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COMBINING FISHING CLOSURE WITH MINIMUM SIZE OF CAPTURE TO IMPROVE OCTOPUS PRODUCTION IN SENEGALESE WATERS: AN EVALUATION USING ANALYTICAL MODELLING

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ABSTRACT: The dynamics of the *Octopus vulgaris* (Cuvier, 1797) population in Senegalese waters is modelled to evaluate the potential impact of combining temporal fishing closure and minimum size of capture on the production of this stock. The study is based on an analytical approach (cohort analysis and simulation of captures on a monthly basis) adapted to the biological characteristics of *O. vulgaris*, a short lifespan species. Several combinations of the two policies (minimum size and fishing closure) are tested to complement the results of previous studies that evaluated each of the two strategies separately, and in addition, to account for the fact that a positive synergistic effect can be expected. The model covers the exploitation period from 1996 to 1999. As in previous simulations (of separate effects), the present results focus on the instability of the responses (positive or negative, significant or not, depending on the situation that prevailed each year) of the octopus stock to such policies. As a consequence it is difficult to identify the ideal combination of closure and size limits that would ensure a substantial improvement in production every year. Nevertheless, a 350g or 500g minimum size policy seems to be profitable when combined with a two-month fishing closure in July–August. The final discussion focuses on the fact that, in addition to its regional range, the present study presents also a broader interest because the methodology proposed here aims to be applicable to other cephalopods and short lived species fisheries.

INTRODUCTION

Populations of *Octopus vulgaris* off the coast of West Africa display strong interannual variations in abundance (Caverivière 1990, Jouffre and Inejih 1997, Faure 2000). This variation obviously complicates the management of a marine resource that is very important for three countries in the area: Morocco, Mauritania and Senegal (Dia 1988, Caverivière 1994; Dia *et al*. 1996, FAO 1997, Diallo *et al*. 2002). Professionals and managers of these fisheries thus require a better understanding of the dynamics of the resource they exploit (Dia *et al*. 1996, Faure 2000, Jouffre *et al*. 2002a).

It is remarkable indeed to note that the major management policies which have occurred in recent years in Morocco Mauritania and Senegal were formulated by keeping the largest account of the octopus resource, often in priority and even in quasi-exclusive reference to this species. It is the case for fishing closures, therefore called "biological rest" , founded initially in Morocco then in Mauritania and finally in Senegal (since 1996). In these three countries, the reasons evoked to justify such closure which concern in fact all the benthic and demersal species are in connection with an improvement of the situation of the octopus fisheries: that is to perpetuate, to stabilize and to raise in the mean level of the annual captures carried out on this species. Vis-à-vis that, the ways for evaluating objectively the impact of these changes in the exploitation pattern on octopuses yields were missing, either through insufficiency of available data or through lack of implementation of an adequate analytical methodology.

In this context, a method of modelling the dynamics of the octopus populations off the Senegalese coast was developed making it possible to simulate the potential impact on production of various exploitation scenarios. The effects of fishing closure and of minimum sizes were analysed (Jouffre *et al*. 2002a and 2002b). The present study aims to complement the results of the preceding research by considering modes of exploitation that simultaneously combine the two policies, as is currently being envisaged by fishing authorities and managers in this region.

In addition to its obvious regional range (described above), this study presents also a broader interest considering that its methods are addressed to a resource (cephalopods) for which the examples of analytical modelling for fisheries management purposes are still very few. Particularly, there is a limited literature about closures in cephalopods fishery. In this context, it is interesting to present an alternative to what already exists in the same field, such as the proposition of Hill and Agnew (2002). The general methodological options presented here aims indeed to be applicable to other cephalopod fisheries.

MATERIALS AND METHODS

1. Data

1.1. General description

The following data are used:

- total octopus catches in weight per month for the whole of Senegal and for the two types of fisheries (artisanal (AF) and industrial (IF)) from January 1996 to December 1999;
- a sample of the monthly catches by commercial categories of homogeneous size covering the same period (January 1996–December 1999) for the two fisheries (AF and IF);
- a sample of individual weightings representative of the composition of each commercial category;
- data and information related to *in situ* estimated growth rates for octopuses off Senegal (Domain *et al*. 2000), data used to construct VPA in order to calculate recruitment.

1.2. Representativeness of the data

Estimate of the total monthly captures

The total catch in weight of octopuses fished monthly in Senegal, as well as the relative shares of artisanal fishing and industrial fishing, are estimated according to two sources which are: (a) investigations carried out by the Oceanographic Research Center of Dakar-Thiaroye (CRODT) and (b) those of the Direction de l´Océanographie et des Pêches Maritimes du Sénégal (DOPM). These two institutions represent the two official sources and the most exhaustive ones concerning fishery statistics in Senegal. Moreover, the two resulting sets of data are independent because they come from separate sampling systems (Sénagne, 1999; Sy, 1995; Ferraris *et al*., 1994). In this work, the data of the CRODT were used as principal reference because this source is based on a finer investigation of the landing sites of artisanal fishing (Ferraris *et al*, 1993, 1994). The second data source (DOPM) is used as a mean to control and improve the quality of the data used. The confrontation of the two sources allowed us to correct certain errors in the initial database punctually (*i.e*. aberrant data resulting from errors of seizure or extrapolation, *etc*). Finally for each one of these two institutions (CRODT and DOPM) the *Octopus vulgaris* capture is submitted to a special attention because of its great commercial value. The whole of the preceding elements leads to consider that the estimations of total monthly octopus captures used in this work are very representative of the total quantities really fished in Senegal.

