.29 ± 21.47	50.74 ± 19.21
Cnidaria			**9.2 ± 9.81**	**17.02 ± 5.49**	1.82 ± 1.97	3.09 ± 1.77
Echinoderms			24.81 ± 14.39	16.41 ± 5.91	24.86 ± 18.62	32.76 ± 15.21
Bivalves			**2.04 ± 3.34**	**20 ± 18.3**	0.39 ± 0.46	1.21 ± 1.23
Cephalopods			**1.64 ± 1.67**	**0.09 ± 0.18**	11.03 ± 13.39	0.08 ± 0.16
Gastropodes			17.04 ± 12.39	16.35 ± 10.02	5 ± 6.53	9.42 ± 7.96
Other molluscs			4.42 ± 6.55	1.95 ± 0.9	3.09 ± 5.23	0.85 ± 0.78
Sponges*			0.07 ± 0.26	0 ± 0	0.03 ± 0.09	0 ± 0
BT-Trap			72.73 ± 21.72	81.12 ± 12.98	43.07 ± 23.97	55.08 ± 31.63
BL-Landed			25.48 ± 21.9	18.56 ± 12.61	46.61 ± 25.1	44.76 ± 31.45
BD-Discarded			**1.79 ± 1.84**	**0.32 ± 0.4**	10.32 ± 13.17	0.16 ± 0.19

Table 2
Output results with the generalized linear models tested for assess the role of fishing days (FD) in catch in number of octopus, accordingly, bait type (H1: Hypothesis 1) and the role of bait type on standardized catch rates (H2: Hypothesis 2).

H1:Hypothesis 1	Resid. Df	Resid. Dev	Df	Pr (>Chi)	AICs
Model 1: CPUE.oct.trap ~ FD	1043	318.07			-3594.5
Model 2: CPUE.oct.trap ~ FD + bait	1041	317.22	2	0.2379	-3593.4
Model 3: CPUE.oct.trap ~ FD * bait	1039	307.48	2	6.762e-08 * **	-3623.6
Model 4: CPUE.oct.trap ~ FD * bait + SizeTrap	**1037**	**295.85**	**2**	**2.828e-09 * ****	**-3661.8**
Model 5: CPUE.oct.trap ~ FD + SizeTrap * bait	1036	300.84	7	2.816e-10 * **	-3641.5
Model 6: CPUE.oct.trap ~ FD * bait + SizeTrap + depth	1036	295.84	7	1.491e-13 * **	-3659.9
H2:Hypothesis 2					
Model 1: CPUEday.oct.trap ~ bait	1042	668.95			-5548.3
Model 2: CPUEday.oct.trap ~ bait + SizeTrap	1040	663.23	2	0.01109 *	-5554.2
Model 3: CPUEday.oct.trap ~ bait + SizeTrap + depth	1039	653.12	1	0.00006569 * **	-5569.9
Model 4: CPUEday.oct.trap ~ bait + SizeTrap + Year	**1038**	**586.25**	**1**	**< 2.2e-16 * ****	**-5691.5**

respectively.

The MDS plot reveal some crab and bait samples are mixed in multidimensional space (Fig. 3). However, PERMANOVA reported highly statistical differences between bait types ($PERMANOVA_{bait\ type}$: df = 1; F=2.294; P = 0.009) with the fishing days covariable having significant effects too ($PERMANOVA_{fishing\ days}$: F =2.0733; P = 0.012). The SIMPER analyses reveals that 10 taxa explain 60% of the dissimilarities found between bait types, which included invertebrates and fish: *Calliactis parasitica* (12.54%), *Varicorbula gibba* (8.38%), *Pagurus* sp. (7.92%), *Paracentrotus lividus* (6.6%), *Hexaplex trunculus* (6%), Calyptraeidae (5.21%), *Astropecten aranciacus* (4.15%), *Sphaerechinus granularis* (4.08%), *Diplodus sargus* (3.72%), and *Paguristes eremita* (3.09%).

