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Corrected pseudo-cohort analysis: Principles, interest and application in West-African fisheries

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1. Introduction

Cohort analysis (Gulland, 1965; Murphy, 1965) is a method based on catch at age data that estimates instantaneous rates of fishing mortality (F) that have affected the stock over time, and past numbers (N) of the stock. It relies on the only assumption that total mortality rates (natural and fishing mortality) of a specific cohort can be represented by a constant value for a given time interval. Cohort analysis is generally conducted in inverse mode because it has the advantage to integrate an essential convergence property (Jones, 1961 in Mesnil, 1980). The relative error linked to the estimation process of a terminal value of fishing mortality F_T (arbitrarily chosen or tuned on exogenous data) tends to decrease when the demographic parameters (number and mortality) of the population youngest age-classes are estimated. For the oldest ages, the convergence is weak but the consequences of these uncertainties decrease with the fishing pressure on the stock, the oldest age groups having a low importance in the catch (Laurec, 1993).

The application of cohort analysis requires the knowledge of the catch demographic structure for several years. In numerous West-African fisheries, such time series are rarely available. Pseudo-cohort analysis can then be conducted with a few year data or even only one. This analysis assumes that the stock and the fisheries are at equilibrium, i.e. recruitment and mortalities at age are assumed constant for the years preceding the year of interest. When this hypothesis is false (note that it is often the case), we easily show that the analysis conducts to strongly biased results. In particular, in period of fisheries expansion (increasing efforts), fishing mortalities can be largely under-estimated, leading to an over-optimistic diagnosis that can have severe consequences. To overcome this strong hypothesis, Laurec and Santarelli-Chaurand (1986) proposed an algorithm that substitutes to the constant mortality at age assumption a constant catchability at age assumption. This assumption is less constraining and does not have the bad consequences mentioned above. Although less common, it is also possible to include in the model interannual variations in recruitment when some indices are available. The method enables the user to take into account potential changes in fishing effort and/or recruitment to correct the estimates derived from equilibrium assumptions. Corrected pseudo-cohort analysis was used as a first approach of assessment for different stocks for which few information was available (Santarelli-Chaurand, 1985; Bertignac, 1988; Lorance et al., 2001), in particular for marine resources of West Africa (Sidibé, 2003; Sidibé et al., 2003; Laurans, 2005) using the ANACO FAO software (Mesnil, 1988).

The objectives of the sub-activity "Corrected pseudo-cohort analysis" within the activity "Data-poor models" are to: (1) present the hypotheses, principles and equations of the corrected pseudo-cohort analysis, (2) develop the method with the free software R, (3) apply the method to the Guinean bobo croaker (*Pseudotolithus elongatus*), the Moroccan sardine (*Sardina pilchardus*), the Moroccan white hake (*Merluccius merluccius*), and the Senegalese octopus (*Octopus vulgaris*) in order to emphasize its interest in terms of assessment for some West-African fisheries. The R scripts as well as a detailed example are given in appendix. A systematic sensitivity analysis to natural mortality rates and terminal fishing mortality was performed, allowing assessing result robustness to the major assumptions made for each case-study.

2. Recalls

2.1. Definitions

Cohort. A cohort is defined as all the individuals of a given stock, born on a given period. In simple cases, there is only a reproduction season each year and therefore a cohort each year. The cohort is then defined either by its year of birth, either by its year of recruitment.

Hence, all animals of a cohort belong to the same age-group, and naturally move from one age-class to another each year. The stock is composed at a given time of the different cohorts corresponding to the different age-groups.

Pseudo-cohort. A pseudo-cohort is defined as all the individuals observed at successive ages, not from one year to another through the lifetime of a real cohort, but for a specific year.

If recruitments and mortality rates at age have been similar from one year to another during the period of interest, the stock is considered at equilibrium and the states of the pseudo-cohort at successive ages are equivalent to any of the cohorts of the stock through time.

2.2. Cohort analysis equations

Cohort analysis is based on two essential equations: the survival and catch equations. A year time step is generally used although considering another time step and several reproduction periods during this time step would poorly affect the equation formalism (Laurec, 1993).

The survival equation implies that the decrease of the number of an annual class is an exponential function of time:

$$N_{a+1,t+1} = N_{a,t} \exp\left(-\left(F_{a,t} + M_{a,t}\right)\right) \tag{1}$$

where N represents the number of fish, a is the age, t is the year, F is the fishing mortality rate and M is the natural mortality rate.

The catch equation expresses the fact that the number of individuals caught during a time period t is proportional to the cohort mean number:

$$C_{a,t} = \frac{F_{a,t}}{F_{a,t} + M_{a,t}} N_{a,t} \left(1 - \exp\left(-\left(F_{a,t} + M_{a,t}\right)\right)\right) \tag{2}$$

where C represents the catches.

From these equations, it is possible to establish a relationship (3) that allows to deduce the stock numbers at each age (N_a) and the fishing mortalities (F_a) from the knowledge on catch ($C_{a,t}$) and natural mortality ($M_{a,t}$):

$$N_{a+1,t+1} = C_{a,t} \frac{\left(F_{a,t} + M_{a,t}\right)\exp\left(-\left(F_{a,t} + M_{a,t}\right)\right)}{F_{a,t}\left(1 - \exp\left(-\left(F_{a,t} + M_{a,t}\right)\right)\right)} \tag{3}$$

2.3. Non corrected pseudo-cohort analysis

"Classic" pseudo-cohort analysis assumes that recruitment and fishing mortalities at each age remained constant during the period of exploitation that have led to the observed catch data. This equilibrium assumption allows us to estimate simply the stock numbers N and fishing mortalities F due to the fishing fleets. The estimate relies on equations (1) and (2) and requires to be initialised by a fishing mortality value F_A for terminal age. The estimate of fishing mortality at age a from $M_{a,t}$, $C_{a,t}$ and $N_{a+1,t+1}$ requires an iterative calculus because it is impossible to analytically express $F_{a,t}$ as a function of these parameters. The 'optim' function of the R software (R Development Core Team, 2006) is used to estimate the value of F at each age. The solving process is summarized in Figure 1a.

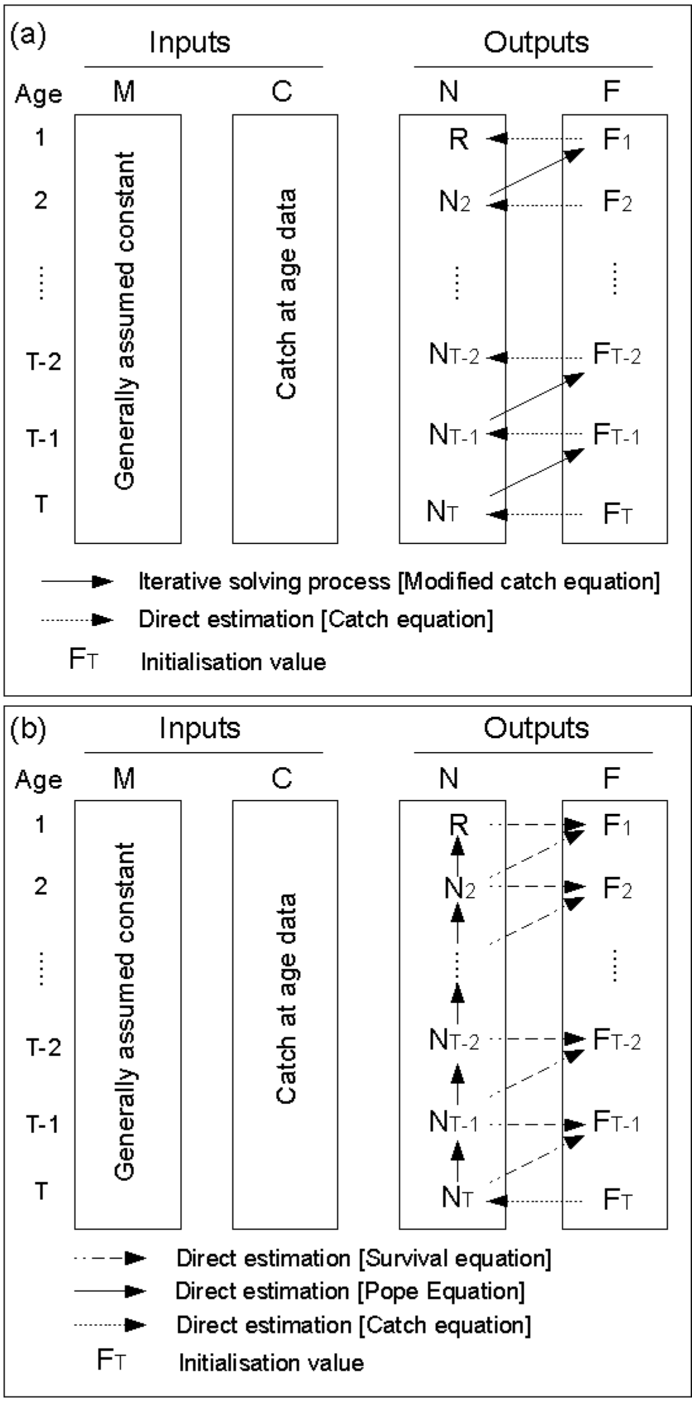


Fig. 1. Scheme representing the estimate of fish numbers and fishing mortality rates at age through (a) "classic" pseudo-cohort analysis (b) pseudo-cohort analysis based on Pope (1972) approximation.

Pseudo-cohort analysis can also be conducted based on Pope (1972) approximation that enables to directly estimate fish numbers from natural mortality rates (generally assumed constant at each age) and catch (Fig. 1b):

$$N_{a,t} = N_{a+1,t+1} \exp\left(M_{a,t}\right) + C_{a,t} \exp\left(\frac{M_{a,t}}{2}\right) \quad (4)$$

where a is age, N represents the numbers, M the natural mortality rates and C the catches.

In a second step, fishing mortalities are deduced from fish numbers from survival equation (Eq. 1). Pope (1972) approximation is considered acceptable for F values less than 1.2 and M values not exceeding 0.3. Within these limits, the relative error on fish numbers N does not exceed 4 % compared to the results of the general method.

3. Corrected pseudo-cohort analysis

3.1. Initial data

Initial data required for solving the model are:

- $C_{a,g,T}$: catch at age a, for métier g and final year T,
- $E_{g,t}$: fishing effort of métier g for year t,
- M_a: natural mortality assumed constant for age a whatever the year,
- R_t: recruitment at year t (R_T for the final year),

3.2. Solving principles

Compared to current ascendant (or indirect) methods used for solving the cohort analysis, the corrected pseudo-cohort analysis is conducted in descending mode (or direct), i.e. from the youngest to the oldest exploited age-groups. It relies on an iterative process that is based on survival and catch equations reformulation.

- The catch equation allows to estimate fishing mortality rates F via an iterative process, by initialising the calculus with a recruitment value R following the catch equation:

$$C_{a,T} = \frac{F_{a,T}}{F_{a,T} + M_{a,T}} N_{a,T} \left(1 - \exp\left(-\left(F_{a,T} + M_{a,T}\right)\right)\right) \tag{5}$$

where $C_{a,T}$, $N_{a,T}$ and $F_{a,T}$ respectively represent catch, number and fishing mortality at age a for the final available year T and M_a is the natural mortality, assumed constant at each age for each year.

- Fishing mortality $F_{a,T,g}$ at age a for year T and métier g is estimated as the ratio of the métier g catches on total catches, following the equation:

$$F_{a,T,g} = F_{a,T} \frac{C_{a,T,g}}{C_{a,T}} \tag{6}$$

where $F_{a,T}$ has been estimated before (Eq. 5), $C_{a,T,g}$ represents the catches at age a for year T and the métier g and $C_{a,T}$ represents the total catches at age a for year T.

- Based on the estimate of $F_{a,T}$, catchability $q_{a,g}$ at age a for each métier g is estimated following the separability assumption:

$$q_{a,g} = \frac{F_{a,T,g}}{E_{T,g}} \tag{7}$$

where $E_{T,g}$ is the fishing effort of métier g for year T.

