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Bioeconomic analysis of the Mauritanian cephalopods fishery*

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Abstract

Cephalopods represent a very significant fishing resource in Mauritania. In particular, *Octopus vulgaris* (Cuvier 1797) whose value increases according to weight is the most valuable species. The resource shows significant inter annual variations in abundance related to the varying environmental conditions off Mauritania and the previously conducted species stock assessments indicate a state of overexploitation and growth over fishing. A bioeconomic single species population dynamics model is developed to estimate the combined impact of fishing closure duration and timing and minimum size at capture in various hypothetical exploitation scenarios to the yearly yield, value of yield and spawning stock biomass. Applying monthly cohort analysis in a Bayesian framework using MCMC sampling enabled us to implement the model with the variability observed in seasonal and inter annual environmental conditions and the uncertainty related to different aspects of the species biology. The currently applied management measure, a two-month closing season in September-October with a minimum size at capture of 500 g, is used as the reference point. The results indicate that the current timing of the closed season is optimal and no considerable gains in value of yield are obtained using other timings. However, increasing the minimum size at capture seems to be profitable. For example, minimum size of 1000 g with a two-month closing season in September-October yields a mean relative gain of 16 % in yearly value of yield. The findings of this study will contribute to the sustainable use of cephalopod fishery resources in Mauritania by providing indicators for the economically optimal harvest of the species. The methodology applied in this study aims to be applicable also to other cephalopods fisheries. This paper was prepared as part of EU 6th framework programme project "Probabilistic assessment, management and advice model for fishery management in the case of poor data availability" (POORFISH), contract no. 22745.

Keywords: *Octopus vulgaris*, cephalopods, Bayes model, fisheries management, bioeconomic

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1. Introduction

The Mauritanian coast line is situated along the northwest coast of Africa between Cape Blanc (20˚N) and the Senegalese border (16˚N). These waters are of great productivity, attributed to the broad continental shelf and the large upwelling (COPACE 2002, Brahim 2004, GT 2006). This upwelling phenomenon is seasonal in the south and permanent in the north (COPACE 2002, Brahim 2004, GT 2006) and its intensity has shown a general decreasing tendency for the past two decades (GT 2006). The hydrological features of the area, and especially upwelling, show significant intra and inter annual variations modifying the potentials of exploitable marine biomasses (GT 2006) making them challenging at manage.

Cephalopods represent a very significant fishing resource in Mauritania especially in terms of commercial value (COPACE 2002, GT 2006). Fishing for cephalopods in the area was initiated by foreign trawlers in the 1960s and national Mauritanian fleets (industrial and artisanal) were introduced to the fishery starting from the 1980s (Inejih 2000, GT 2006). Most of the cephalopods landings (85 %) are conducted by industrial vessels (GT 2006), by those of the national fleet and the EU fleet that has operated in Mauritanian waters since 1996 in the framework of the EU-Mauritanian fisheries agreement (COPACE 2002, GT 2006).

In particular, the most important cephalopod species caught in Mauritania waters is *Octopus vulgaris* (Cuvier 1797) (Inejih 2000, COPACE 2002, Corten *et al*. 2003, GT 2006). It is the most valuable species (COPACE 2002, GT 2006) and thus strongly targeted and showing reduction in abundance (Inejih 2000, COPACE 2002, Corten *et al*. 2003, GT 2006). *O. vulgaris* can be regarded as practically the only target species of the national Mauritanian fleets, both of the industrial fleet as well of the artisanal fleet (Inejih 2000). The previously conducted species stock assessments indicate that the resource is growth overfished (Inejih 2000) and overexploited (Inejih 2000, COPACE 2002, Corten *et al*. 2003, GT 2006).

Conversely to most exploited fish species, the life span of *O. vulgaris* is relatively short (around 1 year) and characterized by post-spawning mortality (Faure 2000, Domain *et al*. 2000, Inejih 2000). This means that in practice there is no overlap between generations and thus, variations in annual recruitment cause large stock fluctuations. Inter annual variations in recruitment success of *O. vulgaris* is concluded to derive from physical and biological environmental factors influencing particularly larval and juvenile survival (Rodhouse *et al*. 1992, Demarcq and Faure 2000, Faure 2000, Inejih 2002, Caverivière and Demarcq 2002, Corten *et al*. 2003). It has been shown for the species off Mauritania that demographic explosions occur especially when upwelling is reinforced (Inejih 2002, COPACE 2002, GT 2006) and thus the understanding of the causes behind the recruitment success can be regarded as baseline for proper management of the species. Currently the *O. vulgaris* fishery in Mauritania is regulated with licences, minimum size at capture of 500 g and closed season in September-October (GT 2006).

This is the first attempt to assess the impact of different management measures in *O. vulgaris* fishery by modelling the species intra annual population dynamics on the basis of the species biology and the fluctuating environmental conditions. Parameters from stock assessments, together with environmental and economic information, are employed in a hierarchical Bayes model using MCMC sampling. Applying monthly cohort analysis in a Bayesian framework enables the consideration of the variability and uncertainty related to different aspects of the species biology and to environmental conditions the species encounters off Mauritania. The timing and duration of the closed season with minimum size at capture are assessed with respect to surplus growth of the stock and profit maximization using yield-per-recruit analysis. Owing to the higher price of larger individuals the value of yield can be reduced if *O. vulgaris* are to be caught to early in their life. The effects of different hypothetical management actions on the yearly relative yield, value of yield and spawning stock biomass are discussed.

The objective of this work is to contribute to the sustainable use of cephalopods fishery resources in Mauritania by providing indicators for the economically optimal harvest of the species and as well to provide the methodological basis of a probabilistic population dynamics model that can be used in simulations of potential impacts of various exploitation scenarios and modified to a more comprehensive spatial and temporal resolution in the future. The methodology applied in this study aims to be applicable also to other cephalopods fisheries.

2. Materials and methods

2.1 Description of the study area

The Islamic Republic of Mauritania is situated in the North West part of Africa between Western Sahara and Senegal. The country has a coastline of 750 km situated between the parallels 16°04' N in the south and 20°36' N in the north (Brahim 2004) and territorial waters of 230 000 km^2 on the Atlantic (Anon. 2005) (Figure 1). The continental shelf up to the depth of 200 m covers an area of 39 000 km^2 and is divided by Cape Timris into two distinct parts; the northern zone and the southern zone (Anon. 2005). In the northern zone (Banc D'Arguin) between Cape Blanc and Cape Timris the continental shelf reaches its maximum width of 60 to 90 km and is characterized by shallow waters of about 50 m in depth (Brahim 2004). Descending from Cape Timris towards the Senegalese frontier, the continental shelf is narrower, 15 to 30 km in width (Brahim 2004).

In Mauritania, there are two hydrological seasons that are separated by seasons of transitions: the cold season extends from November until May and the warm season takes place from June to October (Brahim 2004). Mauritanian waters, situated in a transition zone of currents, are particularly productive and characterized by upwelling waters (COPACE 2002, Anon. 2005). This upwelling phenomenon, caused by currents and wind conditions, shows inter annual and seasonal variations in its intensity (COPACE 2002, Brahim 2004, Anon. 2005). The upwelling is permanent in the northern zone of Banc d'Arguin where the special characters of the area increase its force, and seasonal with smaller intensity in the south (COPACE 2002). Due to the phenomenon's importance on the productivity of Mauritanian waters, this variability has important implications to the biomasses of exploitable marine species in the area (Anon. 2005).