The amount of bycatch of fish remaining in traps (BT category) for the Algarve fleet was estimated as 124312 ± 116555/year and 134687 ± 234593/year specimens for crab and fish bait types. Some of the fish bycatch comprises specimens with size below the minimum landing size (*S. solea*; *S. cantharus*; *D. bellotti*) while for commercial gastropods (*Bolinus brandaris* and *Hexaplex trunculus*) most of the individuals caught were above minimum landing size (Fig. 4).

3.2. Octopus catch rates

When the response variable was the catch of octopus in numbers per trap, with effort in soaking days as predictor variable, the best working model included the soaking days, bait type, the size of the trap, and the interaction between soaking days and bait type (Table 2). Examination of the coefficients of this model show that significantly higher catch rates are obtained with the fish bait type versus live crab type (P-value < 0.01) while in the interaction between days of soaking and bait type the opposite happened: lower catch rates in the interaction between soaking days and fish bait type versus the interaction of soaking days and live crab bait type (P-value < 0.01). In the selected model (Hypothesis1: model 4 Table 2) there was no statistical difference between live crab and mixed (fish and live crab) bait types. The main conclusion thus is that the marginal effect of using live crab bait type is actually the

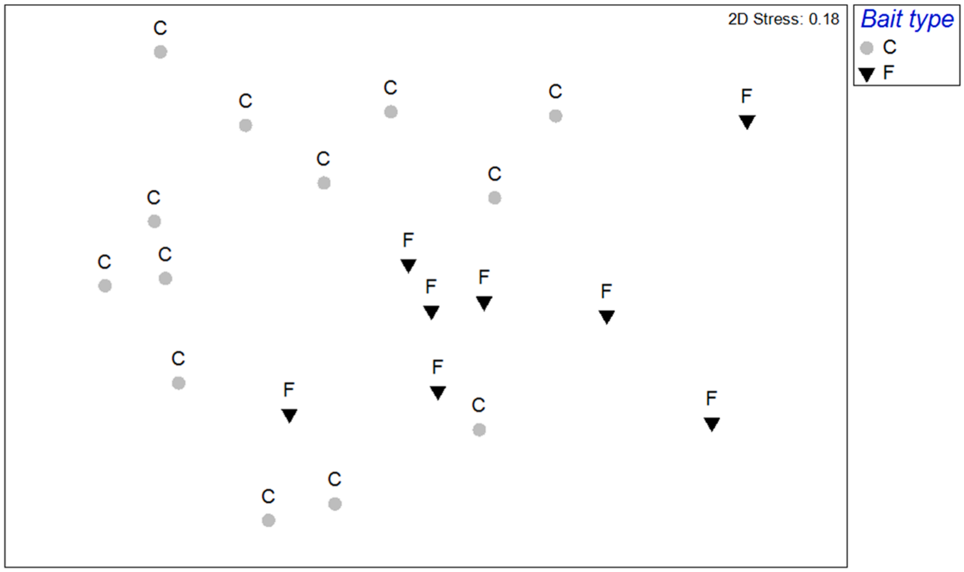

Fig. 3. Multidimensional ordination showing bycatch sample composition among bait types in Algarve octopus fisheries. C -crab and F- Fish.

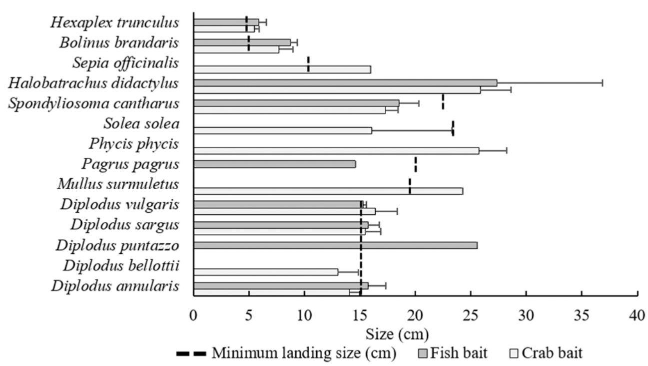

Fig. 4. Mean size of the bycatch main fish specimens regardless bait type, together with minimum landing size if available.

decrease of octopus catch rates in the Algarve octopus fishery. The secondary conclusion is that as soaking days increase the positive effect of fish bait type on octopus catch rates decreases, i.e. the bait type effects on octopus catch diminishes as soaking time increases. Finally, the marginal effect of soaking days is significant (P-value < 0.01) and positive and the effect of trap size is significantly higher for octopus catch rates (P-value < 0.01) in large traps as compared with both, medium and small sized traps. In fact, the effect of large traps is ten times higher than the effect of the fish bait type.