- Based on the catchability and fishing mortality, the survival equation allows to estimate the fish number at each age:

$$N_{a,T} = R_T \exp - \left(\sum_{k=1}^{a-1} \left(\sum_{g=1}^{G} q_{k,g} E_{T-(a-k),g} \right) + M_k \right) \tag{8}$$

where $N_{a,T}$ represents the number at age a in year T, R_T is the recruitment for year T, G is the number of métiers, $q_{k,g}$ is the catchability at age k of métier g and $E_{T-(a-k)}$ is the fishing effort of métier g for year T-(a-k).

Note that the method is often used considering a unique fleet for the fishery, which obviously simplifies the equations. It remains that the separability assumption is less constraining when a métier is clearly defined.

3.3. Correcting for variations in recruitment

When a time series giving information on interannual variations in recruitment is available (e.g. commercial catch per unit effort for the first age-class), recruitment R_t can be expressed relative to recruitment R_T of the final year and available recruitment indices IR:

$$R_t = R_T \frac{IR_t}{IR_T} \tag{9}$$

The equation (8) is then re-expressed following:

$$N_{a,T} = R_t \exp - \left(\sum_{k=1}^{a-1} \left(\sum_{g=1}^{G} q_{k,g} E_{T-(a-k),g} \right) + M_k \right) \tag{10}$$

The solving process used to estimate fish numbers N and fishing mortalities F from the initial value of recruitment R_T of the final year T can be summarized in figure 2.

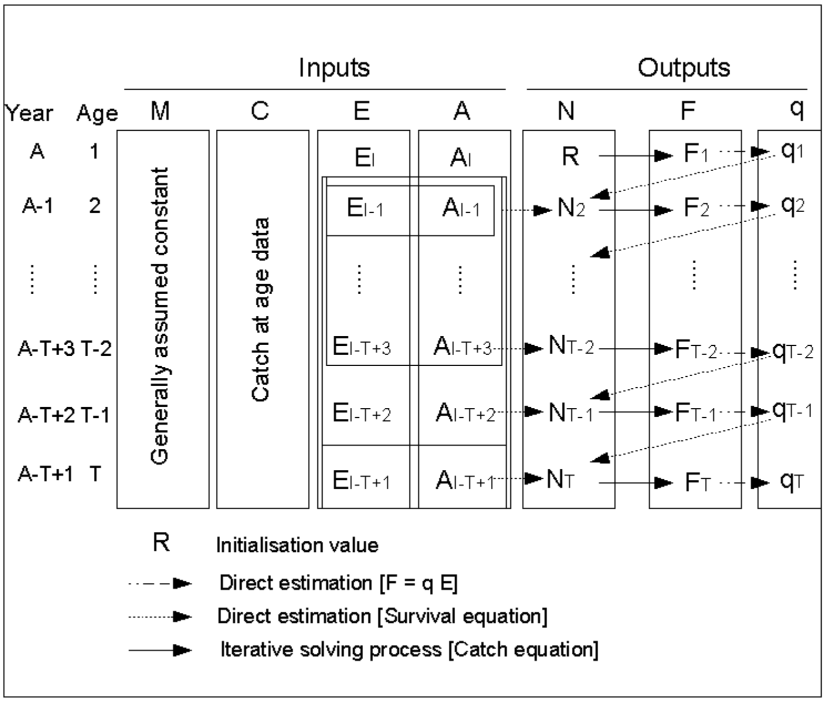


Fig. 2. Scheme representing the estimate of fish numbers and fishing mortality rates at age through a corrected pseudo-cohort analysis.

The initialisation of the solving procedure requires to introduce either a value of recruitment R for the final year T, either an estimate of the fishing mortality or catchability at age for the recruitment. In order to be in the "classical" conditions of cohort analysis, the initialisation is made here by choosing the terminal fishing mortality, an iterative process within the solving procedure allowing to estimate the recruitment that conducts to the selected terminal F (Mesnil, 1988).

4. Case studies

4.1. Materials and Methods

Data required for corrected pseudo-cohort analysis consist in catch at age data for a given year, a time series of relative fishing effort and/or relative index of recruitment and values of natural mortality at age (see above).

Guinean bobo croaker

The bobo croaker (*Pseudotolithus elongatus*) is a commercially important demersal species from the Scianidae family distributed along west-African coasts from Senegal to Angola. The case-study of the Guinean bobo croaker was fully considered by Sidibé (2003) but will be presented here since it emphasizes the interest of the method for demersal fish species in data-poor situations such as found in Guinea.

Corrected pseudo-cohort analysis was performed for the stock of Guinean bobo croaker for the period 1995-2000. Catch statistics were extracted from the observatory system of the Centre National des Sciences Halieutiques de Boussoura (CNSHB). Due to the absence of a regular monitoring in size data sampled, catch at age were estimated for a mean year 1995-2000 (Table I) by aggregating available size data and allocating them to each age through length/age conversion (Sidibé, 2003). The rate of natural mortality (M) was set to 0.28. A value of 0.35 based on the longevity method (Sidibé, 2003) was also considered for sensitivity analysis. Recruitment was assumed constant from 1995 to 2000. The increase observed in the nominal fishing effort, i.e. number of fishing vessels, in the Guinean EEZ for the period 1995-2000 was included in the analysis (Sidibé, 2003). A terminal fishing mortality of 0.8 was used.

Table I. Catch data (in thousands of individuals) for age groups 0-5+ for the mean year 1995-2000.

Age	Catch
0	19458
1	4098
2	4276
3	3609
4	2289
5+	3755

Table II. Relative fishing effort applied to the Guinean bobo croaker stock between 1995 and 2000.

Year	Effort
1995	0.59
1996	0.66
1997	0.73
1998	0.81

1999	0.90
2000	1

Moroccan sardine

Corrected pseudo-cohort analysis was performed for the stock of sardine (*Sardina pilchardus*, Walbaum, 1792) geographically distributed between 26°North and 32°N (zones A and B) corresponding to the central stock (Fig. 3). Results were compared with the outputs from the FAO Working Group on the Assessment of Small Pelagic Fish off Northwest Africa that was based on Biodyn and LCA models (FAO, 2005).

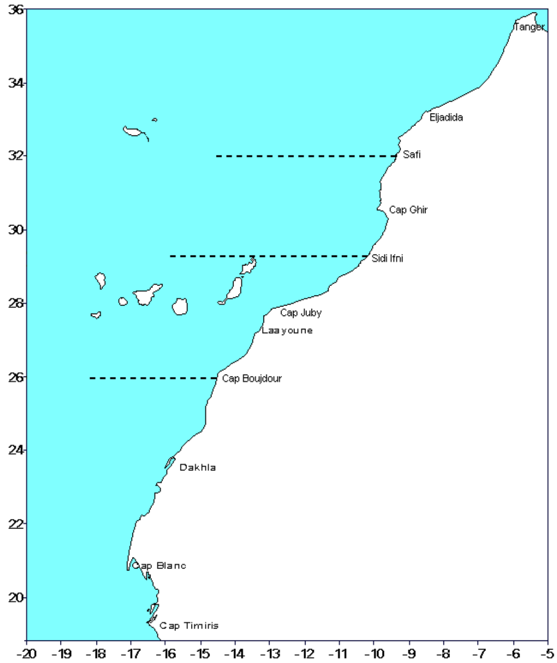


Fig. 3. Sardine stock units and fisheries (Source: FAO, 2005)

Catch data (in thousands of individuals) for age groups 0-6 in year 2004 were extracted from the FAO working group (FAO, 2005) and are given in table III. The relative fishing effort expressed in function of year 2004 was also extracted from FAO (2005) (Table IV). The rate of natural mortality was assumed constant for all ages and in time. Values of 0.4 and 0.6 were considered to test the impact on the results. Recruitment was assumed constant for the period 1998-2004. Values of terminal fishing mortality (F) comprised between 0.3 and 0.8 were considered to perform the pseudo-cohort analysis.

Table III. Catch data (in thousands of individuals) for age groups 0-6 in year 2004.

Age	Catch
0	1358525
1	2293358
2	3719324
3	1006405
4	307211
5	71976
6	12915

Table IV. Relative fishing effort applied to the central Sardine stock between 1998 and 2004.

Year	Effort
1998	0.47
1999	0.71
2000	1.19
2001	0.71
2002	1.20
2003	0.95
2004	1

Moroccan white hake

Moroccan white hake (*Merluccius merluccius,* Linnaeus, 1758) population is considered as a unique stock along the Moroccan coast (FAO, 2006). This species is present in all types of substrate, from Gibraltar to 21° North, and from the coast to 1000 meters deep (Fig. 4).

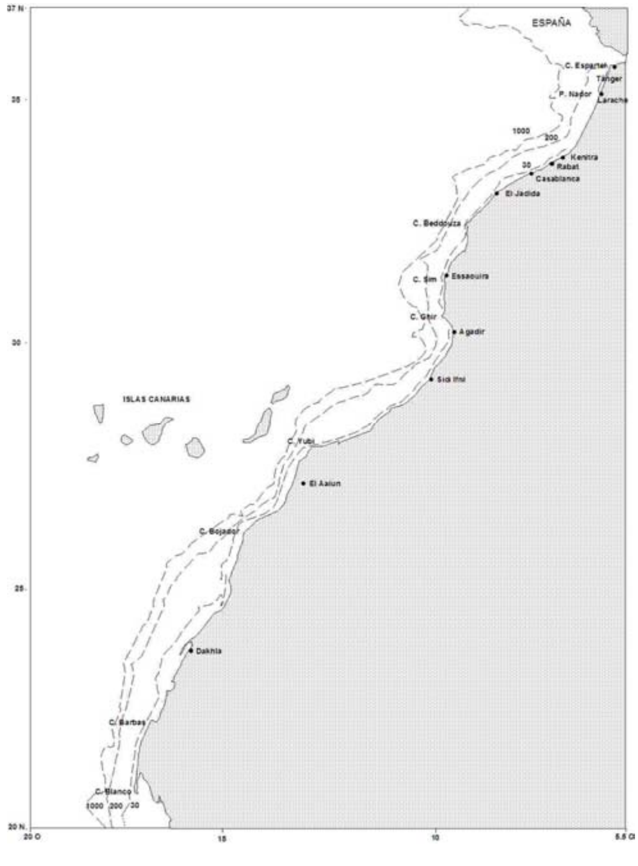


Fig. 4. Area of distribution of white hake along the Moroccan coast.

Until the end of year 1999, Morocco, Spain and Portugal were the main countries directly fishing the white hake stock along the north-Atlantic Moroccan coast. Fishing areas where fishing fleets targeted this resource were limited off the 12-mile line for authorised European fleet (trawlers, gill-netters and longliners) and 6-mile line for national fleet. European trawlers, gill-netters and longliners occurred between 36º N and 28º 42’ N (cape Noun), 32º and 29º N and 35º and 32ºN (sometimes reaching or going further 29º N) respectively. From the end of EU-Morocco fishing agreements towards 1999, only the national fleet operates in Moroccan waters between cape Spartel (36º N) and Laayoune (27º 10’ N). The Moroccan fleet is mostly composed of small coastal fishing units of trawlers and longliners that harvest white hake and pink shrimp within the continental slope. They rarely operate in waters deeper than 150 m.

Corrected pseudo-cohort analysis was run for the stock of white hake for the year 1999 in order to assess the state of the stock at the end of EU fishing agreements and compare results with the outputs of the Working Group on Hakes and Deep Shrimps (FAO, 1997). During both years, the exploitation scheme was equal, the entire hake stock in Moroccan waters was exploited by the different fishing fleets, and data used in this analysis comprise information on all fishing fleets.

Catch data (in thousands of individuals) for age groups 0-9 in year 1999 were extracted from two sources, i.e. the FAO working group (2006) for Moroccan data (coastal fleet), and the IEO “Sampling and Information Net” database (unpublished data) for the Spanish ones trawlers, gill-netters, and longliners. Data were grouped as individuals by length class (1 cm) and converted to individuals by age class (Table V) based on age-length key estimated by Goñi (1983). The relative fishing effort for the period 1990-1999 was expressed in function of year 1999 and also extracted from FAO (2006) (Table VI). The rate of natural mortality was assumed constant at all ages and in time. Values of 0.25, 0.3 and 0.35 were considered to test the impact on the results. Recruitment was assumed constant for the period 1990-1999. Values of terminal fishing mortality (F) comprised between 0.4 and 1.2 were considered when performing the pseudo-cohort analysis. The vector of mean weight at age (g) used for estimating yield per recruit was 15, 30.6, 68.7, 107.9, 200.2, 351.3, 541.3, 717.1, 896.9, and 1115.7 for ages 0-9 respectively.