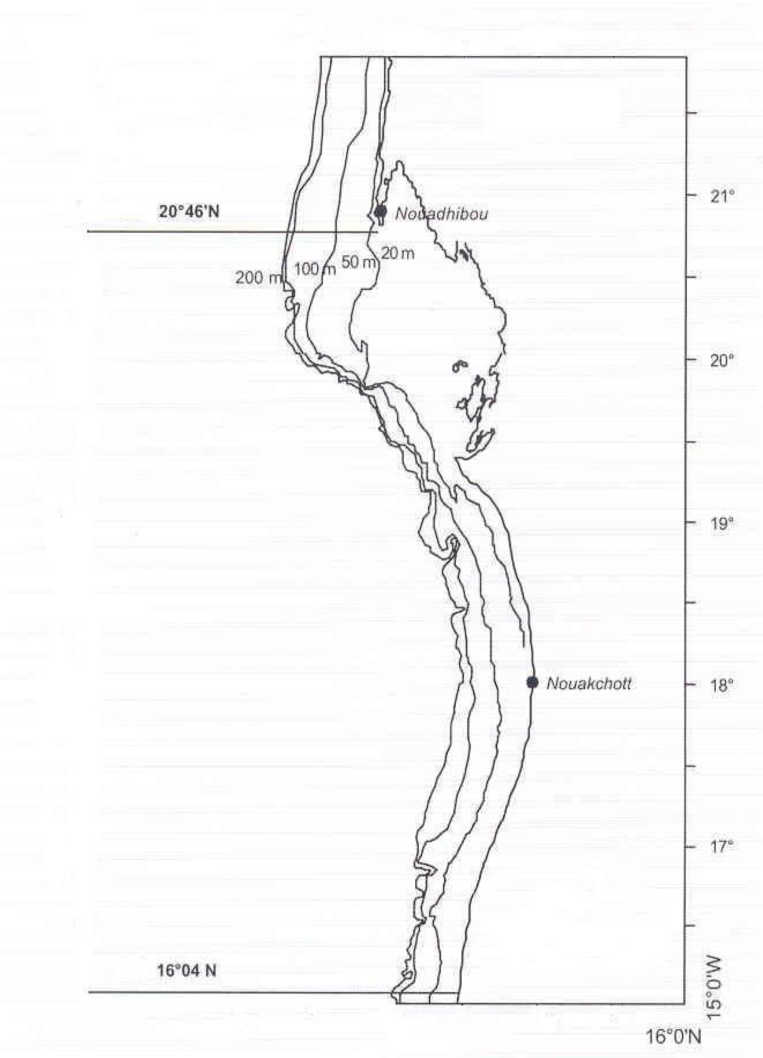


Figure 1. Mauritanian coast line and the major offshore depth curves.

2.2 Data

The following data are used in the model:

1. The mean monthly upwelling indices from 1990 to 2005. Source: Institut Mauritanien de Recherche Océanographique et des Pêches (IMROP).

2. The monthly prices realized from 2000 to 2005 of exported *O. vulgaris* frozen on board. Source: La Société Mauritanienne de Commercialisation des produits de la Pêche (SMCP).

2.3 Model description

The Bayesian hierarchical model constructed here aims to describe the biological characteristics of *O. vulgaris* as well as the impact of the varying environmental conditions the species encounters off the Mauritanian coast. Applying monthly cohort analysis in a Bayesian framework using MCMC sampling allows the implementation of observed variations and uncertainty related to the parameters into the model. The model is age structured describing the intra annual population dynamics of the species, in respect to the seasonal variations as well as differences between sexes.

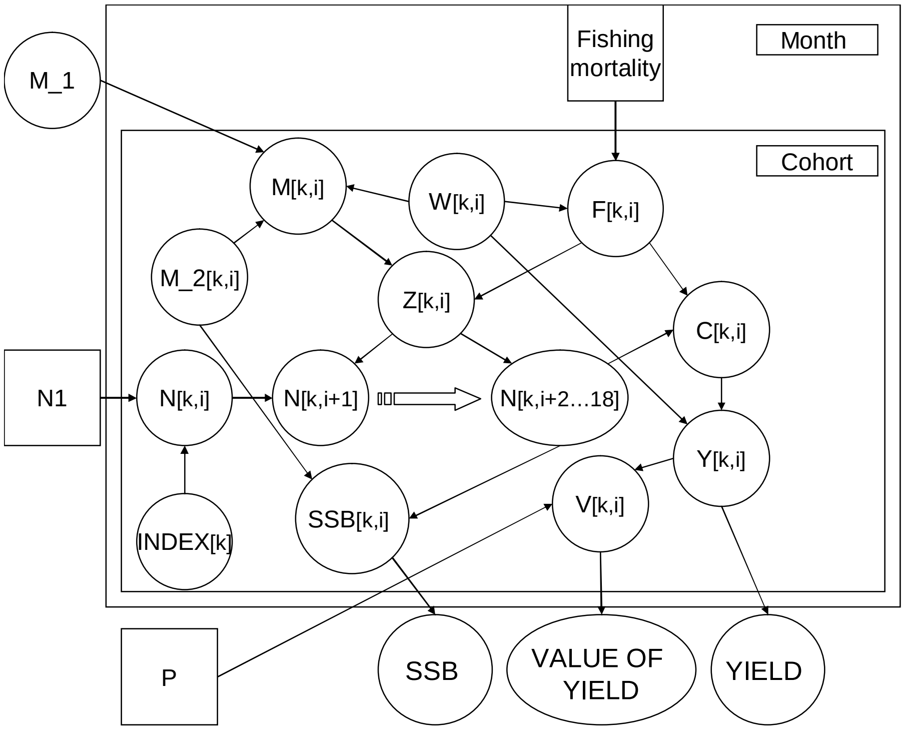
The initial size of each cohort is determined by the level of upwelling in the month of hatching and the monthly escapement results of those individuals that are not affected by the total mortality rate. The model is constructed using unconditional prior distributions for those variables whose estimates contain uncertainty or are assumed uncertain. These prior distributions are generated with the objective to combine the best information available by basing them on estimates obtained from literature and expert knowledge.

The model is used to assess the combined effects of closing season duration and timing with minimum size at capture to yearly yield, the value of yield and the spawning stock biomass using yield-per-recruit analysis. The optimum fishing mortality rate is assessed within each hypothetical exploitation scenario considered in this study. The model gives probabilistic estimates of the relative gains or losses of various exploitation scenarios in reference to the currently applied management measure of two months closing season in September-October with a minimum size at capture of 500 g.

The parameters of the population dynamics model are chosen in respect to the current knowledge of the species biology. Other model parameters are chosen so that the effects of different management measures in terms of fishing mortality to yearly yield, value of yield and spawning stock biomass could be assessed within the model. There are a total of 18 parameters in the model of which price, the initial number of individuals and fishing mortality are assumed to be known exactly (Figure 2). Other parameters are assumed uncertain.

To simplify the model structure the following assumptions were made:

1. The upwelling phenomenon is the only environmental factor determining the number of individuals born to each cohort. The ratio between upwelling intensity and the number of hatching individuals is 1:1.
2. No relation between the spawning stock and the recruitment is assumed to exist.
3. The sex ratio of hatching individuals is 1:1.
4. The first possible size at maturity is equal for both sexes; individuals under 300 g in weight are immature.
5. The catchability after reaching the minimum size at capture is the same for all individuals and no smaller individuals are caught.
6. The catch is taken by a "uniform" fleet that has a constant fishing rate throughout the year with the exception of the closed season when no catch is taken.



k	cohort	N	number of individuals
i	month	N1	initial number of individuals
M_1	first component of natural mortality	INDEX	upwelling index
M_2	second component of natural mortality	C	catch
	describing the post spawning mortality	Y	yield
M	instantaneous natural mortality	V	value of yield
F	instantaneous fishing mortality	P	price
Z	instantaneous total mortality	W	weight
SSB	spawning stock biomass		

Figure 2. Structure of the population dynamics model used to assess yearly yield, value of yield and spawning stock biomass as a function of various hypothetical exploitation scenarios and fishing mortality. Parameters presented in rectangular frames are assumed to be known exactly and those in round frames are assumed uncertain. Parameters of the "cohort" box are dependant on both cohort and month where as parameters of the "month" box, are dependent solely on the month. Parameters outside these boxes are independent of these scales.