When the response variable was the catch of octopus in numbers per trap and per day of soaking, with effort in days of soaking as a standardising variable for the response variable, the best working model included bait type, the size of the trap, and the year (Table 2). Examination of the coefficients of this model shows that fish bait type had significantly higher octopus catch rates versus live crab bait (P-value $<$ 0.01) while the mixed bait type and the size of the trap do not have significant effects. The model coefficient value (Hypothesis2: model 4 Table 2) for bait type reveal that fish catch 3.1% more octopus per trap by soaking day, in number, compared to crabs. The year effects, although irrelevant in this context, also were significant with both, 2021 and 2022, experiencing lower catch rates vis-a-vis 2020.

3.3. Algarve octopus stock status

Out of 40 MAGD tested, 33 achieved successful numerical convergence (Table 1, Suppl. Mat. 1). AIC evaluations inside the subset of variants having the same likelihood function reveal that for all likelihood models, one variant with constant parameters always had the best AIC and consistently, one variant with time-varying parameters always had the worst AIC. This result supports MAGD models without change of fishing operation parameters (k, α, and β) over the entire time series (2006–2020) vis-a-vis models with time-varying parameters and imply that the fishing mechanics and dynamics does not change due to the use or not of live crab bait in the Algarve octopus fishery. The AIC however is only one criteria to judge the worth of variants of MAGD models due to relevant issues with the quality of numerical convergence in large dimensional optimization problems.

The numerical criteria that all variants yield numerical gradients less than 1 in absolute value and that standard errors are successfully calculated and produce lowest coefficients of variation (CVs) yield four variants in the short list, three of them with time-varying parameters. Examination of the histogram of correlation coefficients of these four variants in the short list shows that only two variants can be considered as best from statistical and numerical points of view (Fig. 3, Suppl. Mat. 1). One of these variants had constant parameters and was fitted with the adjusted profile normal likelihood and the conjugated gradient method (CG), and the other variant had time-varying parameters fitted with normal likelihood and CG method. They cannot be directly compared using the AIC since they were fitted with different likelihood functions.

Further examination of CVs for all parameters estimates indicated that the constant parameters variant fitted with adjusted profile normal likelihood and the CG method, had much better statistical precision and nearly full dotation of CV (only missing the CV for k and α) while the time-varying parameters variant fitted with normal likelihood and CG method had fifteen missing CV and three of the present ones were higher than 100%. This result, together with the AIC results (Table 1, Suppl. Mat. 1) quoted at the start of this subsection and the slightly better correlations (Fig. 3, Suppl. Mat. 1) clearly pointed to select the variant with constant parameters fitted with adjusted profile normal likelihood and the CG method (variant number 15 in Table 1, Suppl. Mat. 1) as the best MAGD model for the total monthly catch, effort and mean weight data. The fit of this model to the data is shown in Fig. 4, Suppl. Mat. 1.

M (1/month), N_0 (thousands), 15 recruitment inputs (thousands), k (1/Days), α and β parameter estimates from the best variant are shown in Table 2, Suppl. Mat. 1. Natural mortality was estimated with excellent statistical precision. Its annualised value is 0.7171, high but not as high