Table V. Catch data (in thousands of individuals) for age groups 0-9 in year 1999.

Age	Catch
0	166208
1	1983101
2	3878640
3	4707148
4	3305241
5	1266579
6	758937
7	461054
8	227004
9	107965

Table VI. Relative fishing effort applied to the white hake stock between 1990 and 1999.

Year	Relative effort
1990	0.93
1991	0.99
1992	0.94
1993	0.84
1994	0.76
1995	0.42
1996	0.83
1997	0.88
1998	0.93
1999	1

Senegalese octopus

Pseudo-cohort analysis is generally performed for long-living species and based on yearly catch at age data. For short-living species such as octopus (*octopus vulgaris*), the analysis was conducted on a monthly basis because the exploitation period of octopus is shorter than one year and octopus growth is fast. Four years of catch at age data (1996-1999) were available from the catch database of the CRODT.

Corrected VPA was performed for all months of the year 1997. Input data for the analysis included catch at age (in numbers) and time series of recruitment and fishing mortality from April 1996 to January 1997. According to VPA results, octopus recruitment greatly varies from one month to another (Fig. 5). We used monthly catches for age 5 corresponding to the first age of exploitation as an index of recruitment.

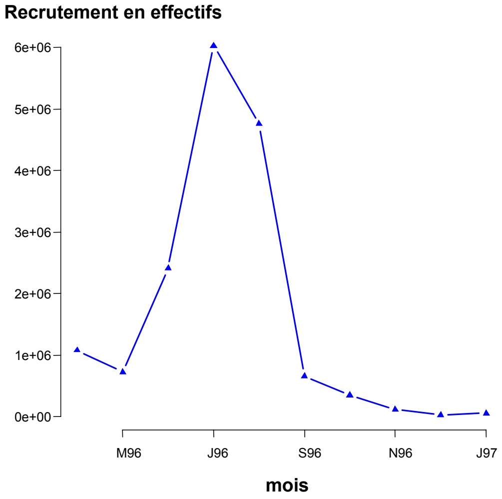


Fig. 5. Monthly variations in Octopus recruitment from April 1996 to January 1997 derived from VPA performed on the full catch at age matrix (Caverivière et al., 2002).

A similar problem was observed for the time series of fishing efforts that generally show important seasonal fluctuations. Fishing effort data remain however not available at a monthly scale. Three different ways were investigated: (i) assuming a constant fishing effort during the period considered, (ii) assuming a similar profile as the recruitment, and (iii) using fishing mortalities F estimated by the VPA performed on the full catch at age matrix. The assumption of constant fishing effort was finally considered in the present analysis.

Catch at age for the month of January 1997 are given in table VII. Relative and absolute recruitment leading to the January catch at age are given in table VIII. The rate of natural mortality was assumed constant at all ages of the exploited phase (5-14 months) and in time, and was set equal to 0.25 (Caverivière et al., 2002). Results were compared with the outputs from the monthly VPA performed on the full catch at age matrix (Caverivière et al., 2002). The vector of mean weight at age used for estimating yield per recruit is given in table IX.

Table VII. Catch data (in thousands of individuals) for age groups 5-14 in January 1997.

Age (months)	Catch
5	828
6	1997
7	14072
8	34762
9	75418
10	19599
11	6648
12	3583
13	1580
14	424

Table VIII. Relative and absolute recruitments for the Senegalese octopus stock between April 1996 and January 1997.

1. Months	Apr-96	may-96	jun-96	jul-96	aug-96	Sept-96	oct-96	nov-96	dec-96	Jan-97
Relative R.	18.45	12.44	41.19	103.06	81.29	11.31	5.97	2	0.53	1
Absolute R.	1079325	727740	2409615	6029010	4755465	661635	349245	117000	31005	58500

Table IX. Mean weight at age (kg) for Senegalese octopus.

Age class	5	6	7	8	9	10	11	12	13	14+
Mean weight (kg)	0.075	0.125	0.2	0.3	0.45	0.7	1.05	1.55	2.25	3.2

4.2. Results

Guinean bobo croaker

Results for the corrected pseudo-cohort analysis based on the mean vector of catch at age data assumed to represent the period 1995-2000 and different values of natural mortality, are summarized in figures 6b-c.

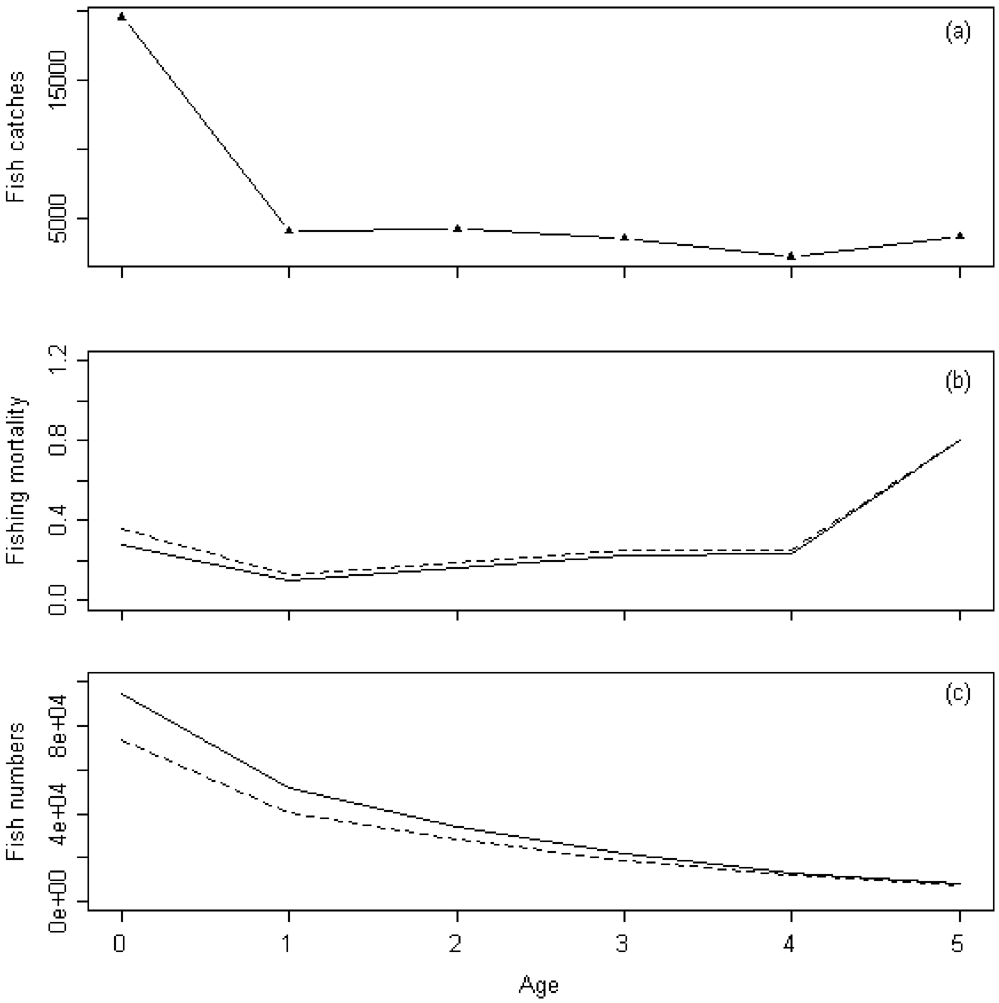


Fig. 6. (a) Total catch at age in 2000 (b) Fishing mortality at age and (c) Numbers at age estimated by corrected pseudo-cohort analysis for values of natural mortality of 0.28 (dashed line) and 0.35 (solid line).

The fishing pattern of the Guinean bobo fishery (Fig. 6b) indicates a high fishing mortality on young (0-1) and old ages (4-5). This is due to the combination of the fishing patterns of the artisanal and industrial fisheries that mainly target large and small fish respectively. The increase in natural mortality from 0.28 to 0.35 poorly modifies the results of the corrected VPA in terms of fishing mortality and numbers at age.

The yield per recruit diagnosis indicates that the Guinean bobo croaker is overexploited, i.e. the fishing effort applied during the period 1995-2000 largely exceeded the fishing effort corresponding to the maximum yield per recruit. Both values of natural mortality (0.28 and 0.5) lead to similar conclusions on the state of the stock (Fig. 7).

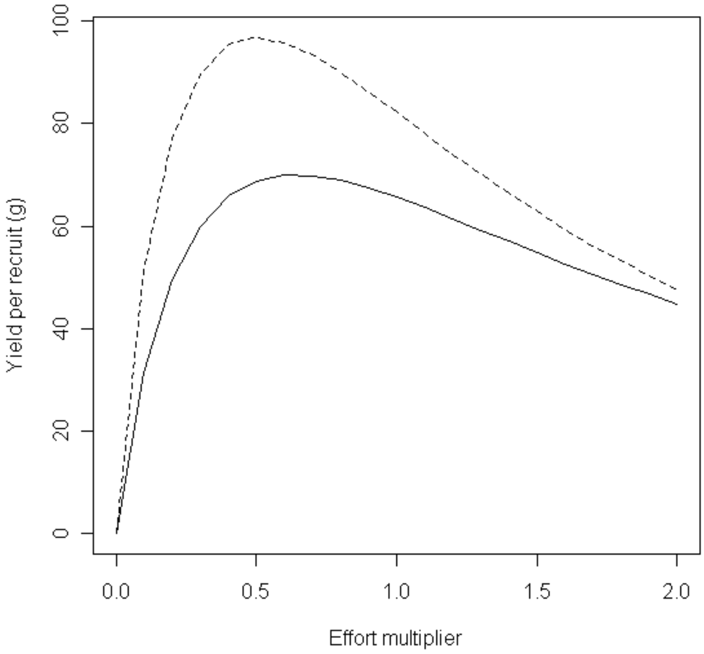


Fig. 7. Yield-per-recruit diagnosis based on rates of natural mortality of 0.28 (dashed line) and 0.35 (solid line), considering a fishing effort multiplier from 0 to 2. The vector of fishing mortality at age was estimated by corrected pseudo-cohort analysis for the period 1995-2000.

Moroccan sardine

Results of pseudo-cohort analysis for the Moroccan sardine based on the year 2004 and on rates of natural mortality of 0.4 and 0.6 are summarized in figures 8-10.