Distribution of the captures by commercial categories

In Senegal, the octopuses caught for export are sorted and distributed by categories of homogeneous sizes, such as the classification named “Mitsubishi” (Table 1), (Dia, 1988; Jouffre *et al*., 2000). Several of the main factories collecting and processing the fishing products in Senegal provided a copy of their files concerning octopuses. These files contained monthly quantities treated, in metric tonnes by commercial categories, as well as information on their source, from industrial fishing (IF) or artisanal fishing (AF). The compilation of these data (that will be called “factories” sample) makes it possible to estimate monthly profiles of the captures according to the 10 Mitsubishi categories, and for each of the two fishery categories (IF and AF). These profiles can be regarded as very representative of the real

Table 1. Weight limits (in grams of eviscerated fresh weight) defining Mitsubishi classification.

Name of the size category	Range of the category (kg , eviscerated fresh weight)
T1	>4.5
T2	[3-4.5]
T3	[2-3]
T4	[1.5-2.0]
T5	[01.2-1.5]
T6	[0.8-1,2]
T7	[0.5-0.8]
T8	[0.3-0.5]
T9	[0.2-0.3]
T10 or Pulpo	≤0.2

profiles of the total capture for the analyzed period because, in this "factories" sample:
(1) the spatial cover is good (all the octopus landings sites in Senegal are present),
(2) the temporal cover is also exhaustively assured (the sample contains the principal factories which treat the octopus and which work without stopping throughout the year),
(3) the sampling ratio is high (the sample represents 52% of the total octopus catches from the whole of Senegal for the studied period).

Reliability of the commercial categories and distributions inside the categories

The commercial category sorting is subjected to a periodical "quality control" by the representatives of the purchasers. During this control, batches of octopuses already sorted and prepared for export are randomly under-sampled and then subjected to individual weighing. The results of these weighings were provided to us by several factories. These data enable to assess the quality of the practised sorting and thus the reliability of the commercial categories. These data also allow theoretical functions describing average distributions within each category (from T1 to T10) to be estimated. These intra-category functions allow the estimation of a distribution even much finer than the commercial classification, *e.g.* in 50g size classes. The access to this degree of resolution was useful at the pre-processing step (see below, section 2.6.).

2. Modelling

2.1. General principles

The general principles are those followed in Jouffre *et al.* (2002a):
- the modelling process is divided into three main steps. Calculations are programmed and carried out on Excel worksheets.
- the model is time based with a one-month time step.
- the natural mortality is estimated according to that of Caddy's method (Caddy, 1996).
- the weight vs age conversions are carried out on the basis of the growth model from Domain *et al.* (2000).

2.2. Three main steps

First step: Preparation of the data to obtain the total matrix of the catches in numbers per age using the data sources listed above.

Second step: Virtual Population Analysis (VPA), or cohort analysis, computed on Excel using Pope's (1972) approximation.

Third step: A short-term simulation model of the Thompson and Bell (1934) type, *i.e.* a "Yield per recruit" model. This model allows annual production for each of the "observed" annual recruitments to be estimated. Estimates are made according to several exploitation scenarios, including the "reference situation" (with no closure and no size limit) and other hypothetical ones (combining different closures varying in date and length with different minimum sizes of capture).

2.3. The one-month resolution option

For the majority of the exploited species, traditional analytical modelling of exploited populations is carried out using an annual basis. This step of time is unsuited to octopus taking into account the speed of the biological phenomena concerned: duration of the exploited phase is largely less than one year and speed of growth is higher than that of the majority of the exploited species (Domain *et al*., 2000). This is why monthly based calculations are chosen here, the result of a compromise between the preceding requirement (specific speed of the biological phenomena) and the necessity of indirect "aging" of octopuses via the weights. Lastly, the octopus capture data available for Senegal are compatible with this time-step.

2.4. Estimation of the natural mortality

Natural mortality (M) must be estimated to parameterize the analytical model. This estimate is made following the method suggested by Caddy (1996). This method is adapted to fecund species with a short lifespan, like octopus. If one admits an average lifespan close to one year, in agreement with recent work on this species in area (Domain *et al*. 2000; Jouffre *et al*, 2000), and an average fecundity ranging between 300,000 and 500,000 eggs per laying, in agreement with the values recorded by Mangold (1983) in her bibliographical review on the species, the method of Caddy gives a monthly value of M close to 0.25 if we consider the period corresponding to the exploited phase (from the 5th month to death). More precisely, the estimate of M varies from 0.244 to 0.255 according to whether average fecundity is estimated at 300,000 or 500,000 eggs. Consequently, a value of M equal to 0.25 can thus be regarded as a starting base acceptable for the model. The same value is also retained by Lanco (1999) and Jouffre *et al.* 2002a. Moreover, the uncertainty on M was subjected to a sensitivity analysis of the results provided by the model (see discussion).

2.5. An age-based modelling

For reasons on which we will return during the discussion, we choose the use of a method based on true cohorts (and not on “pseudo-cohort”, see for example Sparre and Venema 1996). This choice implies the calculations to be articulated on matrices “at ages”. Thus, the matrix of entry of VPA (*i.e*. matrix of the total catches-at-ages) is obtained during a first step of data pre-processing (detailed to the following section). Weight-to-age conversions are founded on the relation of *in situ* growth of Domain *et al.* (2000).