2.4 Parameter estimates

2.4.1 Growth

Since no in situ growth experiments in the sea have been made for the Mauritanian *O. vulgaris* population, the best available information concerning growth comes from the tagging experiments conducted in the neighbouring Senegal (Brahim, K. Institut Mauritanien de Recherche Océanographique et des Pêches (IMROP). pers.comm.) The weight-at-age relationship used in this study is based on the results of these tagging experiments reported by Domain *et al*. (2000). Their results indicate that the growth rate varies significantly between males and females and according to season. They also postulate that the high water temperature during the warm season is likely the limiting factor behind the observed seasonal variation. The growth curves obtained by Domain *et al*. (2000) are expressed in relation to relative age and for the use of them in a sense of distinct age we have followed the reasoning of Jouffre *et al*. (2002). They suggest that *O. vulgaris* of the north-west African coast take about 90 days to reach 50 g in weight. This reasoning is applied to the weight-at-relative-age growth curves of Domain *et al.* (2000) to obtain the growth rates used in this study (Figure 3).

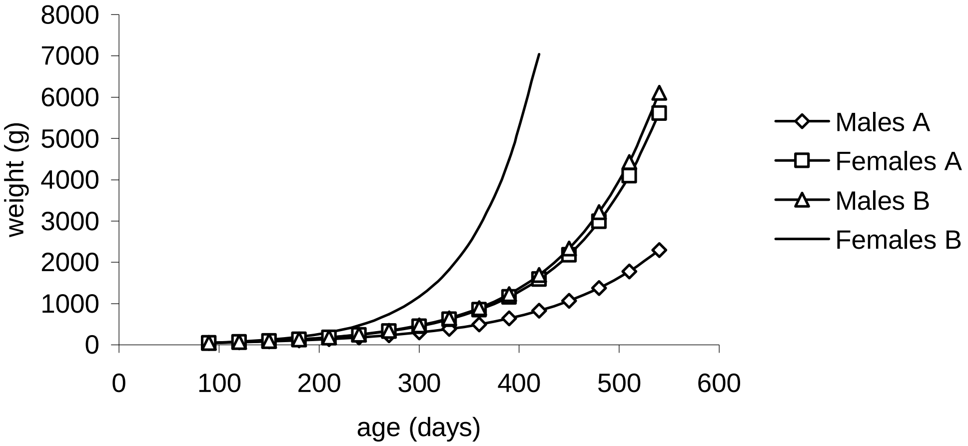


Figure 3. Growth rates for *O. vulgaris* adopted from Domain *et al*. (2000) and modified according to the reasoning of Jouffre *et al*. (2002). The letters A and B in the legend indicate the season in witch the observations were made: A = warm season B = cold season.

Although not proven explicitly, the hypothesis of the existence of two separate sub-annual cohorts off Mauritania having different biological characteristics is described by Inejih (2000). He depicts the cohorts having divergent growth rates and maturity-at-weight relationships; individuals born in spring (cold season) are bigger in weight when recruiting at the end of the year and bigger in weight at maturity compared to those born during fall (warm season) and recruiting in the beginning of the following years warm season. Among others, Pecl *et al*. (2004) discuss the factors behind adult size-at-age variability observed among cephalopods. They highlight the incubation temperatures effect on the size of hatchlings and their future growth: increasing temperatures can reduce hatchling size and lead to a smaller potential of growth. In this context, we have made the assumption that individuals' growth is determined by the season of hatching. The growth curves together with their variances, adopted from Domain *et al*. (2000) and modified according to Jouffre *et al*. (2002), are used to describe the growth of individuals born the season these observations were made respectively. The growth curves are assumed uncertain and modelled using normal distributions.

Taking into account the relatively long estimate of a possible life span (18 months) considered in this study and the properties of exponential growth curves used, the growth has to be limited by setting the highest weight achievable. We have assumed it to be of 10 kg following the results of Guerra (1979, ref. Faure 2000).

2.4.2 Natural mortality

The uncertainty related to the estimate of natural mortality M is discussed in Jouffre and Caverivière (*in press*). They note that despite its importance in fisheries modelling the estimate of this parameter M for *O. vulgaris* is missing. For semelparous species, natural mortality drops off steeply in the early life history, levelling off as sexual maturity is approached and rises steeply following spawning (Caddy 1996). The life span of *O. vulgaris* is characterised by post spawning mortality (Inejih 2000, Faure 2000) and since older individuals are more likely to spawn, natural mortality is likely to increase with age (Hendrickson and Hart 2006). Taking into account that the commonly used constant natural mortality rate can lead to miss interpretation of the reference points as remarked by Hendrickson and Hart (2006) in this study natural mortality is modelled with the use of two parameters; the rate of natural mortality increases with weight as a rate of post-spawning-mortality is added progressively on top of a constant natural mortality rate depending on weight-specific maturation rates. These rates were obtained by adjusting logistical curves into estimates presented by Inejih (2000) (Figure 4). These estimates differ between individuals born during the cold season and the warm season. The rates are used respectively for individuals born the season in which these observations were made. Considering the uncertainty related to the estimate of M and that here it's modelled using two independent rates, both of them were given beta distributions that gives nearly equal probabilities to values between 0 and 0.2. The higher limiting boundary of these distributions was set at 0.2 which equals the estimate given by Dr. Mahfould Ould Taled Sidi (Institut Mauritanien de Recherche Océanographique et des Pêches (IMROP). pers. comm.) and the estimate that has been assessed and previously used for the Mauritanian stock (Jouffre *at al*. 2005).

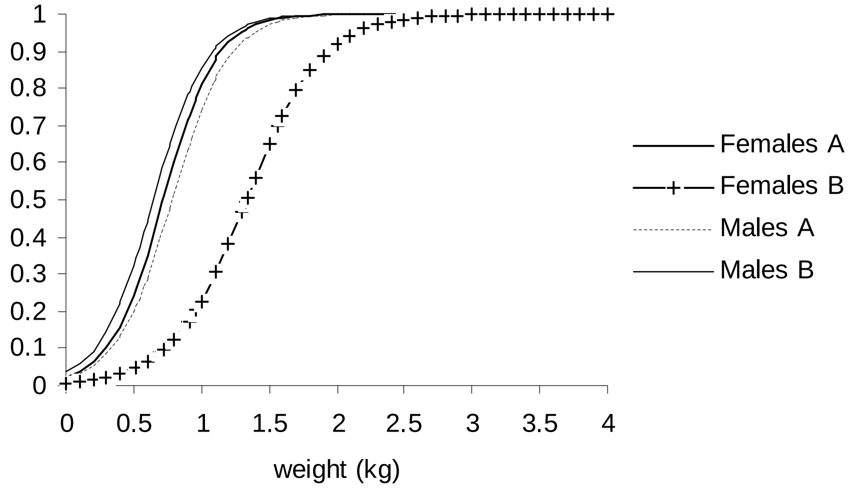


Figure 4. Maturity-at-weight relationship obtained by adjusting logistic curves into estimates derived from Inejih (2000). Letters A and B in the legend indicate the season in witch the observations of the estimates were made: A = September-October for the females and July-September for the males (warm season) B = March-May for the females and February- April for the males (cold season).