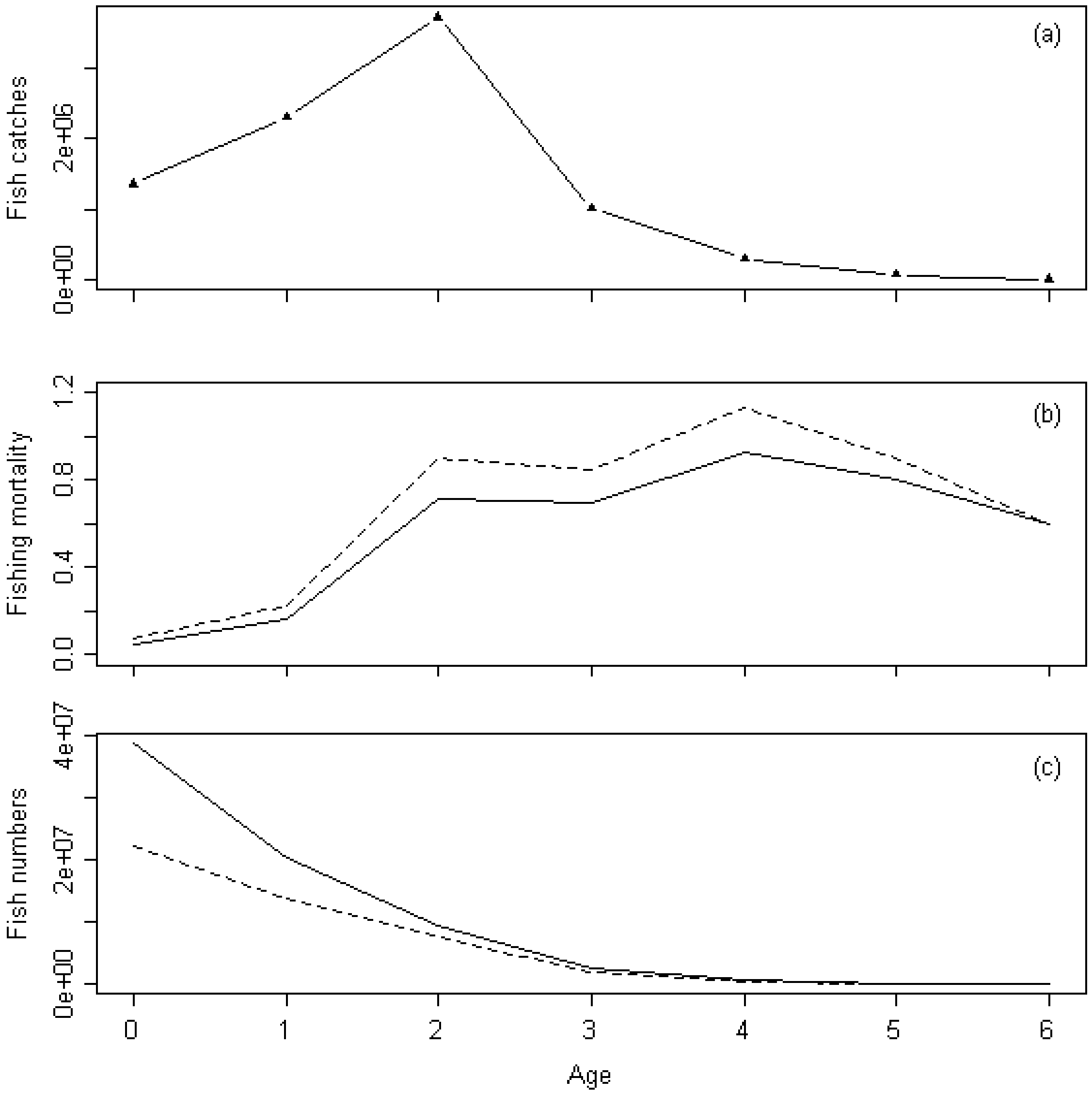


Fig. 8. (a) Total catch at age in 2004 (b) Fishing mortality at age and (c) Numbers at age estimated by corrected pseudo-cohort analysis for values of natural mortality of 0.4 (dashed line) and 0.6 (solid line).

As expected, the vector of fishing mortality at age estimated with a value of M equal to 0.6 is lower than for M equal to 0.4, while the numbers at age are higher. The fishing pattern displays the same shape in both cases. The fishing mortalities for ages 2 to 4 are the highest, excluding terminal age classes that are often poorly represented in the catches. Precedent studies have shown that the age class 2 is fully recruited whereas the results of the present analysis indicate that the age class 0 is recruited.

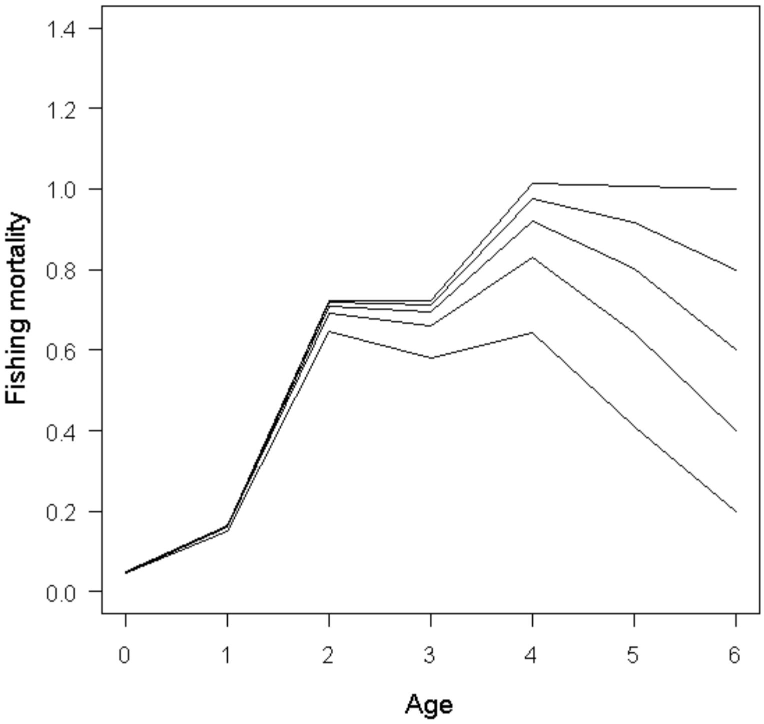


Fig. 9. Sensitivity analysis showing the impact of terminal fishing mortality F_T (0.2-1 by 0.2 steps) on the fishing mortality at age vector estimated by corrected pseudo-cohort analysis (M = 0.6).

The sensitivity analysis conducted for different values of terminal fishing mortality underlines the well-known phenomenon of VPA convergence (Jones, 1961 *in* Mesnil, 1980). Results show that the potential error on terminal fishing mortality poorly affects the fishing mortalities estimated for ages 0-2 **(**Fig. 9).

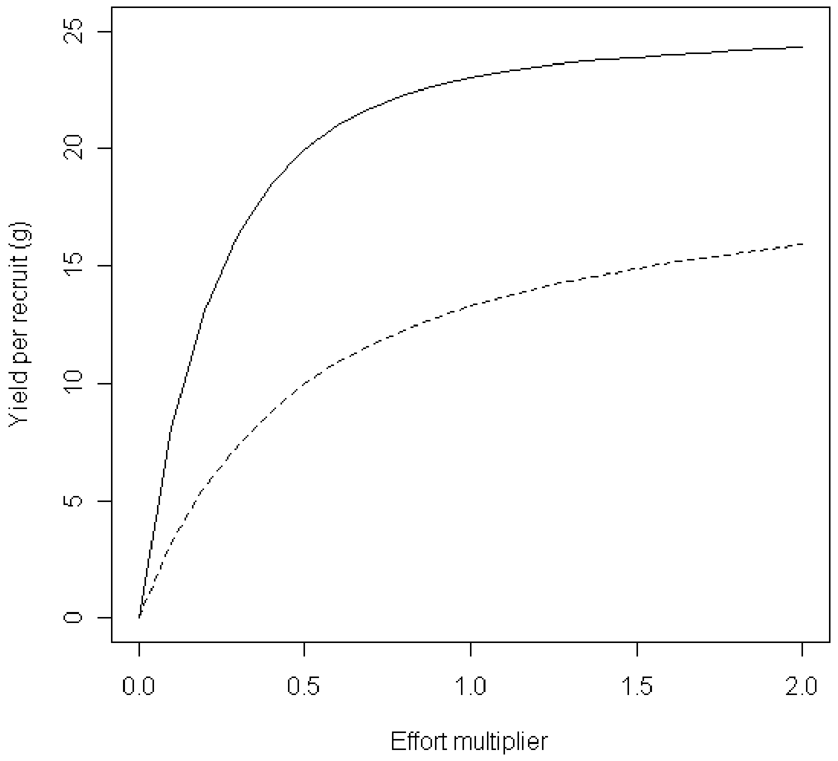


Fig. 10. Yield-per-recruit diagnosis based on rates of natural mortality of 0.4 (solid line) and 0.6 (dashed line), considering a fishing effort multiplier from 0 to 2. The vector of fishing mortality at age was estimated by corrected pseudo-cohort analysis for the year 2004.

Yield per recruit diagnoses based on the fishing mortality estimated for the year 2004 and assuming rates of natural mortality of 0.4 and 0.6 indicate that the stock is at a level of exploitation below the fishing effort that would maximise the yield per recruit (Fig. 10). This suggests that the stock would be currently under-exploited and that an increase in fishing effort could favour an increase in yield per recruit. Nevertheless, “flat-top” curves make difficult the position of the maximum yield per recruit.

Northwest African hake

Results of corrected pseudo-cohort analysis based on catches of the year 1999 for the three values of natural mortality, i.e. 0.25, 0.30 and 0.35 are summarized in figures 11a-c.

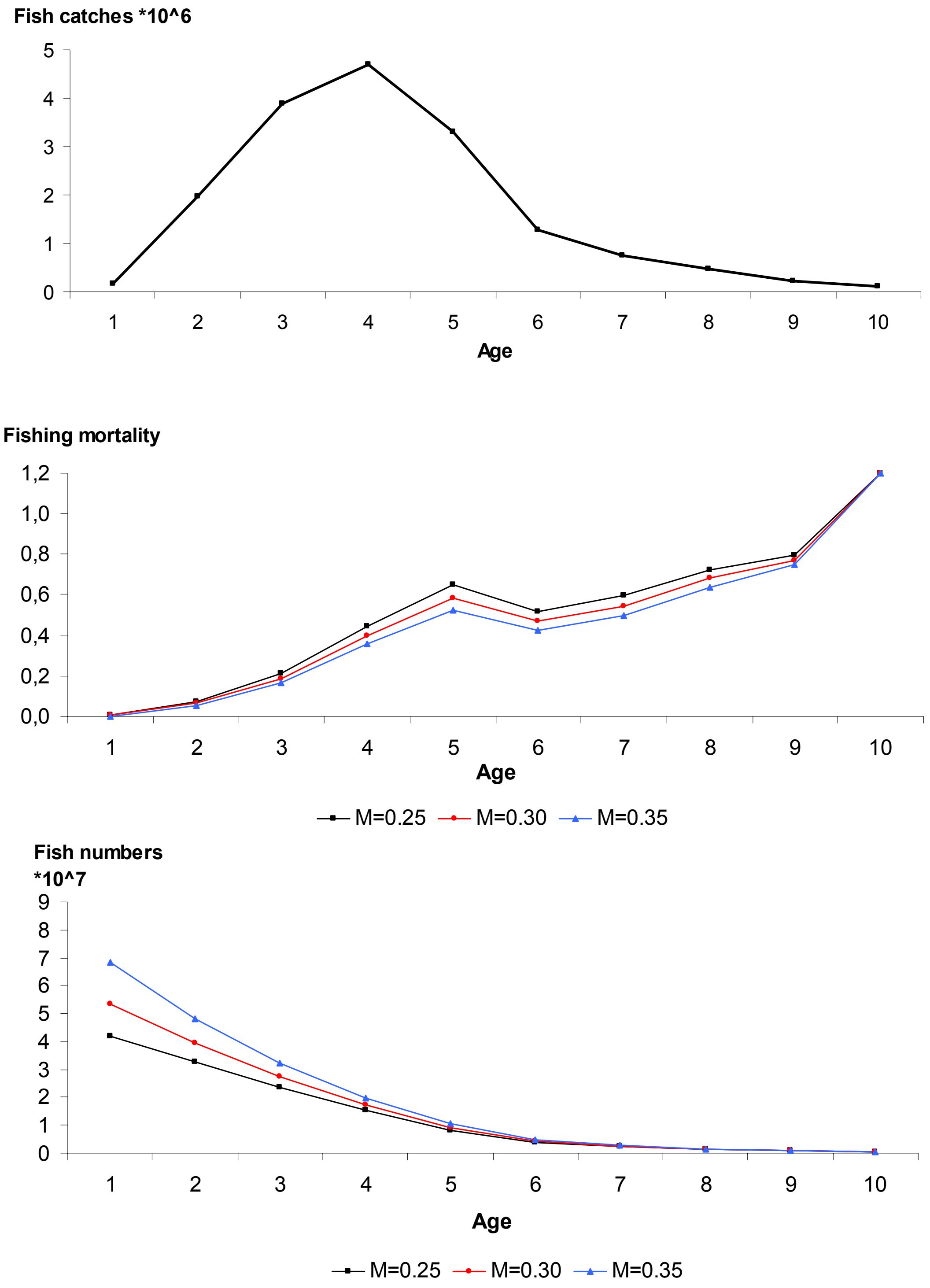


Fig. 11. (Top) Total catch at age in 1999 (Middle) Fishing mortality at age and (Bottom) Numbers at age estimated by corrected pseudo-cohort analysis for values of natural mortality of 0.3, 0.35 and 0.4.