2.6. First step : Preparation of the data

From the data described above, several stages are necessary to obtain the matrix of the captures required by the VPA:

1) firstly, one carries out the extrapolation of the quantities from the factories sample, expressed in commercial categories (10 categories, Mitsubishi classification), to the total monthly captures for the whole country;

2) then, proceeding separately for each commercial category (successively from T1 to T10), one divides the total weight capture of the category in numbers of individuals per class of weights of fine amplitude (50g) using the “theoretical” or estimated average distribution of the category considered (cf. higher). Doing this, one obtains the ten matrices of weight frequencies, of 50g amplitudes (*i.e.* a matrix for each of the categories);

3) the ten preceding matrixes are summed to obtain a single matrix representing the monthly total capture by size classes of 50g;

4) finally that matrix is reorganized according to selected weight limits in order to allow a direct correspondence with monthly age groups (Table 2). These limits are chosen on the basis of the growth curve from Domain *et al.* (2000). On the basis of this new cutting pattern, conversion into age is made in a direct way (method known as “slicing”). One obtains at exit the complete table of the monthly catches-at-ages, which represents the data input of the analytical modelling itself. The last age is noted 14+ because it encompasses the 14 month and older animals.

2.7 Second step : Cohort analysis

The cohort analysis or VPA (virtual population analysis) is used here as an explanatory model of the past dynamics and as a means of estimating the input data required by the following stage

Table 2. Weight limits used for the determination of the age groups in month. The correspondences weight-ages are derived from the model of *in situ* growth of octopus of Senegal (Domain *et al*., 2000).

Weight range (g , eviscerated fresh weight)	Age range (month)
[50 - 100]	5
[100 - 150]	6
[150 - 250]	7
[250 - 350]	8
[350 - 550]	9
[550 - 850]	10
[850 - 1250]	11
[1250 - 1800]	12
[1800 - 2700]	13
>2700	Groupe 14+

(simulation), namely the vectors of monthly recruitment and fishing mortalities. The VPA is led in a version considering a resolution by the Pope approximation (Pope, 1972). So it is an ascending cohort analysis on complete tables, whose simplified formulas of the capture and survival equations are easily programmable in an Excel worksheet.
With the approximation of Pope, the survival equation is:

$$N_{a,t} = N_{a+1,\, t+1}.e^{-(Ma,t)} + C_{a,\, t}.e^{-(0.5Ma,t)}$$

where N represent total numbers of individuals in the population and C represent total captures (in numbers) carried out on this population, at various ages (a) and month (t) (or at the following ages and months : a+1 and t+1).

2.8 Third step : Short-term simulation model
Description of the model

The model used comes from Thompson and Bell (1934) and it is also described in Sparre and Venema (1996). The data inputted are:
- the matrix of fishing mortalities-at-ages, as estimated by the VPA (one uses this matrix without modification during the general evaluation of the observed or "actual" situations and by modifying it for the simulation of hypothetical fishing scenarios (see hereafter),
- the vector of the recruits per month, also estimated by the VPA,
- the vector of the total abundances of the stock, estimated by the VPA, for the first month of simulation (January 1996),

The additional parameters are: (1) the table of correspondence between weights and ages and (2) an estimate of the natural mortality vector M which is taken as equal to that used in the VPA.

The model makes it possible to predict the catch in numbers $[C_{a,t}]$, the production or yield $[Y_{a,t}]$ and the biomass $[B_{a,t}]$, using the following equations:

$$N_{a+1,\, t+1}. = N_{a,\, t}.e^{-(Ma,t + Fa,t)}$$

$$C_{a,t} = (N_{a,\, t} - N_{a+1,\, t+1}).(F_{a,t} /(M_{a,t}+ F_{a,t}))$$

$$Y_{a,t} = C_{a,t} \cdot w_a$$

with w_a, average individual weight at the age a.

$$B_{a,t} = N_{a,t} \cdot w_a$$

One then calculates the total annual production ($S_a\, S_t\, Y_{a,t}$) and the annual average biomass ($S_a\, [S_t\, B_{a,t}]/12$).

According to the logic defined by Thompson and Bell (1934) this system of equations allows one to analyze the effects produced by variations of the fishing effort, on the production and on the biomass of stock. This is done in the following way: In each equation one assigns to F a multiplicative factor mf. Then, one re-computes the annual production and the annual average biomass for various mf values, varying from 0 to 3. This principle is implemented in an initial step known as general assessment of the current exploitation or assessment "at constant exploitation diagram" (see hereafter).

General assessment of the current exploitation

In the logic of the model, the protocol defined above is followed first starting from the values of fishing mortality (Fi) estimated by the VPA and thus corresponding to the current exploitation diagram. This analysis makes it possible to establish a general diagnosis of the exploitation status for each of the four analyzed years and, consequently, to estimate the average situation over the four years. The results can be expressed using classical graphs representing the evolution of the annual production and the annual average biomass according to the effort multiplier (or "mf" factor, with mf=1 corresponding to the current or "observed" fishing effort).

These diagnoses, which are detailed in Jouffre *et al.* (2002a), are not the principal object of the present study which is focussed on hypothetical exploitation scenarios combining fishing closure with minimal sizes of capture. However, for a better comprehension of the general context they will be briefly recalled in the result section.