2.4.3 Upwelling index

The upwelling indices are computed based on upwelling data from years 1990-2005, and are assumed to have a lognormal probability distribution. These monthly indices were firstly given prior distributions with parameters estimated by analysing the data; the mean value and the variance computed from all the upwelling indices were used as distribution parameters. Then, the prior distributions were updated with the monthly specific data to obtain the posterior distributions used in the model. This way the posterior distributions comprises the year to year variation observed in the monthly upwelling intensity and as well the possibility of having and intensity not observed within the time frame of the data. Only the upwelling indices of the northern zone (NDB) were used in this study (Figure 5).

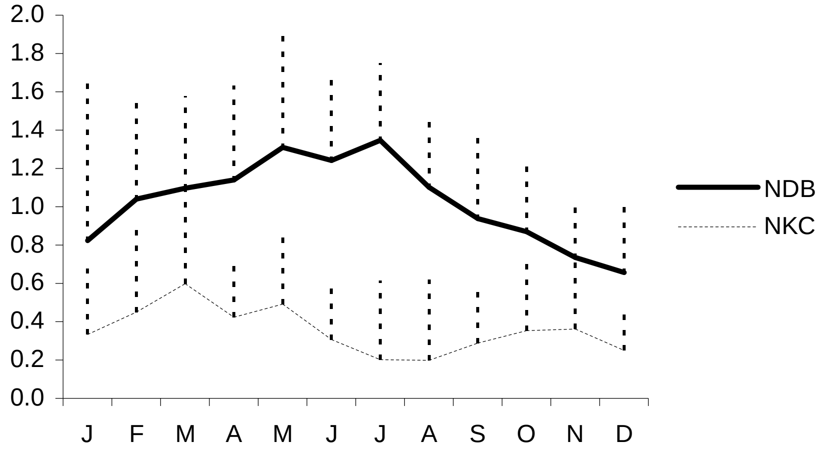


Figure 5. Monthly average upwelling indices and their standard deviations from 1990 to 2005. NDB (Nouadhibou) indicates the northern zone and NKC (Nouakchott) the southern zone. Source: IMROP.

2.4.1 Price[*]

To evaluate the relative gains or losses realized in value of yield of hypothetical exploitation scenarios in reference to the currently enforced management measures, information of the relative value of commercial size groups is implemented in the model. In Mauritania, the sorting of exported *O. vulgaris* is made according to the Mitsubishi classification that consists 10 commercial size groups (T1-T10) (Table 1).

Since the model assumes that no smaller individuals than the minimum size at capture are taken, only the first 7 categories (T1-T7) are used. The relative value of these categories is obtained of a data covering the monthly prices in USD per tonne realized from 2000 to 2005 of exported *O. vulgaris* frozen on board. The data was used to calculate the relative average value for the commercial size groups used (Figure 6). Within the model, individuals are sorted into these commercial categories and given relative value accordingly. These relative values are assumed to be known for certain.

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[*] For the moment, the model makes no difference between fresh weight and eviscerated fresh weight. This information is implemented into the model in the near future.

Table 1. The ranges of Mitsubishi classification size categories (in kg of eviscerated fresh weight).

Size category	Range (kg)
T1	> 4.5
T2	3.0-4.5
T3	2.0-3.0
T4	1.5-2.0
T5	1.2-1.5
T6	0.8-1.2
T7	0.5-0.8
T8	0.3-0.5
T9	0.2-0.3
T10	≤ 0.2

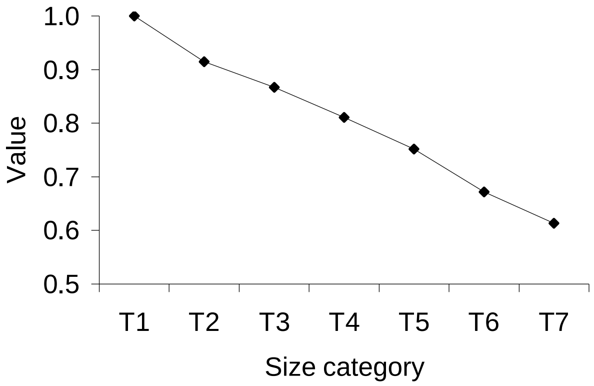

Figure 6. Relative value of the commercial size categories of the Mitsubishi classification.

2.5 Modelling method

The modelling method used in this study is based on the Bayes' theorem by Reverend Thomas Bayes (1702-1762). Bayes' theorem is a mathematical formula used for calculating conditional probabilities. In the Bayesian approach, pre-existing knowledge and/or beliefs about the parameters are expressed in the form of prior probability distributions (Punt and Hillborn 1997). For example, consider two parameters labelled A and B. We are interested in the conditional probability $P(B \mid A)$ that B is true provided that A is true. The probability $P(B \mid A)$ of B given A can be written as:

$$P(B \mid A) = \frac{P(A,B)}{P(A)} \qquad (1).$$

The probability $P(A,B)$ of observing these two events A and B at the same time, i.e. A and B are true:

$$P(A,B) = P(A)P(B \mid A) = P(B)P(A \mid B) \qquad (2)$$

and the probability of $P(A)$ which is the combined probability of all the combinations of hypotheses of the parameter A, i.e. which represents our best estimate of the probability of the parameter A prior to consideration of any evidence:

$$P(A) = \sum_A P(A \mid B)P(B) \qquad (3)$$

are substituted into Eq. 1 to obtain the Bayes' formula

$$P(B \mid A) = \frac{P(A \mid B)P(B)}{\sum_A P(A \mid B)P(B)} \qquad (4).$$

Prior probability distributions can be updated into posterior distributions using observed data. Posterior distribution $P(B \mid A)$ describes the uncertainty related to parameter B after new observation/observations regarding the parameter A have been made. Posterior probability of the parameter B given the parameter A is simply the probability of the hypothesis $P(B \mid A)$ given the data. Posterior distributions often result narrower than the prior ones as information accumulates and the knowledge of the true values of the parameters becomes enhanced (Gelman *et al*. 1995). Among others Gelman *et al*. (1995) give a more detailed description of the Bayes' theorem and methods.

2.6 Model structure

There are a total of 12 cohorts k and 29 months i in the model. The life span of each individual is no longer than 18 months. The cohorts are modelled in time so that the January's cohort is born in month $i = 1$ and its life span exceeds to month $i = 18$ and the February's cohort is born in month $i = 2$ with its life span exceeding to month $i = 19$. This goes on until the December's cohort that's life span begins the month $i = 12$ and ends the month $i = 29$.

The number of individuals $N_{k,i}$ resulting from the hatching of the cohort k in month i is dependent on the prevailing environmental conditions:

$$N_{k,i} = N1 * INDEX_k \qquad (5)$$

where $N1$ is a constant of one thousand (1000) individuals given to each cohort and $INDEX_k$ is the upwelling index that represents the prevailing environmental conditions at the time of hatching of cohort k. Year to year variations of the mean monthly upwelling indices are implemented in the model by using a data from 1990 to 2005. The upwelling indices are assumed to vary according to a lognormal distribution:

$$INDEX_k \sim \log norm(M_k, T) \qquad (6)$$

From the hatching month onwards (the month where the relative strength in numbers of each cohort is determined), the number $N_{k,i}$ of individuals alive in cohort k at month i is:

$$N_{k,i} = e^{(-Z_{k,i})} N_{k,i-1} \qquad (7)$$

where $Z_{k,i}$ is the instantaneous total mortality of cohort k in month i and $N_{k,i-1}$ is the number of individuals of the cohort k alive the preceding month. Total mortality $Z_{k,i}$ consists of the instantaneous fishing mortality $F_{k,i}$ and the instantaneous natural mortality $M_{k,i}$. Fishing mortality contributes to the total mortality of those individuals that have reached the minimum size at capture.