The northwest African hake fishery exhibits the same fishing pattern whatever the values of natural mortality used. As expected, the vectors of fishing mortality decrease with natural mortality whereas numbers at age increase. The highest fishing mortalities correspond to age-classes 2-6, as terminal age-classes 7-10 are rarely found in the catches (Fig. 11).

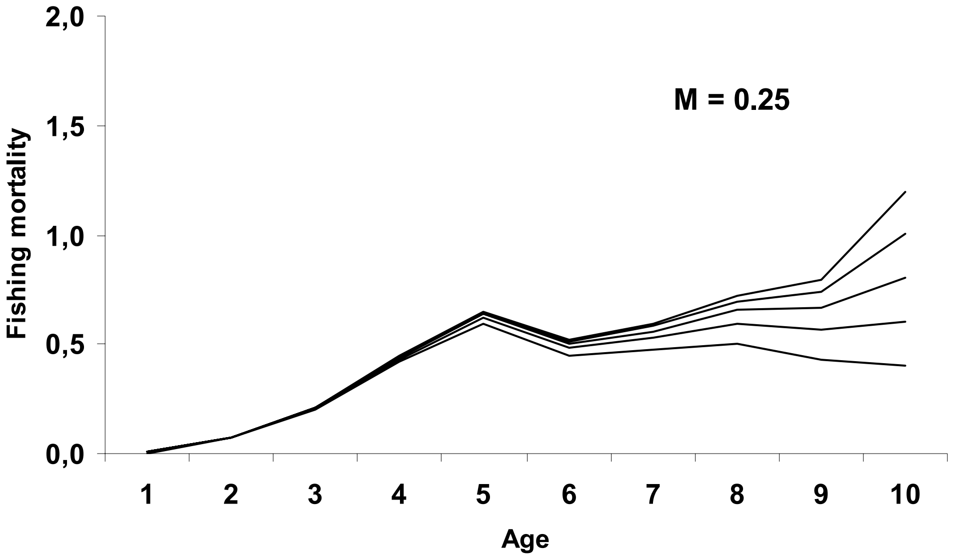


Fig. 12. Sensitivity analysis showing the impact of terminal fishing mortality F_T (0.2-1 by 0.2 steps) on the fishing mortality at age vector estimated by corrected pseudo-cohort analysis (M = 0.25).

The sensitivity analysis carried out for different values of terminal fishing mortality underlines the well-known phenomenon of VPA convergence (Jones, 1961 *in* Mesnil, 1980). It shows that the potential error on terminal fishing mortality poorly affects the fishing mortalities estimated for the five first age classes (Fig. 12). The analysis is performed here for a rate of natural mortality of 0.25, considered the most consistent value for this stock. Moreover, analyses conducted with other M values led to similar results. The analysis converges towards the “true” value of F when moving towards the youngest age classes.

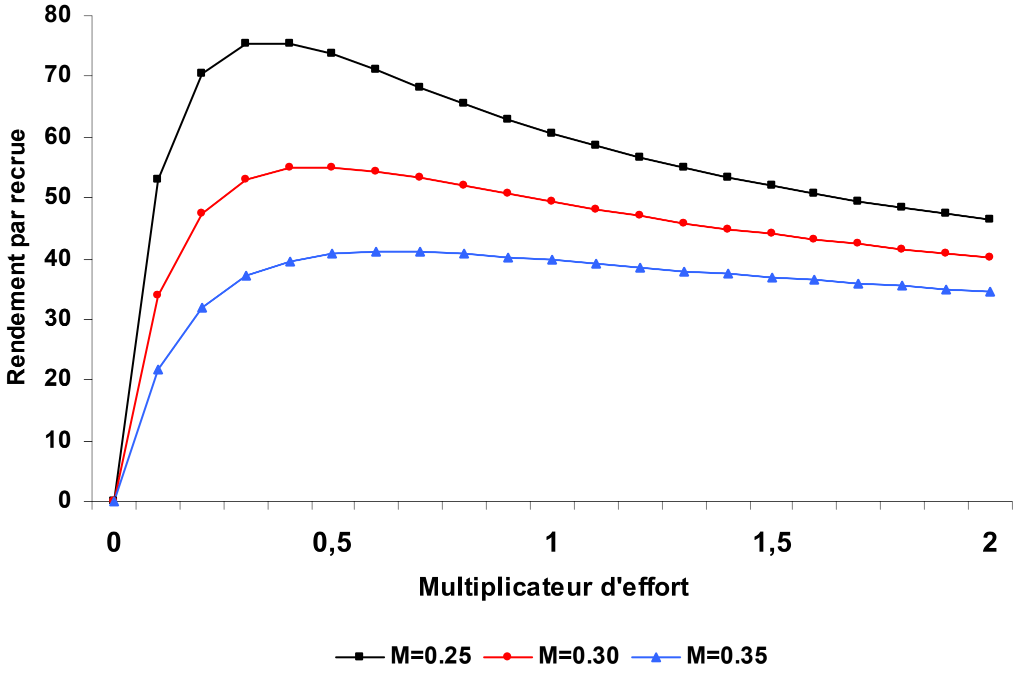


Fig. 13. Yield-per-recruit diagnosis based on different rates of natural mortality, considering a fishing effort multiplier from 0 to 2. The vector of fishing mortality at age was estimated by corrected pseudo-cohort analysis for the year 1999.

The yield per recruit diagnosis based on the vector of fishing mortality estimated for the year 1999 shows different results according to the value of natural mortality considered, i.e. 0.25, 0.30 and 0.35 (Fig. 13). The highest value (0.35) indicates a yield per recruit close to the maximum yield per recruit. This would suggest an equilibrium situation close to full exploitation for the northwest African hake. This value is however high for this stock. By contrast, the yield per recruit curve obtained for the lowest and most consistent value of natural mortality suggests that the hake stock is highly overexploited. In this case, it is highly recommended to lower the fishing pressure on the stock to increase the yield per recruit.

Senegalese octopus

Figure 14a indicates that the most part of catches concern ages 6-11 months. The exceptional recruitment observed during the warm season (May to September 1996) consisted in a significant part of total catches in the following months. In this period, octopuses reach their fifth or sixth month of life. The results of corrected pseudo-cohort analysis, accounting for changes in recruitment through time, are summarized in figure 14-b,c. These results were obtained for the month of January 1997. For the other months, the corrected VPA did not converge.

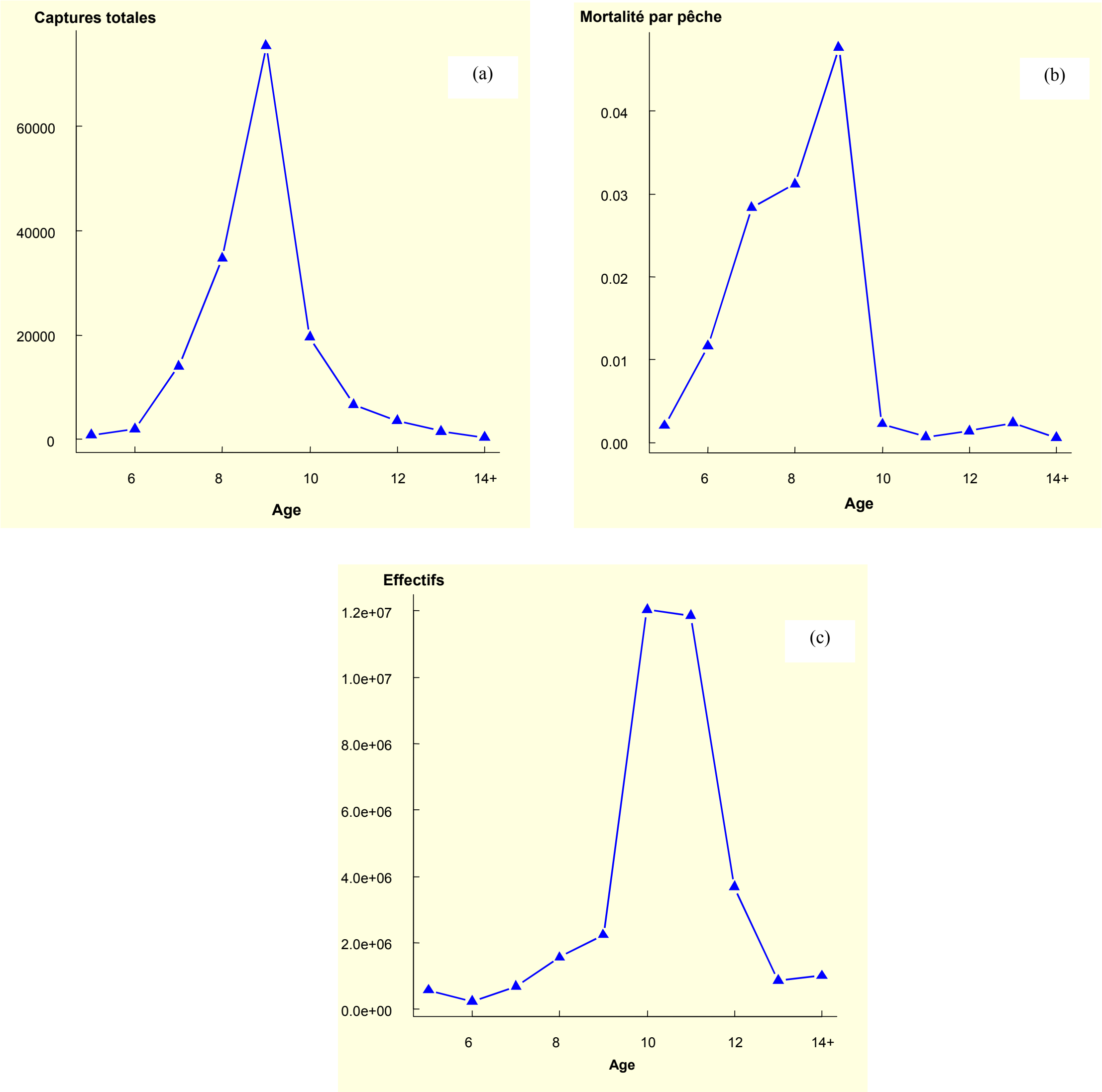


Fig. 14. (a) Total catches at age (landings) in January 1997 (b) Fishing mortality at age, and (c) Numbers at age estimated by corrected pseudo cohort analysis.

Mean fishing mortalities applied on ages 5-9 months represent the main part of fishing pressure exerted on octopus stock in January 1997 (Fig. 14b). Old individuals (i.e. 10 months and more) are almost not fished. They reached a maturity state that allow them to escape from fishing gears, decreasing their vulnerability and hence catchability.

The survival equation re-expressed in the pseudo-cohort analysis allows estimating the numbers at age in January 1997 (Fig. 14c). This figure shows that most of the stock abundance consists of age classes of 9-12 months. These age classes correspond to juvenile and adult phases. Individuals at ages 5-8 and 12+ are less numerous. High numbers at ages 9-12 are highly linked to the high recruitments observed in the precedent months. Hence, the high octopus production of January 1997 is closely related to the good recruitments observed during the warm season of 1996.

Again, the sensitivity analysis performed on terminal fishing mortality underlines the well-known of VPA convergence (Fig. 15). The error on terminal fishing mortality poorly affects fishing mortalities estimated, showing that the outputs of the analysis are robust to the values of terminal fishing mortality used.

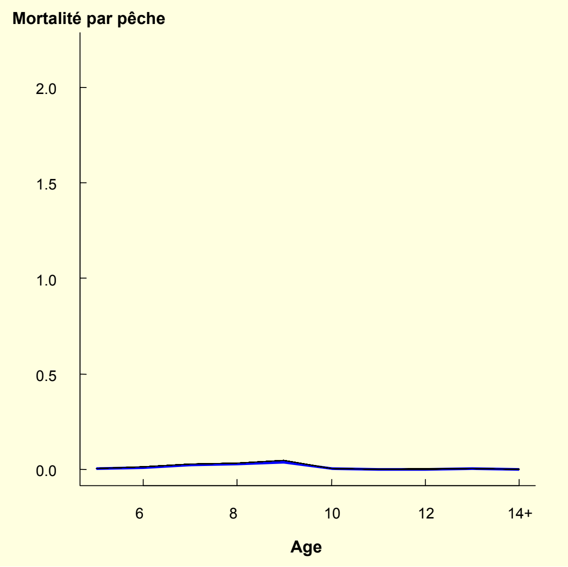


Fig. 15. Sensitivity analysis showing the impact of terminal fishing mortality on the vector of fishing mortality at age estimated by corrected pseudo-cohort analysis.