Principle of simulation of minimal sizes

To test the effects of minimal sizes of capture policies, the same general protocol is applied: the initial matrix of fishing mortalities (resulting from the VPA) is modified by cancellation (zero setting) of the mortalities at the ages which one wishes to preserve from fishing. In practice, the effects of various policies introducing the following minimal catch sizes: 100g then 150g, 250g, 350g, 500g and 800g (expressed in fresh weight not eviscerated), are simulated by cancellation of the fishing mortalities at the ages lower or equal to 5, 6, 7, 8, 9 and 10 months, respectively. The correspondences between eviscerated and uneviscerated weights are made using the relation of Fernandez *et al.* (1996).

Principle of simulation of fishing closures

In reality, the analyzed years (1996 to 1999) were in different situations regarding fishing closure. Indeed, in 1996 a closure took place from July 4th to July 20th. In 1997 the closure happened from June 1st to July 15th. In 1998 there was no closure and in 1999 the closure was located in the area of Mbour (Small Coast, in the south of Dakar) for the period from June 24th to July 10th.

For inter-annual comparisons of the effects of different fishing closure policies it is necessary to refer to a constant and unique situation (*i.e.* reference situation), the most convenient being naturally that of an exploitation without closure. For the years that have had a closure period, the simulation of the reference situation (without closure) is made by modifying some of the fishing mortalities (F) in the input of the simulation model (Thompson and Bell model): *i.e.* the F relating to the months concerned with closure (partially or completely closed months) are corrected. The corrections are determined after examination of the profile of the monthly captures by fisheries, the intra-annual evolution of the exploitation being different according to the years and fisheries (AF and IF). This was made and described in detail in Jouffre *et al*. 2002a. The same correction factors are used here. They are summarized in Table 3.

Table 3. Definition of the corrections carried out on the fishing mortalities (resulting from the VPA on the observed situations) in order to simulate the theoretical situations of reference (without fishing closure) for each year.

Year	Closure period	Corrections carried on F for no-closure simulations	Assumptions lying under the corrections
1996	4-20 July	July F vector multiplied by 1.5	Compensation of the 15 days closure, in a context where AF is still in launching phase (on a low level in June) and IF is in stable phase (from March to September).
1997	1 June-15 July	June F vector assumed to be equal to the May one; July F vector multiplied by 1.5	The hypothetical without closure June is estimated that by the observed previous month situation, in a context where IF and AF seemed both stabilized on a level raised since May. The hypothetical July fishing mortality is increased moderately because the observed captures carried out at the end of July are those of a recovery after closure.
1998	No closure	No correction	Reference situation conforms to reality carriage return.
1999	24 June-10 July Mbour district only	July F vector multiplied by 1.5	Situation overall comparable with that of 1996 (total activity in ascending phase).

From this reference situation, others closure configurations can then be simulated according to the same general principle as for the minimal sizes, *i.e.* by using the Thompson and Bell model after having cancelled fishing mortalities of the months for which one wishes to simulate a closure. For each simulated closure, the total production over the year (estimated by the model) is compared with that obtained in the corresponding reference situation (without closure).

2.9. Sensitivity analyses

The sensitivity analyses relate to the parameters which pose problems to estimate: here that relates mainly to the natural mortality. The sensitivity analysis is carried out according to the same principle as for the simulations of various fishing scenarios. For a modified value of the parameter (or vector) of natural mortality, all the data processing sequence is thus renewed with the new value. Indeed, in order to preserve the coherence of modelling, the assumptions concerning parameterization of the models must remain unchanged from the VPA to final simulations.

RESULTS

General diagnosis on the level of exploitation for the analyzed years

This diagnosis has already been a published (Jouffre *et al*. 2002a), therefore its result is not detailed nor discussed in the present study which is interested in scenarios of hypothetical exploitations, those combining fishing closure with minimal sizes of capture. Figure 1 is thus a simple recall intended to show that, for the four analyzed years, the model seems to reveal situations of full exploitation, with sometimes a light overexploitation (growth overexploitation). On the other hand, no risk of recruitment overexploitation appears probable.

Simulations combining fishing closure with minimal sizes of capture

Table 4 gives the percentage of gains (positive numbers) or losses (negative numbers) for expected production values compared to annual reference values[1], according to several hypothetical scenarios combining closure and minimum size policies. In spite of a certain interannual variability of the results, the best configuration seems to be a two-month fishing closure in July–August combined with a 350g or 500g minimum size policy.