Natural mortality $M_{k,i}$ is composed of two components:

$$M_{k,i} = M\_1 + M\_2_{k,i} \qquad (8)$$

where the parameter M_1 is constant for all individuals at all times and $M\_2_{k,i}$ is added progressively on top of M_1. Parameter $M\_2_{k,i}$ describes the post spawning mortality:

$$M\_2_{k,i} = M\_2a_{k,i} * M2a \qquad (9)$$

where the parameter $M\_2a_{k,i}$ describes the individual's probability of being mature and $M2a$ is the mortality rate. Since the bigger individuals are more likely to be mature the maturity-at-weight relationship is implemented as a logistic function:

$$\text{logit}(M2a_{k,i}) = c_{k,i} + d_{k,i} * W_{k,i} \qquad (10)$$

where $c_{k,i}$ and $d_{k,i}$ are function parameters and $W_{k,i}$ is the individuals weight in cohort k at month i.

Individuals within a cohort are given growth rates according to sex and the month of hatching. Individual’s weight $W_{k,i}$ at the age of 90 days:

$$W_{k,i} = e^{(a_k b_k)} \qquad (11)$$

where a_k and b_k are sex and cohort specific parameters. The weight $W_{k,i}$ from this age onwards:

$$W_{k,i} = W_{k,i-1} e^{(a_k 30)} \qquad (12)$$

where $W_{k,i-1}$ is the weight of the preceding month.

Biomass $B_{k,i}$ of cohort k in month i :

$$B_{k,i} = N_{k,i} * W_{k,i} \qquad (13)$$

Catch $C_{k,i}$ obtained of cohort k in month i :

$$C_{k,i} = N_{k,i} * (1 - e^{(-Z_{k,i})}) * (F_{k,i} / Z_{k,i}) \qquad (14)$$

Yield $Y_{k,i}$ obtained of cohort k in month i :

$$Y_{k,i} = C_{k,i} * W_{k,i} \qquad (15)$$

Spawning stock biomass $SSB_{k,i}$ is composed of individuals that have been affected by post spawning mortality:

$$SSB_{k,i} = N_{k,i} * (1 - e^{(-Z_{k,i})}) * (M\_2_{k,i} / Z_{k,i}) \qquad (16)$$

Value of yield $VY_{k,i}$ obtained of cohort k in month i:

$$VY_{k,i} = Y_{k,i} * p \qquad (17)$$

where p is the value.

Yearly value of yield VY , yield Y and spawning stock biomass SSB are obtained by summing over:

$$VY = \sum VY_{k,i} \qquad (18)$$
$$Y = \sum Y_{k,i} \qquad (19)$$
$$SSB = \sum SSB_{k,i} \qquad (20)$$

2.7 Computation of the model

The model was computed using WinBUGS 2.1 software (Thomas *et al*. 2006). The model was run using three MCMC chains for 3000 iterations each. Convergence of the simulation was assessed by viewing visually the simulated chains. The chains seemed to converge within the first 1600 iterations. These first 1600 iterations were discarded and the last 1400 iterations were used in the inference.

Currently, the fishery is managed using two measures: closed season in September-October, and minimum size at capture of 500 g. The model was used to evaluate 54 different exploitation scenarios comprising the following policies: no closing season with various minimum sizes at capture, timing of the two month closed season, one month closing season with the minimum size of 500 g, one month closing season in addition to the currently used two month closing season and a two month closing season with a minimum size of 1000 g. The optimum level of fishing mortality was computed within each of the exploitation scenarios. To assess all these various combinations an overall amount of 281 computations were conducted.

3. Results

The highest relative value of yield obtained within the current management policy of closure in September-October with a minimum size at capture of 500 g is obtained with monthly fishing mortality of 0.3 (Table 3). This value is used as the reference point, and all of the other values are given as relative to this value. This point was used as the reference point as well regarding yield and spawning stock biomass (Tables 8 and 13). The mean relative gains or losses in value of yield, yield and spawning stock biomass resulting of the currant and hypothetical exploitation scenarios are shown in Tables 2-16.

The one month closing scenario with a minimum size of 500 g results in losses in value of yield (Table 4) and spawning stock biomass (Table 14) and in gains of yield (Table 9). The three month closing season scenario with a minimum size at capture of 500 g leads to minor gains in value of yield (Table 6) and spawning stock biomass (Table 16) and to losses of yield (Table 11). Raising the minimum size at capture results in noticeable gains in value of yield within some exploitation scenarios (Tables 2 and 5), in considerable gains in spawning stock biomass of most scenarios (Tables 12 and 15) and in explicitly to losses of yield (Tables 7 and 10). The effects of the three month closing season scenario and raising the minimum size at capture scenarios are illustrated in Figure 7 by comparing the current exploitation policy with hypothetical policies of: closure in August-October with a minimum size of capture of 500g, no closing season with a minimum size of 1000 g and closure in September-October with a minimum size at capture of 1000 g. The uncertainty related to the mean values of these parameters is shown with 95 % credible intervals (Figure 7).

3.1 Value of yield

The current policy gives the highest relative value of yield (Table 3) compared to other hypothetical closure timings and durations shown in Tables 3 and 4 and as well when no closure is used (Table 2). However, the three month closing season scenario gives higher gains in value, if only 1.8 % at its best with a closure of August-October (Table 6, Figure 7). Raising the minimum size at capture to 2000 g gives the highest gain in value, 24.4 %, of the minimum sizes tested (Table 2).

3.2 Yield

The highest increase of yield, 6.7 %, is obtained with a policy of no closed season and a minimum size of 500 g (Table 7) and the relocation of the closed season to November-December would result in a gain of 3,5 % (Table 8). All the three month closing season scenarios (Table 11) and those with a higher minimum size than 500 g (Tables 7 and 10) result in losses of yield.

3.3 Spawning stock biomass

Raising the minimum size at capture and reduction in fishing mortality are clearly beneficial regarding the relative spawning stock biomass (Tables 12-16). The current closure policy yields a gain of 12.9 % compared to the scenario without closing (Tables 12 and 13). A gain of 4.4 % would be realized by changing the current timing to December-January (Table 14).

Tables 2-6. Comparison of the relative value of yield* in terms of different management measures and fishing mortality. In each table the highest value is circled, the highest value of each row is bolded and all values equal or higher than the reference point are highlighted. The reference point in table 2. is highlighted with rectangular frames. Management measures compared in figure 6 are marked with frames. *Note that the results concerning the value of yield are based on preliminary results.

Table 2. Comparison of different minimum sizes at capture.

Management measure	VALUE OF YIELD						
Minimum size	**0.1**	**0.2**	**0.3**	**0.4**	**0.5**	**0.6**	**0.7**
500 g	0.719	**0.937**	0.933	0.845	0.733		
750 g	0.740	1.031	**1.095**	1.051	0.962		
1000 g	0.716	1.047	**1.156**	1.148	1.084		
1250 g	0.672	1.010	1.140	**1.160**	1.112		
1500 g	0.640	0.986	1.144	**1.190**	1.163		
1750 g	0.609	0.962	1.137	**1.207**	1.202		
2000 g	0.590	0.935	1.130	1.225	**1.244**	1.218	
3000 g	0.441	0.738	0.937	1.054	1.118	**1.138**	1.124

Table 3. Comparison of a two months closing season with a minimum size at capture of 500 g.