Based on the vector of fishing mortality estimated in January 1997, a yield per recruit diagnosis is performed assuming a constant rate of natural mortality equal to 0.25. The diagnosis indicates a low use of the recruitment given the fishing pattern. The current fishing mortality is very low compared to the value maximising the yield per recruit (Fig. 16). This suggests that the stock of octopus would be under-exploited. An increase in the fishing effort would favour a better use of the recruitment.

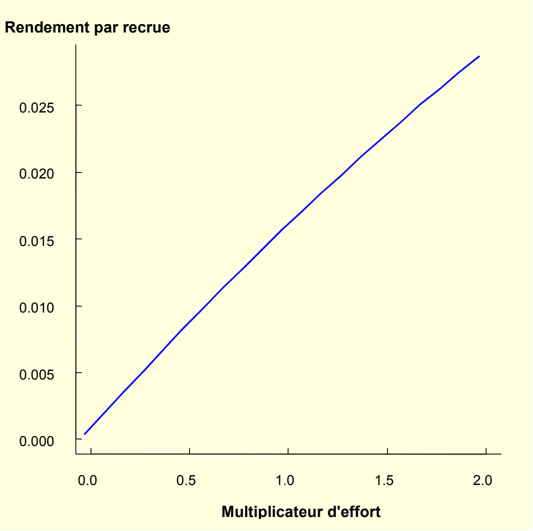


Fig. 16. Yield per recruit diagnosis based on the vector of fishing mortality estimated by pseudo-cohort analysis in January 1997, considering a fishing effort multiplier from 0 to 2.

4.3. Discussion

Guinean bobo croaker

The application of corrected pseudo-cohort VPA to the Guinean bobo croaker allowed us to show the interest of the method to conduct stock assessment for a long-living demersal species when few data is available. The time series of relative fishing effort was based on a crude index of effort, i.e. the number of fishing vessels targeting the bobo in the Guinean EEZ. Although this index might not precisely represent the evolution in fishing effort on bobo, the diagnostic of overfishing is robust since it is mainly driven by the increasing trend in fishing effort. This trend has been observed in the last decade for a large array of species in the Guinean EEZ.

In this case study, the corrected VPA was based on catch at age data derived from several assumptions on the artisanal and industrial fishing fleets and on data available from several years (1995-2000). The analysis mainly aims to be a first attempt to assess the state of the stock in a data-poor situation and absolute values of outputs might be considered with care. The diagnostic of overfishing for the bobo was consistent with outputs from surplus production models (Sidibé, 2003). The method is complementary with surplus production models since it allows the user to diagnostic how the recruitment is used in the fishery based on the fishing mortalities estimated with the VPA. Multi-fishery yield per recruit analysis can also be used as a modelling approach to investigate how the balance between artisanal and industrial fishing efforts can be modified to increase the production in the bobo fishery (Sidibé, 2003).

Compared with biomass models, age-structured models aim to focus on the fishing pattern to eventually define proper management control rules based for instance on mesh size regulation. Such management options might however be difficult to implement in several West-African fisheries regarding the multi-species characteristics of the artisanal fisheries. Corrected VPA coupled with yield per recruit diagnostic and short-term projections remains a major fisheries-scientist tool to track signs of overfishing in a fishery in a data-poor context. The detection of early warning signs of overfishing could then favour initiating appropriate protocols of data collection to confirm/infirm the diagnostic and implementing required management rules.

Moroccan sardine

A stock assessment for sardine in zone A+B was conducted by the FAO Working Group (WG) on the Assessment of Small Pelagic Fish off Northwest Africa with the logistic surplus production model (Schaefer, 1954). The WG also attempted to use length cohort analysis (LCA) for this stock. Outputs of the surplus production model indicated that the current biomass of the stock were well above biomass at the Maximum Sustainable Yield (MSY) and that current fishing mortality was lower than fishing mortality at MSY (Table X).

Table X. Stock assessment indicators derived from the FAO working group for Sardine (A+B).

Stock/index of abundance	B/B_{MSY}	F_{cur}/F_{SYCur}	F_{cur}/F_{MSY}
Sardine, Area A+B / Nansen	149 % (5%)	88 % (5%)	45 % (10%)

For zone A+B, results showed an increasing trend during the period from 1998. Predicted abundance in 2004 was the highest for the time series since 1996 (Fig. 17).

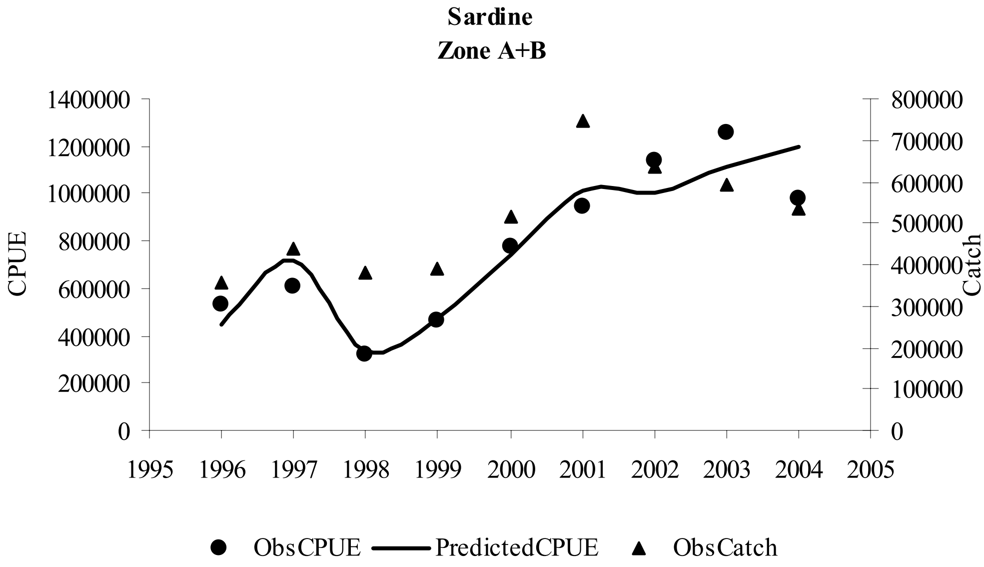


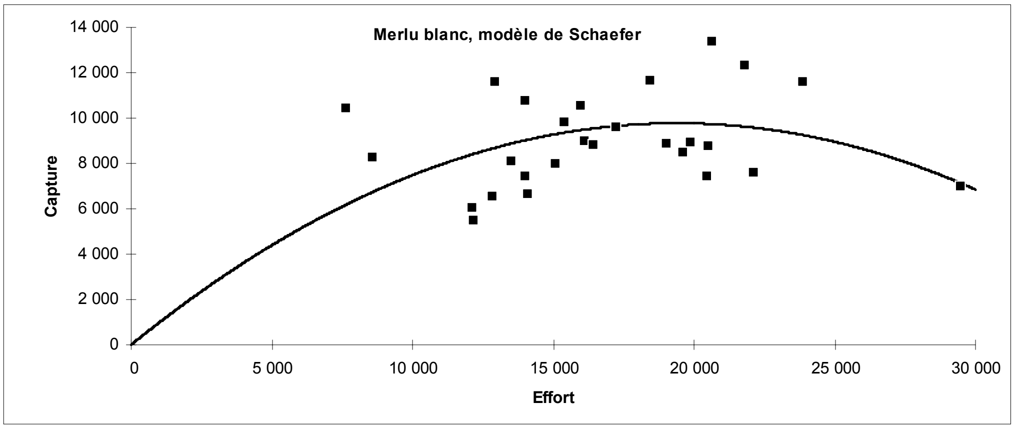
Fig. 17. Observed and predicted abundance indices, and catch for Sardine Zone A+B. CPUE = catch per unit of effort.

Results from LCA showed a high exploitation of size classes comprised between 18 and 21 cm and 23 and 25 cm (ages 1-4). High exploitation of young age classes is mainly explained by the demand in can industry. In addition, yield per recruit estimates indicated that the stock was moderately exploited with fishing mortality values comprised between F_{max} et $F_{0.1}$. The "flat top" shape of the yield per recruit curve suggested to use $F_{0.1}$ rather than F_{max} as reference point. Results obtained from corrected pseudo-cohort analysis are similar to the general outputs from the FAO WG. Nevertheless, the FAO WG also showed that there was no correlation between cohorts except for ages 0 and 1. In this context, the present results must be considered with great care.

Northwest African hake

Moroccan white hake is a long-living species highly exploited. Consequently, pseudo-cohort analysis is very appropriate for this type of resource. The assessment of white hake was made by the Working Group on Hakes and Deep Shrimps (FAO, 1997) following two approaches: 2 surplus production models (Schaefer, 1954; Fox, 1970) and length cohort analysis (Jones, 1984). The analytical approach was based on size structure of the landings and performed with the ANALEN software for analysing length frequency catch and simulating multispecies fisheries (Chevalier and Laurec, 1990). Results based on analytical and surplus production led to contradictory results in terms of exploitation.

On one hand, surplus production models indicated that the current biomass was very close to the biomass at MSY (Fig. 18). On the other hand, analytical results showed a situation of overfishing for the 2 periods considered, 1992-94 and 1994-96 (Fig. 19).



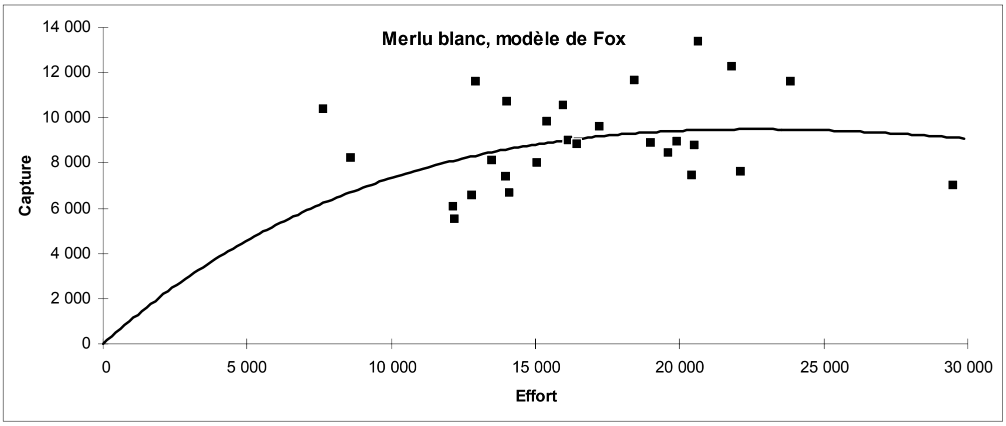


Fig. 18. Catch and fishing effort for white hake according to Schaefer and Fox model (FAO, 1997).

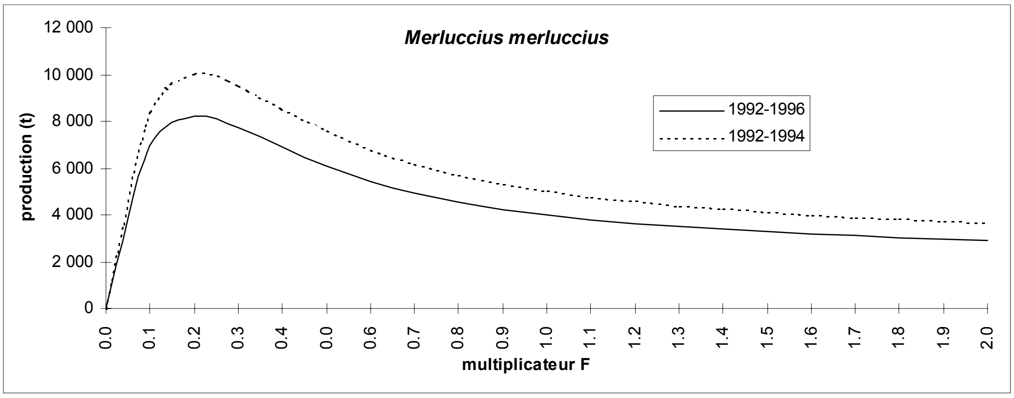


Fig. 19. Yield-per-recruit diagnosis for a value of natural mortality of 0.25 (FAO, 1997).