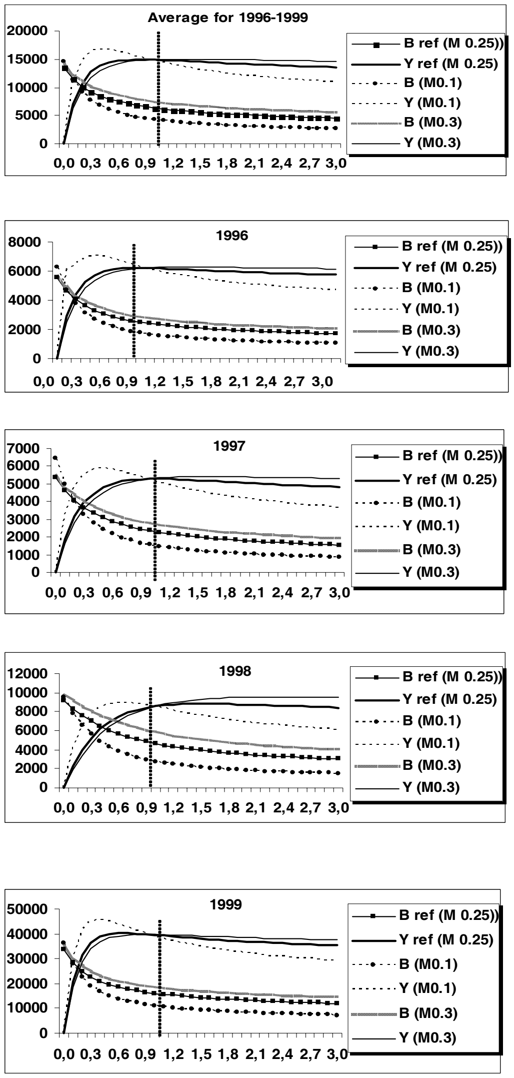

Figure 1. Estimate of the instantaneous biomasses B and the annual yield Y (in metric t) derived from various levels of efforts (with mf in abscissa varying from 0 to 3, actual effort corresponding to mf=1) and under various assumptions of natural mortality M (*i.e.* 0.25, 0.1 and 0.3).

[1] Calculation of these percentages are following the formula: P = 100*(HY-RY)/RY, where HY = yield from hypothetical scenario and RY = yield from reference situation.

Table 4. Percentage of gains (positive numbers) or losses (negative numbers) for expected production values compared to annual reference values (without any closure or size policy), according to several hypothetical scenarios combining closure and minimum size policies.

Reference period and corresponding production (in metric tons)	First month of the closure	Duration of the closure in months(mo) and minimal size in grams (g)								
			250 g			350g			500g	
		1 mo	2mo	3mo	1 mo	2mo	3mo	1 mo	2mo	3mo
1996-1999(15807t)	May	1.5%	2.4%	8.1%	3.9%	4.3%	9.2%	9.2%	8.9%	11.2%
	June	3.0%	8.9%	14.9%	5.1%	10.2%	15.7%	10.0%	12.8%	16.1%
	July	7.5%	13.3%	7.4%	9.3%	14.9%	8.4%	13.0%	16.8%	8.2%
	August	5.5%	13.3%	-5.4%	8.1%	7.6%	-3.7%	13.1%	12.0%	-1.8%
	September	2.3%	-1.5%	-20.8%	4.9%	0.6%	-22.0%	10.6%	4.5%	28.0%
1996(6181t)	May	2.3%	2.4%	9.4%	5.69%	5.3%	10.9%	12.0%	10.8%	12.9%
	June	2.3%	9.4%	16.8%	5.4%	11.1%	17.5%	11.4%	12.8%	17.3%
	July	8.5%	15.6%	5.7%	10.8%	17.2%	6.4%	14.9%	18.8%	3.7%
	August	5.6%	15.6%	-14.1%	9.4%	7.0%	13.5%	15.4%	11.5%	16.0%
	September	1.4%	-5.1%	-13.9%	5.2%	-3.8%	-17.1%	11.8%	-2.5%	26.0%
1997(5297t)	May	4.0%	4.0%	4.9%	7.2%	6.7%	6.7%	13.4%	11.2%	8.1%
	June	4.6%	7.6%	8.8%	8.3%	10.9%	11.2%	15.7%	16.2%	13.2%
	July	6.0%	7.3%	2.8%	9.3%	10.1%	4.6%	15.5%	14.3%	4.2%
	August	5.1%	7.3%	-3.7%	8.6%	8.1%	-2.6%	15.4%	12.9%	-3.9%
	Sepember	3.5%	-1.4%	-3.0%	7.5%	1.9%	1.3%	14.1%	5.0%	2.5%
1998(8571t)	May	0.9%	0.9%	1.6%	1.5%	1.3%	1.7%	-0.6%	-1.1%	-1.7%
	June	1.3%	2.1%	-1.8%	2.0%	2.5%	-1.2%	0.4%	0.0%	-4.5%
	July	2.0%	-1.7%	-21.2%	2.5%	-0.9%	-21.1%	0.4%	-3.8%	-24.1%
	August	-1.9%	-1.7%	-50.2%	-0.7%	-18.3%	-52.2%	-2.7%	-20.6%	55.8%
	September	-7.7%	-24.9%	-27.4%	-7.8%	-27.4%	-30.4%	-9.9%	-34.1%	38.6%
1999(39179t)	May	1.2%	2.4%	9.8%	3.7%	4.5%	11.0%	10.4%	10.4%	14.3%
	June	3.2%	10.6%	19.4%	5.4%	11.9%	20.1%	11.4%	15.4%	21.3%
	July	8.7%	17.0%	14.6%	10.6%	18.6%	15.8%	15.2%	21.3%	16.5%
	August	7.1%	17.0%	5.6%	9.8%	13.3%	8.5%	15.9%	19.2%	12.7%
	September	4.4%	4.3%	-22.8%	7.3%	7.3%	-24.1%	14.4%	14.1%	-30.1%

Nevertheless, it must be pointed out that even the best strategy gives some negative result (see year 1998, Table 4).
Table 5 gives the sensitivity of the above results to estimated natural mortality (M) in order to try and evaluate the impact of the uncertainty of this parameter.

DISCUSSION

We will discuss first the methodological aspects and then those concerning fisheries management.