Management measure	VALUE OF YIELD				
Min. size 500 g					
Closing season	**0.1**	**0.2**	**0.3**	**0.4**	**0.5**
Jan.-Feb.	0.560	0.805	**0.877**	0.859	0.794
Feb.-Mar.	0.546	0.768	**0.817**	0.781	0.710
Mar.-Apr.	0.539	0.734	**0.762**	0.716	0.647
Apr.-May	0.546	0.731	**0.751**	0.701	0.622
May-June	0.635	0.835	**0.840**	0.768	0.671
June-July	0.699	0.914	**0.918**	0.832	0.726
July-Aug.	0.710	0.943	**0.961**	0.890	0.789
Aug.-Sep.	0.710	0.957	**0.987**	0.923	0.827
Sep.-Oct.	0.698	0.957	**1**	0.945	0.853
Oct.-Nov.	0.665	0.931	**0.994**	0.950	0.865
Nov.-Dec.	0.637	0.909	**0.984**	0.957	0.882
Dec.-Jan.	0.608	0.877	**0.962**	0.945	0.881

Table 5. Comparison of a two months closing season with a minimum size at capture of 1000 g.

Management measure	VALUE OF YIELD					
Min. size 1000 g						
Closing season	**0.1**	**0.2**	**0.3**	**0.4**	**0.5**	**0.6**
Jan.-Feb.	0.527	0.827	0.979	1.037	**1.040**	1.003
Feb.-Mar.	0.520	0.812	0.960	**1.016**	1.013	0.970
Mar.-Apr.	0.515	0.780	0.895	**0.922**	0.898	0.850
Apr.-May	0.526	0.778	0.883	**0.895**	0.869	0.813
May-June	0.626	0.921	**1.021**	1.020	0.969	
June-July	0.692	1.001	**1.108**	1.095	1.033	
July-Aug.	0.695	1.012	1.125	**1.137**	1.076	
Aug.-Sep.	0.704	1.039	1.161	**1.172**	1.119	
Sep.-Oct.	0.683	1.016	1.142	**1.161**	1.118	1.045
Oct.-Nov.	0.635	0.964	1.102	**1.134**	1.105	1.042
Nov.-Dec.	0.603	0.922	1.073	**1.115**	1.097	1.046
Dec.-Jan,	0.572	0.881	1.026	**1.075**	1.063	1.018

Table 4. Comparison of a one month closing season with a minimum size at capture of 500 g.

Management measure	VALUE OF YIELD				
Min. size 500 g					
Closing season	**0.1**	**0.2**	**0.3**	**0.4**	**0.5**
Jan.	0.657	0.899	**0.942**	0.886	0.791
Feb.	0.636	0.862	**0.893**	0.836	0.740
Mar.	0.640	0.856	**0.875**	0.812	0.716
Apr.	0.622	0.833	**0.849**	0.779	0.691
May	0.648	0.857	**0.860**	0.791	0.694
June	0.708	**0.922**	0.918	0.829	0.721
July	0.711	0.933	**0.939**	0.854	0.744
Aug.	0.716	0.947	**0.957**	0.879	0.769
Sep.	0.715	0.948	**0.967**	0.889	0.780
Oct.	0.707	0.946	**0.964**	0.891	0.790
Nov.	0.685	0.931	**0.960**	0.897	0.791
Dec.	0.678	0.924	**0.963**	0.910	0.812

Table 6. Comparison of a one month closing season with a two months closing season in September-October and a minimum size at capture of 500 g.

Management measure	VALUE OF YIELD				
Min. size 500 g					
Closing season					
Sep.-Oct. and	**0.1**	**0.2**	**0.3**	**0.4**	**0.5**
Jan.	0.625	0.900	**0.979**	0.953	0.887
Feb.	0.604	0.866	**0.939**	0.912	0.845
Mar.	0.617	0.874	**0.940**	0.909	0.835
Apr.	0.603	0.849	**0.913**	0.883	0.808
May	0.628	0.874	**0.928**	0.893	0.814
June	0.685	0.939	**0.982**	0.932	0.842
July	0.690	0.949	**0.995**	0.951	0.860
Aug.	0.692	0.960	**1.018**	0.980	0.892
Nov.	0.650	0.930	**1.008**	0.989	0.924
Dec.	0.643	0.925	**1.009**	0.989	0.915

Tables 7-11. Comparison of the relative yield in terms of different management measures and fishing mortality. In each table the highest value is circled, the highest value of each row is bolded and all values equal or higher than the reference point are highlighted. The reference point in table 7. is highlighted with rectangular frames. Management measures compared in figure 6 are marked with frames.

Table 7. Comparison of different minimum sizes at capture.

Management measure	YIELD						
Minimum size	**0.1**	**0.2**	**0.3**	**0.4**	**0.5**	**0.6**	**0.7**
500 g	0.671	0.965	1.066	**1.067**	1.017		
750 g	0.558	0.834	0.950	**0.976**	0.948		
1000 g	0.470	0.717	0.836	**0.878**	0.872		
1250 g	0.372	0.568	0.658	**0.691**	0.686		
1500 g	0.331	0.514	0.606	**0.639**	0.639		
1750 g	0.301	0.477	0.574	0.615	**0.621**		
2000 g	0.279	0.451	0.550	0.595	**0.608**	0.599	
3000 g	0.189	0.321	0.408	0.460	0.486	**0.495**	0.493

Table 8. Comparison of a two months closing season with a minimum size at capture of 500 g.

Management measure	YIELD				
Min. size 500 g					
Closing season	**0.1**	**0.2**	**0.3**	**0.4**	**0.5**
Jan.-Feb.	0.536	0.817	0.941	**0.978**	0.964
Feb.-Mar.	0.540	0.808	0.926	**0.957**	0.936
Mar.-Apr.	0.544	0.805	0.916	**0.935**	0.913
Apr.-May	0.554	0.816	0.920	**0.941**	0.908
May-June	0.587	0.849	0.942	**0.948**	0.911
June-July	0.605	0.872	**0.965**	0.964	0.921
July-Aug.	0.618	0.897	0.995	**1.007**	0.967
Aug.-Sep.	0.618	0.904	1.010	**1.019**	0.984
Sep.-Oct.	0.600	0.891	1	**1.017**	0.983
Oct.-Nov.	0.587	0.882	1.002	**1.029**	1.006
Nov.-Dec.	0.576	0.876	1.000	**1.035**	1.011
Dec.-Jan.	0.553	0.844	0.976	**1.017**	0.999

Table 9. Comparison of a one month closing season with a minimum size at capture of 500 g.

Management measure	YIELD				
Min. size 500 g					
Closing season	**0.1**	**0.2**	**0.3**	**0.4**	**0.5**
Jan.	0.613	0.904	0.904	**1.041**	1.009
Feb.	0.603	0.890	0.890	**1.021**	0.989
Mar.	0.613	0.896	0.896	**1.018**	0.981
Apr.	0.610	0.890	0.890	**1.009**	0.971
May	0.624	0.908	0.908	**1.014**	0.973
June	0.639	0.920	0.920	**1.014**	0.969
July	0.645	0.931	0.931	**1.030**	0.983
Aug.	0.648	0.940	0.940	**1.046**	1.003
Sep.	0.642	0.935	0.935	**1.049**	1.006
Oct.	0.633	0.927	0.927	**1.049**	1.005
Nov.	0.630	0.928	0.928	**1.057**	1.017
Dec.	0.622	0.921	0.921	**1.055**	1.022

Table 10. Comparison of a two months closing season with a minimum size at capture of 1000 g.