The present analysis leads to similar conclusions as obtained during precedent WGs on white hake stock assessment that were based on different methods, i.e. the white hake stock is overexploited (FAO, 1978, 1986, 1990, Anonymous, 1991).

Fishing mortality vectors estimated during the WGs of 1991 and 1997 show a high fishing pressure by trawlers on young fish and by gill nets and offshore longliners on spawners. This tends to support the hypothesis of the stock overfishing.

Contradictions during the 1997 WG could be due to the raw data used. In the surplus production models, errors could have arisen from the standardisation process of fleet fishing efforts.

We used 3 different M values in this assay, 0.25 (the same than WG 1997), 0.30 and 0.35. Using the first value, the results obtained were very similar to the WG 1997 analytical model, nevertheless the state of overfishing was less pronounced. The method seems very sensitive to the value of natural mortality M, suggesting a stock state close to MSY using M = 0.35 (Fig. 13).

Comparing the outputs from the different tested values, we suggest that the proper and more realistic rate of natural mortality is 0.25, since the results are more consistent. Here, the corrected pseudo-cohort analysis shows a situation of overfishing but results appears intermediary between the contradictory results of the 1997 WG. The present method could then be appropriate to assess the state of white hake and derive a retrospective analysis of the stock history. Applications of the model with more recent data should help to confirm the general interest of the method for long-living species such as hake.

Senegalese octopus

Corrected pseudo-cohort analysis gives a solution for the month of January and for an initial value of recruitment (Table VIII). Results show that octopus comprised between 7 and 10 months represent most of the catch in Senegal. Individuals of 9-12 months are more numerous but remain poorly caught by the different fishing gears. This could be interpreted as a lower vulnerability of old octopus to fishing (Jouffre et al., 2002).

For the yield per recruit diagnostic, the increase in fishing effort does not always conduct to an increase in production (Gascuel, 1994). This situation mainly depends on the future recruitment, particularly unpredictable in the case of octopus.

Corrected VPA shows two major constraints here: (i) a constant fishing effort, and (ii) the assumption about an initial value for recruitment. The assumption of a constant fishing effort is false for octopus fisheries that are typically seasonal (Jouffre et al., 2002). Gascuel (1994) also underlined the importance in changes in fishing strategies and tactics for artisanal Senegalese fishing fleets. Such changes have strong impacts on specific fishing power and hence on fishing effort. Concerning recruitment, the initial value cannot be arbitrary but has to be consistent with the fishery. Catches at age 5 are not a good index of evolution in recruitment for octopus. Solari A. P. et al. (2006) show that these catches depend on the fishermen strategies and do not take into account discards. Therefore, they can be considered as an approximation of trends in recruitment on the mid-term. By contrast, they do not reflect well inter-monthly variability in octopus recruitment (Fig. 5).

The absence of corrected VPA convergence for the months of the year 1997 other than January might be due to the quality of catch data. The catch at age matrix, that is the basis of the analysis, is derived from estimates of catch for each age. Discards are not taken into account in these estimates but are considered low regarding the high value of octopus. On the other hand, the distribution of octopus catch between ages can bias estimates. Catch available by weight class are difficult to split between ages due to large differences in individual octopus growth. This tends to bias the distribution of catch.

For a value of recruitment for the terminal month (e.g. 58 500), relative recruitment directly gives the absolute recruitment for each month. However, for some recruitment values, the estimated recruitment estimated for some months is too low to give rise to the observed catches. Consequently, the R script does not converge. VPA at equilibrium based on Pope approximation is used to initialise the recruitment. This initialising method allows the user to define the recruitment order of magnitude. Nevertheless, it might not work for octopus because of the large variations in recruitment form one month to another. The main sources for uncertainty in VPA diagnostics come from catch extrapolation procedures, assessment of discard, and natural mortality estimates (Gascuel, 1994). Here, the high sensitivity of the outputs due to these problems combined with the assumption on initial recruitment lead to the absence of convergence in some cases.

Corrected VPA is more appropriate than VPA at equilibrium, particularly for a high fluctuating resource such as Octopus. In addition, it is less constraining than VPA on a full catch at age matrix. Nevertheless, a VPA performed on the full catch at age matrix should obviously be performed when data are available. Corrected VPA is only based on 1 year of data and might therefore require more accuracy and precision in the acquisition data process to yield consistent results. Data quality could therefore explain the lack of convergence in several runs. Future work should focus on the definition of better indices of relative fishing effort and recruitment.

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Appendices

Appendix 1 - An example of application: the MORBRAS seabass multispecies fishery

The example of the seabass fishery (*Dicentrarchus labrax*) in MORBRAS (South Brittany) was considered to illustrate the results of an application of the corrected pseudo-cohort developed with the R software. We used data available in the PhD. thesis of Bertignac (1988) who considered 4 "métiers" that targeted the seabass stock: longliners (LL), pelagic trawlers (PT), small fishing coastal trawlers (SFCT) and "MISC." that included small fishing multi-purpose trawlers, mobile gears and gill netters.

Table XI. Catch at age for the métiers composing the MORBRAS seabass multispecies fishery (Bertignac, 1988).

Age	LL	PT	SFCT	MISC.	Total
2	8	0	8	7	23
3	438	184	1103	6435	8160
4	13955	1827	11285	20817	47884
5	16933	2245	5938	4023	29139
6	47864	7158	9773	3656	68451
7	22925	4792	2749	905	31371
8	23117	7151	1722	570	32560
9	4684	1767	228	117	6796
10	15853	5378	678	131	22040
11	10942	3524	483	60	15009
12	8839	1429	368	115	10751
13	18524	2533	213	42	21312
14	8141	1481	87	111	9820
15	9850	2470	265	157	12742
16	4485	1161	224	117	5987
17	3608	563	87	0	4258
18	2642	617	85	51	3395
19	1310	477	0	0	1787

Table XII. Relative fishing effort for the métiers composing the MORBRAS seabass multispecies fishery (Bertignac, 1988).

Years	LL	PT	SFCT	MISC.
1985	3500	800	550	430
1984	2900	600	400	600
1983	2200	450	200	760
1982	1500	350	100	900
1981	800	200	100	900
1980	800	50	100	1000
1979	800	50	100	1100
1978	800	0	100	1150
1977	800	0	100	1250
1976	800	0	100	1350
1975	800	0	100	1350
1974	800	0	100	1350
1973	800	0	100	1350
1972	800	0	100	1350
1971	800	0	100	1350
1970	800	0	100	1350
1969	800	0	100	1350
1968	800	0	100	1350

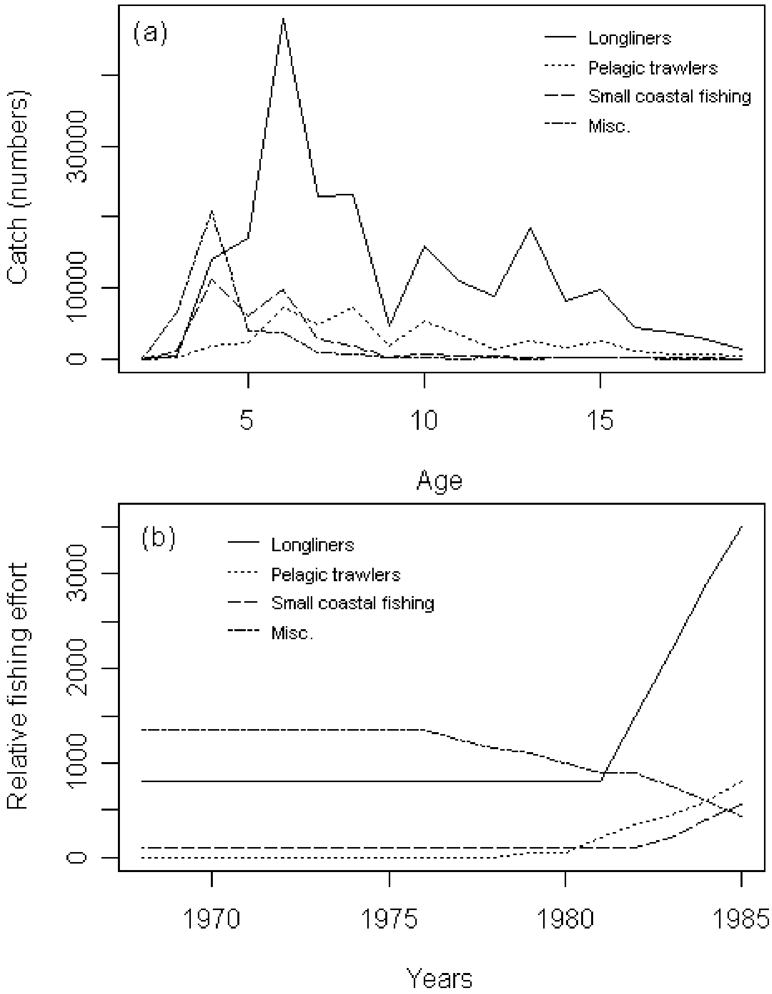

Fig. 20 (a) Fish numbers landed by age-group and fishing métier in MORBRAS in 1985 (b) Temporal evolution of effective fishing efforts by métier that exploited seabass in MORBRAS from 1968 to 1985.

Input data were mainly composed of catch at age in numbers and time series that indicated the fishing effort evolution from 1968 to 1985 (Fig. 20). Effective fishing efforts for each métier were estimated from a standardisation process based on the relative fishing power of each métier (Bertignac, 1988). The rate of natural mortality was assumed constant at age and during the period of analysis and set equal to 0.2. The analysis was conducted under a constant recruitment assumption.

Outputs of the corrected pseudo-cohort analysis that took into account fishing efforts evolution are summarized in figures 21b and c.

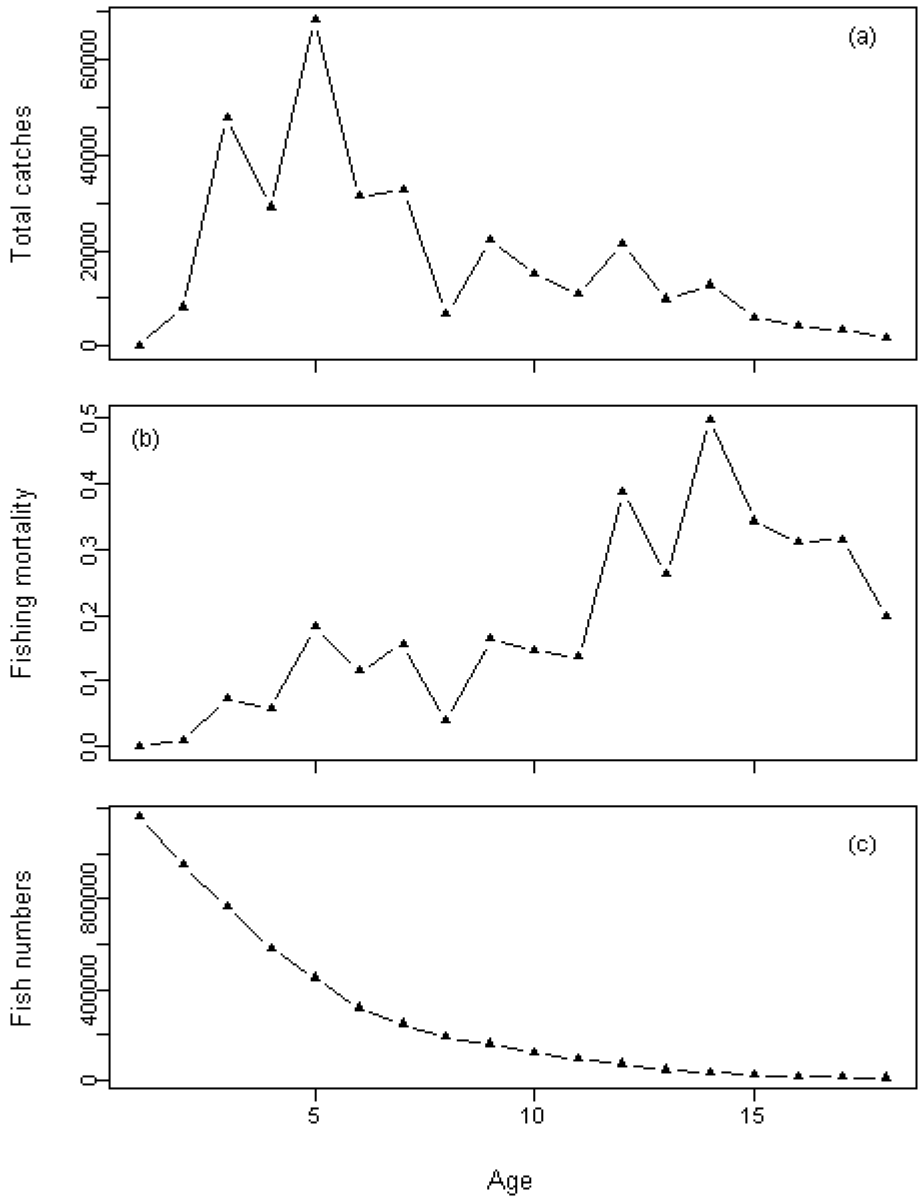

Fig. 21 (a) Total catches (landings) by age-group in 1985 (b) Fishing mortality by age group estimated by the corrected pseudo-cohort analysis (c) Fish numbers at age estimates based on the corrected pseudo-cohort analysis.