Age-based modelling

The initial catch data are structured in weight (commercial categories) and analytical methods based directly on size (or in weight, which returns to same) do exist in fishery science. Thus, to model on this basis could seem a tempting option, especially if one considers that weight-to-age conversion is always a delicate operation because it introduces additional uncertainty. However, the methods based on the sizes imply modelling on pseudo-cohorts and not on true cohorts, and the recourse to the pseudo-cohort goes with two major constraints. Firstly, it implies the acceptance of assumptions concerning the constancy of recruitment and the constancy of the exploitation diagram. In fact, it is necessary for all the cohorts to undergo the same "history". These assumptions are impossible to assume in the present situation which relates to a typically seasonal exploitation and to a recruitment pattern also known to be strongly seasonal (Caverivière *et al.*, 2000). In

Table 5. Sensitivity of the above results to the natural mortality parameter (M): Percentage of gains (positive numbers) or losses (negative numbers) for expected production values compared to annual reference values (without any closure or size policy), according to several hypothetical scenarios combining a two-month fishing closure in July-August with minimum size policies.

Reference period and corresponding production(in metric tons)	Minimal Size	M=0.1	M=0.25	M=0.3
1996-1999(15807t)	250g	39%	13%	6%
	350g	45%	15%	7%
	500g	56%	17%	7%
1996(6181t)	250g	46%	16%	7%
	350g	53%	17%	8%
	500g	66%	19%	6%
1997(5297t)	250g	35%	7%	1%
	350g	46%	10%	4%
	500g	69%	14%	1%
1998(8571t)	250g	24%	-2%	-9%
	350g	31%	-1%	-10%
	500g	41%	-4%	-16%
1999(39179t)	250g	42%	17%	10%
	350g	47%	19%	11%
	500g	57%	21%	12%

particular, this recruitment cannot be assimilated to a constant phenomenon, nor even a purely random one, especially at the inter-monthly scale defined by the model temporal step of calculation. Secondly, our modelling must be able to simulate changes in the exploitation from one month to another. For example, in this study, various scenarios combining a closure and limiting size of exploitation are simulated. It is obvious that such a simulation is not possible with methods postulating constancy of the exploitation diagram. For these two principal reasons, a modelling option based on true cohorts (and thus on ages) appears inevitable.

Use of the *in situ* growth from Domain *et al*. (2000)

The recourse to (and consequently the choice of) a growth model is essential in the analytical approach. Considering the double influence of it, (1) at the beginning of the analysis when preparing the catches-at-ages matrix and then (2) at the end of the process for calculation of the simulated biomass productions, it is advisable to reconsider this question a little.

Two reasons prevailed in the choice of the model of Domain *et al*. (2000). Firstly this model is the only one to be established on the Senegalese stock. Secondly it is the only *in situ* growth model (to date and to our knowledge) to be obtained for this species by direct monitoring of individual weights, as the technique of tag-recapture allows it. This reason appears determining to us. Indeed, the very great individual variability of *Octopus vulgaris* growth rates, already underlined by various authors (Mangold, 1983; Forsythe and Van Heukelem, 1987) and still confirmed in Senegal by Domain *et al.* (2000) provides a solid argument to prefer this model to others founded on modal decompositions from population monitoring.

Estimate of natural mortality

The taking into account of natural mortality M, and in particular its estimate using rates independent of those of fishing mortality, constitutes a delicate point of analytical modelling in fisheries biology. Concerning octopus, an additional difficulty lies in the fact that there are very few experiments or work available in the literature and thus the expertise concerning the estimate of this parameter M[2] for octopus is missing. Consequently, the uncertainty attached to this estimate is perhaps the principal factor limiting the precision of the conclusions to await from analytical models on octopus. In the current state of the analyses, the only way likely to improve the situation seems to be the multiplication of the similar case studies on the same species. These similar studies should deal of course on other stocks but also on the present one for a longer period, so that the diversity of the analyzed situations results in reducing the extent of uncertainty on M.

Here, the range of the values tested on M rises directly from preceding work (Jouffre *et al*. 2002a). Some explorations of the cohort analysis made there tended to show that the extent of the possible values for this parameter should be included in the range considered here (from M = 0.1 to M = 0.3). Apart from this range it was indeed impossible to fit a coherent cohort analysis to the observed catches data.

A non self-regenerating model

The present model is not of a self-regenerating type. In other words it assumes that recruitment is not affected by fishing mortality. We can consider this assumption to be acceptable here, considering former studies on the same stock (Caverivière *et al.* 2002) which did not reveal any correlation between the spawning stock biomass and the recruitment of the following year. On the contrary it seems to us that trying to model the influence of fishing mortalities and consequently the influence of biomasses of a given year (year i) on future recruitments (at year i+1) will be dangerous here because the stock-recruitment relationship is particularly difficult to encircle in the case of this population. The recruitment of an exceptional intensity which occurred in 1999[3] is particularly significant from this point of view. The very unusual biomasses of 1999 were not followed by observable positive effects on its descendant, since the following year was rather a bad year for octopus fishing. It seems more plausible on the contrary that, by exhausting in drastic manner their usual prey (in particular the stocks of bivalves (sp) which life duration is higher than their predatory octopuses), this disproportionate mother-population could have had a considerable limiting effect on the survival conditions of her own offspring.

The "no-closure" situation as a reference

As seen before, the situation without closing was taken as reference to calculate production gains or losses consequent to hypothetical policy effects and to compare them from year to year. For the years having actually known a closure, the necessary recourse to this reference implies its estimate through modelling. The difficulty lies here in the numerical expression (in entry of the simulation model) of a no-closure assumption on the basis of an observed situation with closure. Conversely, on the basis of a real situation without closure, it is theoretically easier to simulate a hypothetical closure: that can be made, in a simple and logical way, *i.e*. by cancellation of the fishing mortalities for the corresponding period. Even if in both cases, the question is to consider a correction on fishing mortalities, it is obvious that this correction implies a greater arbitrary part in the first case than in the second one[4]. One can estimate, however, that this problem has a weak incidence on the results presented here. Indeed, the results from Jouffre *et al*. 2002b tend to show that one closure duration lower than two months (such as real closures over the analyzed period) would be of limited impact on the related annual production value.