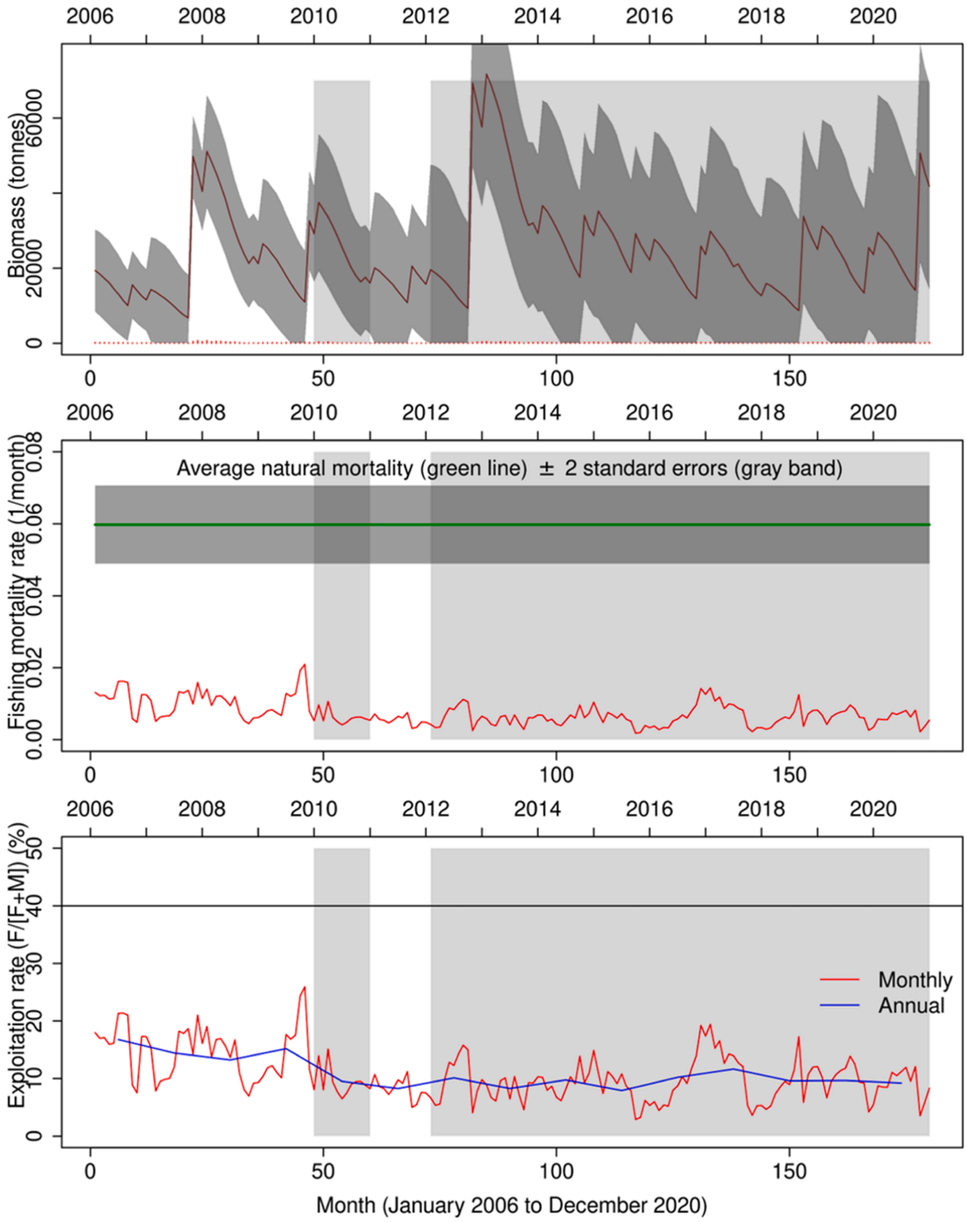

Fig. 5. Stock and exploitation status in the octopus fishery in the Algarve as estimated from multi-annual generalised depletion models. Annual periods of banned live crab bait are shown as shaded year blocks. Top panel: biomass (brown line) with 2 standard error band (grey). Mid panel: fishing mortality (red line) and natural mortality (green straight line) with 2 standard error band (grey). Bottom panel: exploitation rates (red and blue lines) and line of 40% exploitation rate.

as expected for a life history of 1–2 years. Recruitments are in the order of a few million to a few dozen million octopus per year and they are generally estimated with good statistical precision. Effort response α is close to proportional while abundance response is clearly hyperstable.