Management measure	YIELD					
Min. size 1000 g						
Closing season	**0.1**	**0.2**	**0.3**	**0.4**	**0.5**	**0.6**
Jan.-Feb.	0.349	0.560	0.679	0.739	**0.756**	0.748
Feb.-Mar.	0.349	0.560	0.678	0.733	**0.748**	0.743
Mar.-Apr.	0.356	0.564	0.675	0.723	**0.732**	0.715
Apr.-May	0.373	0.582	0.688	0.734	**0.735**	0.715
May-June	0.417	0.637	0.739	**0.771**	0.765	
June-July	0.439	0.666	0.765	**0.793**	0.780	
July-Aug.	0.442	0.674	0.777	**0.823**	0.817	
Aug.-Sep.	0.446	0.686	0.806	**0.844**	0.842	
Sep.-Oct.	0.428	0.664	0.780	0.825	**0.826**	0.800
Oct.-Nov.	0.405	0.634	0.753	0.804	**0.809**	0.790
Nov.-Dec.	0.389	0.617	0.741	0.798	**0.813**	0.801
Dec.-Jan,	0.373	0.596	0.715	0.773	**0.786**	0.776

Table 11. Comparison of a one month closing season with a two months closing season in September-October and a minimum size at capture of 500 g.

Management measure	YIELD				
Min. size 500 g					
Closing season					
Sep.-Oct. and	**0.1**	**0.2**	**0.3**	**0.4**	**0.5**
Jan.	0.537	0.817	0.942	**0.978**	0.962
Feb.	0.530	0.808	0.932	**0.965**	0.950
Mar.	0.543	0.817	0.938	**0.971**	0.951
Apr.	0.540	0.813	0.933	**0.961**	0.942
May	0.553	0.828	0.941	**0.970**	0.943
June	0.567	0.841	0.950	**0.970**	0.941
July	0.571	0.847	0.954	**0.975**	0.946
Aug.	0.572	0.849	0.958	**0.973**	0.946
Nov.	0.553	0.834	0.959	**0.991**	0.971
Dec.	0.547	0.830	0.955	**0.993**	0.976

Tables 12-16. Comparison of the relative spawning stock biomass in terms of different management measures and fishing mortality. In each table the highest value is circled, the highest value of each row is bolded and all values equal or higher than the reference point are highlighted. The reference point in table 12. is highlighted with rectangular frames. Management measures compared in figure 6 are marked with frames.

Table 12. Comparison of different minimum sizes at capture.

Management measure	**SSB**						
Minimum size	**0.1**	**0.2**	**0.3**	**0.4**	**0.5**	**0.6**	**0.7**
500 g	**1.378**	1.089	0.886	0.740	0.631		
750 g	**1.513**	1.308	1.156	1.039	0.945		
1000 g	**1.606**	1.459	1.345	1.260	1.189		
1250 g	**1.661**	1.555	1.481	1.422	1.374		
1500 g	**1.697**	1.612	1.542	1.494	1.457		
1750 g	**1.713**	1.642	1.594	1.551	1.515		
2000 g	**1.724**	1.667	1.620	1.587	1.562	1.539	
3000 g	**1.764**	1.735	1.711	1.692	1.677	1.661	1.650

Table 13. Comparison of a two months closing season with a minimum size at capture of 500 g.

Management measure	**SSB**				
Min. size 500 g Closing season	**0.1**	**0.2**	**0.3**	**0.4**	**0.5**
Jan.-Feb.	**1.471**	1.224	1.040	0.898	0.791
Feb.-Mar.	**1.456**	1.203	1.014	0.874	0.766
Mar.-Apr.	**1.443**	1.184	0.995	0.852	0.744
Apr.-May	**1.433**	1.174	0.984	0.843	0.737
May-June	**1.424**	1.166	0.978	0.838	0.736
June-July	**1.418**	1.158	0.965	0.828	0.725
July-Aug.	**1.421**	1.165	0.971	0.834	0.728
Aug.-Sep.	**1.434**	1.177	0.985	0.846	0.741
Sep.-Oct.	**1.441**	1.189	1	0.858	0.752
Oct.-Nov.	**1.448**	1.198	1.011	0.868	0.759
Nov.-Dec.	**1.461**	1.212	1.024	0.884	0.777
Dec.-Jan.	**1.472**	1.225	1.044	0.903	0.794

Table 14. Comparison of a one month closing season with a minimum size at capture of 500 g.

Management measure	**SSB**				
Min. size 500 g Closing season	**0.1**	**0.2**	**0.3**	**0.4**	**0.5**
Jan.	**1.424**	1.155	0.959	0.811	0.702
Feb.	**1.417**	1.148	0.952	0.806	0.700
Mar.	**1.412**	1.140	0.938	0.790	0.683
Apr.	**1.405**	1.132	0.932	0.787	0.677
May	**1.401**	1.126	0.928	0.787	0.680
June	**1.398**	1.125	0.925	0.784	0.676
July	**1.396**	1.118	0.922	0.778	0.670
Aug.	**1.401**	1.128	0.928	0.785	0.675
Sep.	**1.408**	1.132	0.936	0.792	0.682
Oct.	**1.411**	1.137	0.938	0.795	0.685
Nov.	**1.413**	1.139	0.940	0.800	0.689
Dec.	**1.424**	1.151	0.957	0.810	0.701

Table 15. Comparison of a two months closing season with a minimum size at capture of 1000 g.

Management measure	**SSB**					
Min. size 1000 g Closing season	**0.1**	**0.2**	**0.3**	**0.4**	**0.5**	**0.6**
Jan.-Feb.	**1.661**	1.548	1.460	1.387	1.327	1.281
Feb.-Mar.	**1.657**	1.545	1.453	1.382	1.317	1.271
Mar.-Apr.	**1.644**	1.516	1.422	1.338	1.271	1.218
Apr.-May	**1.633**	1.495	1.392	1.310	1.246	1.194
May-June	**1.630**	1.484	1.376	1.295	1.231	
June-July	**1.628**	1.482	1.377	1.292	1.228	
July-Aug.	**1.628**	1.488	1.379	1.300	1.240	
Aug.-Sep.	**1.621**	1.487	1.385	1.307	1.242	
Sep.-Oct.	**1.628**	1.500	1.403	1.326	1.266	1.212
Oct.-Nov.	**1.639**	1.512	1.422	1.350	1.286	1.239
Nov.-Dec.	**1.650**	1.528	1.437	1.359	1.300	1.251
Dec.-Jan,	**1.654**	1.532	1.442	1.369	1.305	1.257

Table 16. Comparison of a one month closing season with a two months closing season in September-October and a minimum size at capture of 500 g.