As in previous simulations of separate effects of fishing closure *vs* minimum size (in Jouffre *et al*. 2002b and 2002a respectively), the present results focus on the instability of the responses in the case of a combined policy as a function of recruitment each year. According to the model, even the best configuration, namely a 350g or 500g minimum size policy combined with a two-month fishing closure in July-August, would not ensure a substantial improvement in production each year: for example in 1998 it would have resulted in a loss rather than a gain.

Nevertheless, this particular combination seems to be "more or less" profitable (for three out of four of the observed years), resulting in

[2] or more exactly of a vector of M by age.

[3] Situation having involved captures ten times higher than the average of the previous years (Diallo *et al*. 2002)

[4] in the second case the target value of the F (zero) is predetermined by the assumption of non fishing.

an overall gain in production for the whole period. According to simulations computed with a "median" value for the natural mortality parameter M (M=0.25) the gain is estimated to be around 15%. But it should be noted that the model does not allow the gain to be determined without a large range of uncertainty, as shown by sensitivity analysis using extreme values of M.

Considering both the uncertainty linked to the modelling method and the interannual variability of the recruitment that led to considerable variability of the response of the stock to policies dealing with size and closure, the present results should thus be considered with caution. At the end of this study, what does appear to be relatively clear (because remaining relatively constant in the different simulations) is the best policy combining size limits with closure (July-August closure with 350 or 500g minimum size). It is more difficult to evaluate expected average gains. A significant improvement in this point can probably be achieved by increasing the number of similar simulations based on other observed situations (involving data for other periods in Senegal and/or other octopus stocks in West Africa).

This combined strategy seems better than either alone if we compare its expected gains with those obtained in previous simulations of separated effects (Jouffre *et al*. 2002 a and b). Nevertheless this point is to be considered with care in the absence of a wider range of studied years (*i.e*. recruitment cases) and because of the uncertainties discussed above.

Reliability of the diagnoses and of the results of simulated scenarios

In the significant uncertainty attached to some of the results presented here and in Jouffre *et al*. 2002a, there is (1) the part due to the estimate of the parameters of the model and which can be improved, (2) the part due to the natural inter-annual variability of the observed situations. Through the studied case (on the octopus population exploited in Senegal) we are convinced that the natural variability of type (2) is probably very important.

Consequently, whatever the future model improvements will bring in terms of reduction of the methodological uncertainty of type (1), the quantified response to the question of changes in the exploitation diagram in octopus fisheries will probably always keep a significant level of intrinsic uncertainty. Even if fishery modelling is also a way to reduce fishery management risks, it is probably useful to recall at the end of the present study that management decisions concerning octopus exploitation will have to deal with strategies integrating this high factor of risk, logically significantly higher than those on resources of lower natural variability.

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REFERENCES

Caddy, J.F. 1996. Modelling natural mortality with age in short-lived invertebrate populations: definition of a strategy of gnomonic time division. Aquat. Living Resour., **9**: 197–207.

Caverivière, A. 1990. Étude de la pêche du poulpe (*Octopus vulgaris*) dans les eaux côtières de la Gambie et du Sénégal. L'explosion démographique de l'été 1986. Centre Rech. Océanogr. Dakar-Thiaroye, Doc. Sci., **116**: 1–42.

Caverivière, A. 1994. Le poulpe (*Octopus vulgaris*) au Sénégal : une nouvelle ressource. **In**: M. Barry-Gérard, T. Diouf and A. Fonteneau (ed.). L'évaluation des ressources exploitables par la pêche artisanale sénégalaise. tome II. Paris, Orstom, Colloques et Séminaires. pp. 245–256.

Caverivière A., M. Diallo, F. Domain and D. Jouffre. 2000. Répartition côtière du poulpe *Octopus vulgaris* sur la Petite Côte du Sénégal et son exploitation par la pêche artisanale. **In**: D. Gascuel, P. Chavance, N. Bez and A. Biseau (eds.). "Les Espaces de l'halieutique". 4ème forum halieumétrique, IRD éditions, Paris, coll. Colloques et séminaires. pp. 269–283.

Caverivière A., M. Thiam and D. Jouffre (eds). 2002. Le poulpe commun *Octopus vulgaris*. Sénégal et côtes nord-ouest africaines. Editions IRD, Paris, Colloques et séminaires : 385 p.

Dia, A. D., M. Diop and D. Jouffre. 1996. Pêcheries au coeur d'un enjeu de développement, les pêcheries démersales mauritaniennes du poulpe et des crevettes côtières. Confrontation entre stratégies des acteurs et mesures institutionnelles: Eléments d'analyse, **In**: IIFET 96 symposium acts, Marrakech, 1–4 juillet 1996, International Institute for Fisheries Economics and Trade : 22 p.

Dia, M. A. 1988. Biologie et exploitation du poulpe (*Octopus vulgaris*) (Cuvier, 1797) des côtes mauritaniennes. Univers. Bretagne Occidentale, Thèse Doct. 3e cycle, 164p.