Time series of biomass, fishing mortality and exploitation rates derived from model parameters are show in Fig. 5. The years of banned use of live crab bait are marked in shaded time blocks. There is no evidence of any increased fishing pressure or increased exploitation rates during the periods of no banning. If anything, exploitation rates have been decreasing very slowly from the start of the time series, but that apparent decline does not appear connected to the periods of presence or absence of the ban. In particular, year 2011, when the ban was not imposed, presents similar exploitation rates as in the subsequent period when the ban was enforced, and lower exploitation rates than in 2010, year in which the ban was enforced.

3.4. Bait consumption

The monthly bait consumption differed statistically between bait types (Fig. 6) for weight (Man-Whitney: U<0.01; $P < 0.01$) and economic value (Man-Whitney: $U = 9.0$; $P < 0.01$). The quantity of fish required for bait a boat for octopus fishery per month is ~1/3 more in weight than if crabs is used and twice the economic value than if crab is used.

4. Discussion

Octopus artisanal fisheries are regionally important worldwide at socioeconomic level. In recently years octopus fishery certification actions [7] have led to deepen more about octopus stock status and fishing efficiency methods, namely in line with an ecosystem based ecological approach to fisheries. Effective conservation of harvested resources requires an understanding on how the resource responds to exploitation

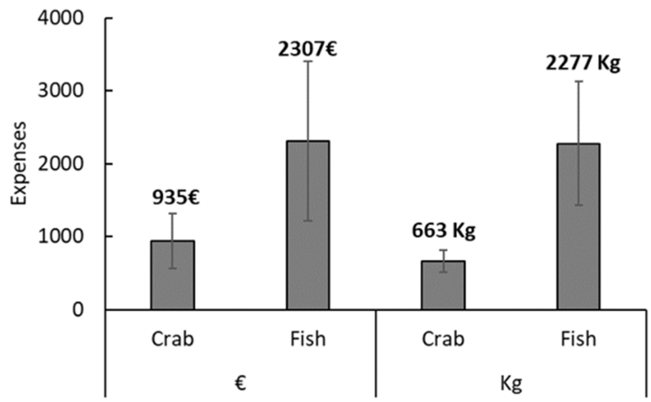

Fig. 6. Expected monthly mean (and standard deviation) weight bait consumption and expenses (€) of an Algarve boat that fish 12 days/month with 1000 traps/day, by bait type (crab and fish). Prices for 2020–2021.

from changing/new fishing practises, such is the case of live crab bait in the Algarve. Several questions that are of major concern to the octopus fishing sector have been studied to understand the effect of fish and crab bait on bycatch, catch rates and sustainable harvesting.

Studies on octopus fishery bycatch are scarce though octopus as bycatch has been studied in other ground/trap fisheries [10,14]. Likewise, the bycatch composition and quantities from the Portuguese trap octopus fishery is virtually unknown [42]. In number and weight bycatch reported by Saldanha [42] represent 49% and 7.8% in average while in the present study bycatch in numbers was far higher regardless of bait type (74% and 86% for crab and fish). The same fish species occurring with low frequency were identified in both studied (e.g. *C. conger*; *D. annullaris*; *D. vulgaris*; *S. cantharus*; *Symphodus bailloni*).