Management measure	**SSB**				
Min. size 500 g Closing season Sep.-Oct. and	**0.1**	**0.2**	**0.3**	**0.4**	**0.5**
Jan.	**1.489**	1.255	1.077	0.939	0.827
Feb.	**1.483**	1.242	1.067	0.925	0.817
Mar.	**1.474**	1.236	1.050	0.911	0.803
Apr.	**1.466**	1.226	1.040	0.905	0.798
May	**1.464**	1.223	1.040	0.907	0.800
June	**1.463**	1.220	1.043	0.903	0.801
July	**1.461**	1.222	1.043	0.904	0.799
Aug.	**1.465**	1.230	1.055	0.925	0.822
Nov.	**1.482**	1.248	1.078	0.944	0.837
Dec.	**1.486**	1.255	1.081	0.948	0.837

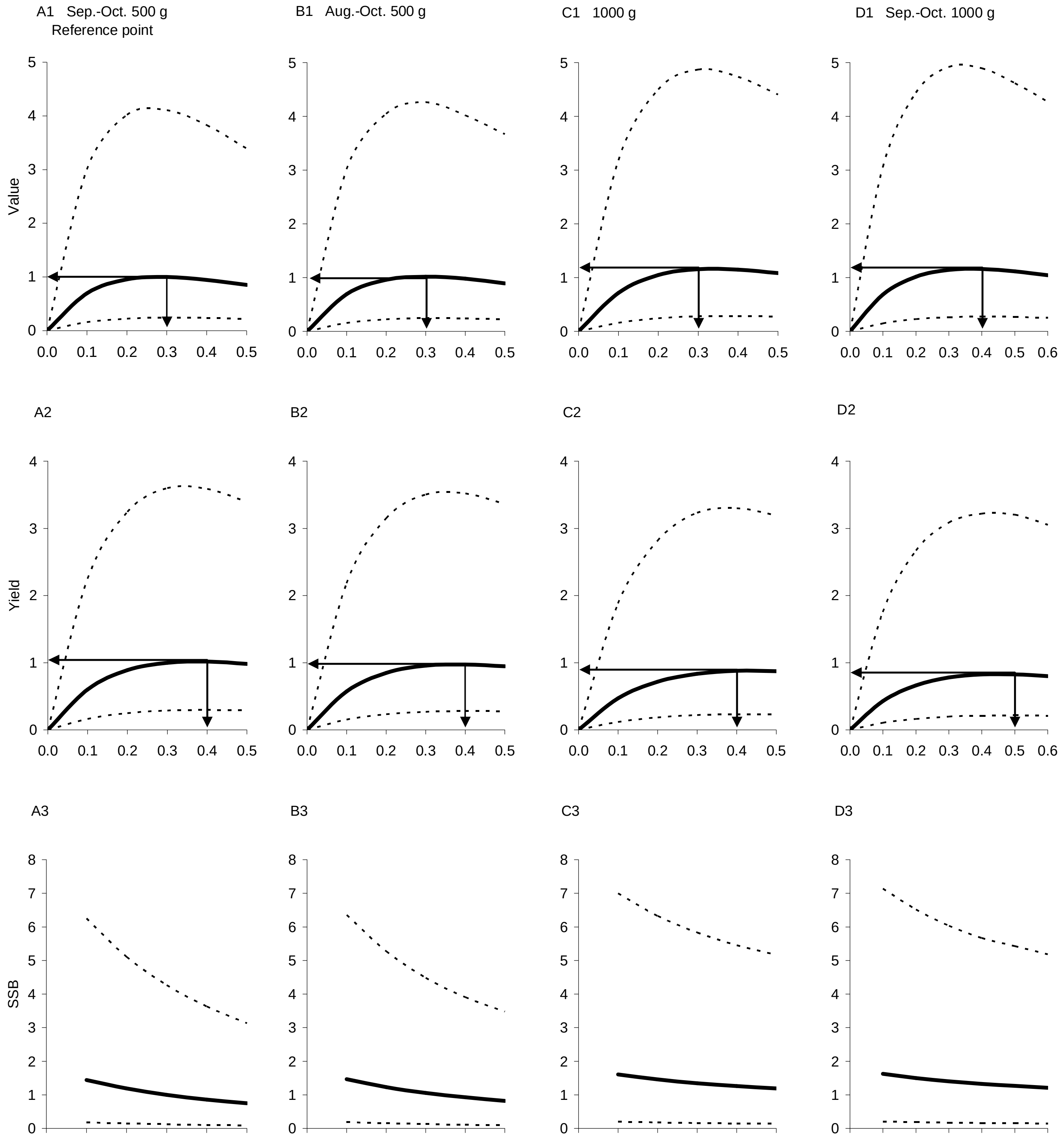

Figure 7. Comparison of the mean relative value of yield A1-D1*, yield A2-D2 and spawning stock biomass A3-D3 in terms of different management measures and fishing mortality. Arrows indicate the level of fishing mortality where the highest value is realized. The 95 % credible interval is shown with dash lines.
A = closing season September-October with a minimum size at capture of 500 g
B = closing season August-October with minimum size at capture of 500 g
C = no closing season with minimum size at capture of 1000 g
D = closing season September-October with minimum size at capture of 1000 g
* Note that the results concerning the value of yield are based on preliminary results.

4. Discussion

Probabilistic models for cephalopods stock assessment purposes are almost non-existent despite the well-recognized uncertainty related to the knowledge on the aspects of the species biology and to the stock responses in changing environmental conditions. In this study, the use of Bayesian approach enabled the consideration of uncertainty related to the biological aspects of *O. vulgaris* and to the environmental conditions the species encounters off Mauritania. In this context, the present study is clearly an improvement since the modelling method used has the ability to treat uncertainty explicitly.

No previous bioeconomic analysis is conducted for the Mauritanian *O. vulgaris* fishery. The objective of the previous species stock assessments in Mauritania has been the assessment of the potentials of production (in biomass) and the maximum sustainable yield (MSY). In the light of the results presented in this study, having the maximum production or MSY as the objective in assessments of optimal exploitation scenarios can result in losses regarding the value of yield.

The effects of the timing and duration of the closed season in Mauritania has been previously assessed by Jouffre *et al*. (2005) who noted that the current policy of closure in September-October has no significant effects on the volume of annual *O. vulgaris* captures and other timings and durations would have only minor negative or positive effects. They also concluded that the closing season has positive effects on the potentials of reproduction of the species but, however, remains probably insignificant regarding the future of the stock.

The results of this study indicate that the current timing of the closed season is optimal and no considerable gains in yearly value of yield are obtained using other timings. However, increasing the minimum size at capture seems to be profitable. For example, minimum size of 1000 g with a two-month closing season in September-October yields a mean relative gain of 16.1 % in yearly value of yield. Considering yield, our results are in concordance with the results obtained by Jouffre *et al*. (2005) since no significant gains are obtained by reassessing the timing or duration of the closed season. Although the relation between spawning stock biomass and recruitment remains unknown for the species, there will be a point at which the spawning stock becomes so low that recruitment is affected (Boyle and Rodhouse 2006). The current results indicate that significant gains in spawning stock biomass can be achieved by raising the minimum size at capture.

The uncertainty related to the mean relative values of the variables assessed within this study (yearly value of yield, yield and spawning stock biomass) comprises the uncertainty related to the biological aspects of the species and the uncertainty and variation related to the environmental conditions off Mauritania. This uncertainty is relatively large; in a scenario in which all the uncertain components are favourable regarding the biological potentials of the species the variables are likely to have higher values of several orders of magnitude compared to the mean values presented.

The hierarchical Bayesian model constructed in this study can be used as the basis for a more comprehensive model, in the best spatial and temporal resolution possible, describing the Mauritanian *O. vulgaris* fishery and as well other cephalopods fisheries. This can be achieved, for example, by adding new components in the model such as the different fishing fleets and their incomes. This would enable the assessment of the management options on the distribution of incomes between the fleet segments. With some modifications, the model can also be used to predict the recruitment several months in advance knowing the environmental conditions prevailing the time of hatching and to assess the management measures accordingly.

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