F.A.O. 1997. Yearbook of fisheries statistics. Catches and landings, F.A.O. Fish. Ser. 80 : 713 p.

Diallo, M., D. Jouffre, A. Caverivière and M. Thiam, 2002. The demographic explosion of *Octopus vulgaris* in Senegal during the 1999 summer. Bulletin of Marine Science. Vol. 71, No. 2, pp. 1063–1065

Domain, F., D. Jouffre and A. Caverivière. 2000. Growth of Octopus vulgaris from tagging in Senegalese waters. J. Mar. Biol. Ass. U.K., **80**(4): 699–706.

Faure, V. 2000. Dynamiques spatiale et temporelle des populations de poulpes (*Octopus vulgaris*) en Afrique de l'Ouest : Influence des fluctuations environnementales et des relations interspécifiques. Thèse doc., univ. Montpellier-II, 403 p.

Fernandez-Nunez, M., C. Hernandez-Gonzalez, C. Raya and E. Balguerias. 1996. Reproductive biology of octopus Octopus vulgaris Cuvier, 1797, from North-Western African coast (21°N–26°N). Shellfish Committee C.M. K/15 : 19pp.

Ferraris, J., V. Fonteneau and O. SY. 1993. Structuration de la base de données « Pêche artisanale » et chaîne de traitement informatique. Archive du Centre Rech. Océanogr. Dakar-Thiaroye, n°192: 39p.

Ferraris, J., B. Samb and M. Thiam. 1994. Les statistiques de pêche au CRODT: description des systèmes de collecte et de traitement des données **In**: M. Barry-Gérard, T. Diouf and A. Fonteneau (eds.). L'évaluation des ressources exploitables par la pêche artisanale sénégalaise. Orstom éditions, Paris, coll. Colloques et séminaires, Tome **2**: 73–93.

Forsythe, J. and W. Van Heukelem. 1987. Growth. **In**: P.R. Boyle (ed.). Cephalopod life cycles, vol. II. Comparative reviews. Academic Press, London. pp. 135–156.

Hill, S. and D. J. Agnew. 2002. Optimal harvest strategies for single-cohort squid populations. Bulletin of Marine Science, **71**(1): 371–381.

Jouffre, D. and C.A. Inejih. 1997. La pêche au poulpe en zone Nord Ouest Africaine : surexploitation? **In**: pré-acte du 3ème Forum Halieumétrique, Association Française d'Halieumétrie, Montpellier (France), 1–3 juillet 1997, « La Surexploitation » doc. AFH-ORSTOM: 8pp.

Jouffre, D., C. Inejih and M. Simier. 2000. Cycle biologique du poulpe (Octopus vulgaris) au large du Cap-Blanc (Mauritanie). **In**: D. Gascuel, P. Chavance, N. Bez and A. Biseau (eds.). “Les Espaces de l’halieutique”. 4ème forum halieumétrique, IRD éditions, Paris, coll. Colloques et séminaires. pp. 264–267.

Jouffre, D., S. Lanco, D. Gascuel and A. Caverivière. 2002(a). Niveaux d’exploitation des stocks de poulpes du Sénégal de 1996 à 1999 et tailles minimales de captures : une évaluation par modélisation analytique. **In**: A. Caverivière, M. Thiam and D. Jouffre. (eds.). Le poulpe commun *Octopus vulgaris*. Sénégal et côtes nord-ouest africaines. Paris, IRD, coll. Colloques et Séminaires. pp. 269–295.

Jouffre D., S. Lanco, D. Gascuel and A. Caverivière, 2002 (b). Evaluation par modélisation analytique des effets de périodes de fermeture de la pêche du poulpe au Sénégal *In ibid*. Paris, IRD, coll. Colloques et Séminaires. pp. 297–316.

Lanco, S. 1999. Adaptation d’un modèle structural à une ressource instable en vue de mesurer l’impact de fermetures de pêche. Application au stock de poulpe (*Octopus vulgaris*, Cuvier 1797) sénégalais, Mémoire de D.E.A. « Océanologie biologique et Environnement marin », Ecole Nationale Supérieur Agronomiques de Rennes: 49p (+ annexes).

Mangold, K. 1983. Octopus vulgaris. **In**: P.R. Boyle (ed.). Cephalopod Life Cycles, Species Accounts., Academic Press (London), Vol I.: 335–364.

Pope, J.G. 1972. An investigation of the accuracy of virtual population analysis using cohort analysis. ICNAF Res. Bull. **9**: 65–74.

Ségnane, P. 1999. Diagnostic des systèmes statistiques de traitement des données statistiques des pêches maritimes. Rapport d’étude DOPM-SCAC, Dir. de l’Océanogr. et des Pêch. Marit . (Dakar): 139p.

Sparre, P. and S. Venema. 1996. Introduction à l’évaluation des stocks de poissons tropicaux. Première partie : Manuel, FAO (Rome), Document technique sur les pêches, No 306/1, Rev. 1. : 401p.

Sy, O. 1995. Analyse critique des données statistiques fournies par la DOPM dans le cadre de la pêche artisanale au Sénégal., Mémoire de fin d’étude d’ingénieur, Ecole Nationale d’Economie Appliquée (Dakar): 85p + annexes.

Thompson, W.F. and F.H. Bell F.H. 1934. Biological statistics of the pacific halibut fishery. 2. Effect of changes in intensity upon total yield and yield per unit of gear. Rep. Int. Fish. (Pacific Halibut) Com., (8): 49 p.