The trap gears are benthic static gears. Most species caught are either sessile or mobile sandy benthic macroinvertebrates. In number the commercial groups with higher bycatch percentage were Crustacean (20%), Fish (20%), Echinoderms (25%), Gastropods (17%). However, fish as bait catch larger numbers of fish species in higher abundance. Fish bait also catches more other specific commercial groups such as Cnidaria, bivalves and gastropods in weight. The number of bycatch species do not match among bait types and multivariate analyses reveal different bycatch composition among bait types, mainly due to different invertebrate species. Nevertheless, most of the bycatch is comprised by invertebrate's species without commercial value that can be discarded and for which survival rates are expected to be high. In fact, some invertebrate species caught in sandy bottom dredge fisheries [3,22] such as *Pinnotheres pisum*, *Polybius* spp, Asteroidea, *Atelecyclus undecimdentatus*, *Liocarcinus depurator*, *Pagurus* spp. have low discard mortality rates. Gastropods, are also expected to have high survivor discard rate due their hard shells [49]. In a similar trap fishery for squids, Vasconcelos et al. [50] recorded that some vertebrate fish species found in the present work have low damage and high survival rates (e.g. *D. annularis*, *D. sargus*, *S. cantharus*, *H. didactylus*, *S. cantharus*). For the octopus fishery in Algarve, between 15 and 30 m depth, the survival of *D. bellottii*, *H. didactylus* and *S. notata* is also expected to be 100% if rejected to the sea [42]. The low frequency of occurrence and abundance also shows that the impact over cnidaria (*Eunicella verrucosa*) of the octopus fishery is less than recorded for instance in gill nets in the Algarve [12]. Almeida et al [2] showed using life cycle inventory data, that it was possible to recognize the selectivity capacity of fishing gears since on average only 0.04 kg of other species are caught per 1 kg of octopus. The present results show that the bycatch impact of the octopus artisanal fisheries is overall low, regardless of bait type, and more so when using live crab bait. These results indicate that the Algarve octopus trap fishery has a minor environmental impact. Also noteworthy is the fact that the observed list of bycatch species do not include endangered, threatened or protected species as listed by the IUCN. Nevertheless, further technical improvements of the trap gear could focus on the handling of BT-bycatch species, some of which are commercially important for other fishing sectors and gears. For instance, crab estuarine traps are similar to marine octopus traps except for the existence of a lateral "door/opening" that allow easy removal of all individuals caught without fisher intervention. This would allow to remove easily and efficiently all bycatch items while fishers re-bait the traps to soak.

The fishery with live crab bait was banned after some fishers postulated that octopus traps with live crab bait can stay more days in the water thus increasing fishing effort and octopus catch rates. Fishers in the opposite camp argued that fish bait was more efficient and would catch more octopus with less soaking time. Our results, with scientifically directed fishing under standardized fishing operational conditions, clearly show that fishers arguing against the ban were correct: the use of live crab bait does not increase octopus catch rates. On the contrary, the use of fish bait increases octopus catch rates (catch rates with fish were 3.1% higher than with crabs) although this effect itself decreases with increasing soaking time. That is, results, regarding soaking days effect on octopus catches with crabs, showed that the number of octopus caught with crabs is maintained over an extended soak time, comparatively to fish. These differences in octopus catch rates among bait types arise from different attractive capacity of each bait during soaking time. Fish as bait can only be used for short times because it is eaten by macrofauna benthic amphipods [21] while live crab and mixed bait types can remain fishing for longer periods.

Trap size has the highest impact on octopus catch rates, almost ten times stronger than the effect of using fish as bait. Results denoted gear saturability as a trap cannot retained many octopus potentially due to space competition and/or octopus behaviour and ecological/biological species-specific traits. Therefore, to regulate octopus catch rates down in order to improve sustainability, management should alternatively focus on trap size instead of on bait type.

The European Common Fisheries Policy (CFP) established that cephalopod fisheries should have a local/national management. This requires data collection systems and appropriate stock assessment models. Here we have shown that multi-annual generalized depletion models are suitable for the stock assessment task, in line with recommendations by experts [4]. These models are flexible enough to allow for time-invariant versions that test hypotheses of changes in the dynamics of fishing. In this work we developed a custom-made version of a method and software [35,37] that uses elementary fishing data to fit a model that included changes in three fishing operational parameters, namely a generalized catchbility (k), the effort response (α) and the abundance response (β), versus a model with constant fishing operational parameters. If bait type had the effect alleged by some fishers of the octopus fishery in the Algarve, model versions with time-varying fishing operational parameters would have been better at explaining the data than model variants with constant fishing operational parameters. Yet model variants with constant parameters was superior in AIC as well, numerical and statistical quality. The selected model variant showed no effect of banning live crab bait on exploitation rates and general stock status.

In a recent project (ParticiPesca) that aims at introducing co-management in Algarve artisanal fisheries, initiatives were implemented to develop monitoring, assessment and management concept, because that has been defined as the roadmap to MSC-Certification [41]. However, one of the shortcomings that led to failure in the certification process was the lack of knowledge of stock status [7]. Other issues were specific to the octopus fishery were the large number gears at sea, non-compliance with the minimum landing size regulation and unreported/undeclared landings sold at auction sites, as similarly concluded in previous reports [29,46,47]. Despite such potential constraints to resource sustainability stock assessment results in this study show that natural mortality has been higher than fishing mortality and that instantaneous exploitation rates ($M/[M+F]$) have been low, less than 20%, over the whole time series encompassing 2006–2020. This indicates enforced regulations for octopus (Portaria n.º 27/2001;

Regulation No. 1127-B/2019) achieved their goals, such as the minimum landing weight (750gr), number of traps/pots per vessel and fishery closured at weekends in Algarve. Furthermore, exploitation rates have been decreasing slowly reflecting the mid-term decrease of fishing effort (in boat and fishing trips per year) described by Leitão et al. [21]. The model also shows high variability in octopus biomass dynamics, thus revealing a typical inter-annual dynamic commonly associated to octopus and other cephalopods fisheries [1,4,26,33,43,45]. Results of generalized depletion models can be used to fit population dynamics models that are capable to evaluating stock productivity and biological reference points connected to it [33,34]. Achievement of that kind would need to be undertaken in future research.

Some further aspects related to the crabs use as bait are worth considering. Over the last few decades fish bait prices have increased substantially and in line with fuel costs, making fishing operations costs to increase. Some vessels prepare fish bait in advance by salting the fish during some hours to allow the bait to fish longer. Traps are baited at the vessel, during the fishing trip. The price of crabs is lower that of fish, and crabs can be used multiple times at different soaks. In general, onboard activities are easier and cleaner with live crabs. Crabs may substitute fish bait which is mostly based on sardine (*Sardina pilchardus*), horse mackerel (*Trachurus* spp.) and mackerel (*Scomber* spp.), relieving fishing pressure on those stocks. Some mackerel stocks have been listed for precautionary quotas in ICES region IX and sardine stock is under a recovery plan (https://www.dgrm.mm.gov.pt/peixes).

Thus, live crab bait in the Algarve octopus fishery allow making better use of marine biodiversity (catch diversification), reduce fishing effort on forage fish species and promote other small-scale estuarine fishing communities, those that conduct the crab fishery.

Since the fish bait is consumed by other organisms or deteriorates within 24 h, traps require daily maintenance to replace it. Thus, live crab bait decreases the number of times a boat need to go fishing because crabs can be re-used several times as bait. In terms of bait used by Algarve octopus vessels with traps, it is necessary on average 0.7 kg of bait to catch 1.1 kg of octopus [2]. The emissions of CO_2 to the atmosphere are related to diesel combustion in octopus fishery [2]. The use of live crab bait decreases fuel consumption and thus decrease carbon emissions, while increasing revenue to fishers. Therefore, crab as bait represent a practical example of ecosystem-based approach and smart climate fisheries adaptation to climate change.

Compared to other octopus fisheries that use fish as bait, the use of crabs as bait in artisanal trap octopus fisheries is less common with the exception, to the authors best knowledge, in Korea, where traps are commonly baited with crabs [20], and Algarve. Regardless of the bait type, the approach/results of these study can be used elsewhere to support management decisions and promote bait diversification in octopus fisheries.

5. Conclusions

This study provides important information on ecological and stock assessment status that can be used to MSC Algarve octopus fishery certification and support co-management initiatives by enriching information on octopus fisheries. We did not find evidence that bycatch, octopus catch rates, and octopus exploitation rates were higher when fishers use live crab bait vis-a-vis the use of fish bait in the Algarve octopus fishery. With regards to bycatch we observed a higher total number and total weight of bycatch when using fish bait, therefore higher environmental impact. In connection with octopus catch rates we observed the opposite of what has been claimed and that led to a ban in the use of live crab bait: higher octopus catch rates when using fish bait with a negative interaction of fish bait type with days of soaking. Furthermore, stock status from stock assessment shows that the periods of live crab bait use do not impose stronger pressure or increase exploitation rates of octopus. Therefore, we find that the policy of banning traps with live crab bait in the Algarve octopus fishery was not supported on scientific grounds.

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 paper.

Data availability

The data that has been used is confidential.

Acknowledgments

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.marpol.2023.105878.

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