The sensitivity analysis conducted on the terminal fishing mortality F_T (0.2-1.0) emphasized the convergence process (Jones, 1961 *in* Mesnil, 1980) and showed that the potential error on F_T poorly affected the fishing mortalities at age estimated for the first 14 age groups (Fig. 22).

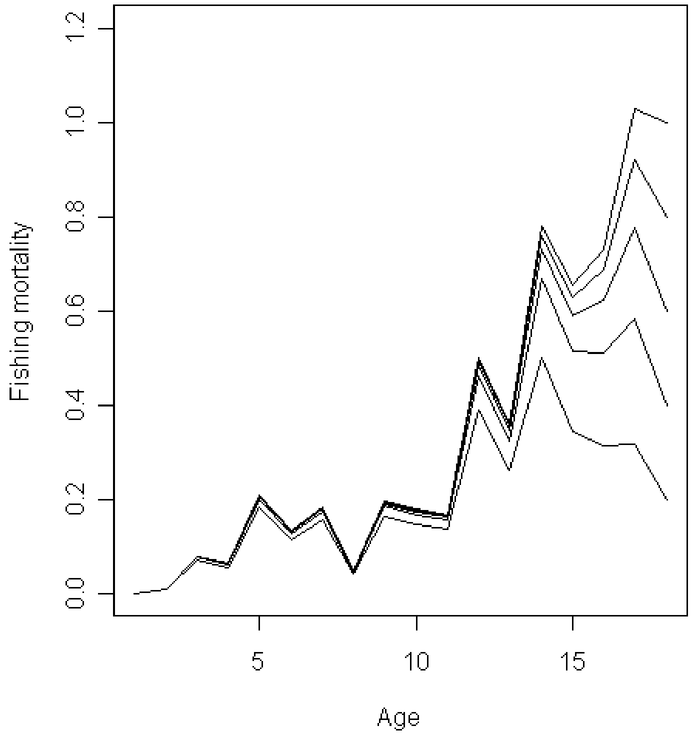

Fig. 22. Sensitivity analysis showing the impact of terminal fishing mortality F_T on the fishing mortality vector estimated by corrected pseudo-cohort analysis.

A yield per recruit diagnosis was then conducted based on the fishing mortality at age estimated for the final year, i.e. 1985, assuming that the natural mortality rate was constant and equal to 0.2. The diagnosis indicated a good use of the recruitment according to the current fishing pattern since the mean fishing mortality in 1985 corresponded to the yield per recruit maximising value F_{max} (Fig. 23). Nevertheless, this optimistic diagnosis was not as good in 1985 since the equilibrium situation predicted by the model led to a 20% decrease in catch (under a constant recruitment assumption). The fishery was at this time in a non-equilibrium situation due to the recent fishery development (Bertignac, 1988).

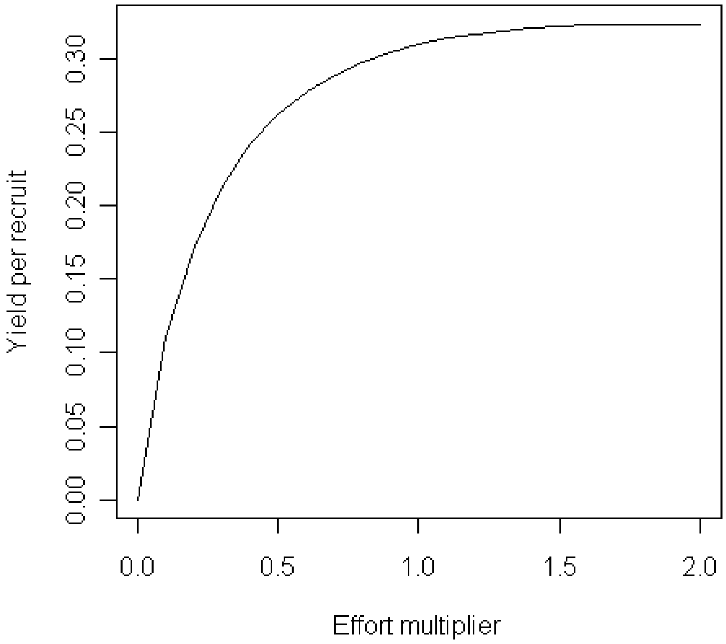

Fig. 23. Yield per recruit diagnosis based on the fishing mortality vector estimated through corrected pseudo-cohort analysis, considering a fishing effort multiplier from 0 to 2.

Appendix 2 - R scripts with comments for corrected pseudo-cohort analysis (seabass multispecies fishery)

```
#############
rm(list=ls())
rep <- "E:/manu-boulot/ISTAM/VPA rectifiee/CS0 Bar"	#Chemin d'accès à spécifier
setwd(rep)	#Change le chemin d'accès (où les fichiers de données sont présents)
#############

### Données d'entrée
# Contient les vecteurs aux ages de mortalite naturelle (MAT_M) et de capture (MAT_C)
MAT_C<-read.csv("captures-bar.txt", header=T, sep='	')  #Données de captures
MAT_Eff<-read.csv("efforts-bar.txt",header=T,sep=' ')  #Données d'efforts de pêche
recrutement<-read.csv("recrutement-bar.txt",header=T,sep='	')  #Données de recrutement
attach(recrutement)
Mortal<-as.vector(read.csv("mortalite-bar.txt",header=T,sep='	')) #Donn.es de mrtalité naturelle
attach(Mortal)

age<-length(MAT_M) #Définit le nombre de classes d'âge

### Fonction calculant la différence entre les captures (observées) et l'expression des captures
# en fonction de N, M et F (x : inconnu) -- La minimisation de cette fonction permet l'estimation de F

F_a_min <- function(x)
{
res<-(MAT_CTOT[indice]-(MAT_N2[indice]*(x/(x+MAT_M[indice])*(1-exp(-x-MAT_M[indice])))))^2
res
}

### Calcul des effectifs à chaque âge à partir de la série d'effort et de recrutement
# et de la capturabilité selon l'équation de survie
F_effectif1<-function(indice)
{
res<-MAT_N2[1]*(MAT_rec[indice+1]/MAT_rec[1]) #calcul du R qui a conduit à l'effectif
i<-1
for (j in indice:1)
{

if (nb_flot < 2)
	{
	res<-res*exp(-(MAT_Q[i,]*MAT_Eff[j+1,])-MAT_M[j]) # calcul de l'effectif (1 seul métier)
	}
else
	{
	res<-res*exp(-apply((MAT_Q[i,]*MAT_Eff[j+1,]),1,sum)-MAT_M[j]) # calcul de l'effectif (multi-métiers)
	}

i<-i+1
}
res
```

```
}

### VPA rectifiee descendante à partir d'une valeur initiale de R
F_pseudo_rectif<-function(init)
{

MAT_F2<<-MAT_C/MAT_CTOT # attention, initialisation de F2 au ratio de chaque metier
indice<<-1
MAT_N2[indice]<<-init
MAT_F2[indice,]<<-MAT_F2[indice,]*optimize(F_a_min,interval=c(0,2))$minimum    #
réallocation du F estimé pour chaque métier
MAT_Q[indice,]<<-MAT_F2[indice,]/MAT_Eff[1,]
MAT_N2[indice+1]<<-F_effectif1(indice)


for(compteur in 2:(age))
{
indice<<-compteur
MAT_F2[indice,]<<-MAT_F2[indice,]*optimize(F_a_min,interval=c(0,2))$minimum
MAT_Q[indice,]<<-MAT_F2[indice,]/MAT_Eff[1,]

if (indice<age) MAT_N2[indice+1]<<-F_effectif1(indice)
}
#on renvoie la somme
 if (nb_flot < 2)
          {
          MAT_F2[age,] # si 1 seul engin
          }

 else
          {
          apply(MAT_F2[age,],1,sum) # si multi-engins
          }
}

### VPA rectifiée à partir d'une valeur initiale de FT
F_pseudo_rectif_global<-function(init)
{

res<-(FT-F_pseudo_rectif(init))^2
res
}


### Initialisation du recrutement par la méthode de Pope  - minimisation nécessite
d'initialiser
# le calcul par une valeur "pas trop loin" de la solution

#Calcul_N_Pope<-function(indice)
F_rempli_N <- function(indice)
{
MAT_N[indice]<<-
MAT_N[indice+1]*exp(MAT_M[indice])+MAT_CTOT[indice]*exp(MAT_M[indice]/2)
}
#Calcul_F_Pope<-function(indice)
F_rempli_F <- function(indice)
{
```

```
MAT_F[indice]<<-log(MAT_N[indice]/MAT_N[indice+1])-MAT_M[indice]
}

# Calcule l'effectif à l'age a en connaissant M(a), F(a) et C(a)
F_effectif<-function(age)
{
res<-MAT_C[age]*(MAT_M[age]+MAT_F[age])/(MAT_F[age]*(1-exp(-MAT_M[age]-
MAT_F[age])))
res
}

F_effectiftot<-function(age)
{
res<-MAT_CTOT[age]*(MAT_M[age]+MAT_F[age])/(MAT_F[age]*(1-exp(-MAT_M[age]-
MAT_F[age])))
res
}

####### Methode de Pope ####

# Analyse en pseudo-cohorte isolée à partir d'une valeur initiale de F
VPA_Pope<-function(init)
{
#Affichage de la valeur initiale cad de la mortalite par pêche terminale
#print(paste("La valeur de F terminal est", $init))
print(init)

# Calculs suivant l'approximation de Pope
# Valeurs terminales de F et N
MAT_F[age]<<-init
MAT_N[age]<<-F_effectiftot(age)

# Calcul des effectifs et mortalites par pêche suivant Pope (pas de solveur)
for(i in 2:age-1) {
F_rempli_N(age-i)
F_rempli_F(age-i)
}
}

indice<-age

# Initialisation des valeurs des paramètres
MAT_F<-rep(NA,age) # mortalite par peche methode de Pope
MAT_N<-rep(NA,age) # effectifs methode de Pope
MAT_N2<-rep(NA,age) # effectifs methode rectifiee
nb_flot<-length(MAT_C[1,])  # nombre de flottilles
MAT_CTOT<-apply(MAT_C,1,sum) # somme des captures de chaque flottille
MAT_Q<-MAT_C    #initialisation des capturabilites par les captures
indice<-1 # age de recrutement

#------------------------

# Résolution par la méthode de Pope
VPA_Pope(0.2)
MAT_N

### VPA rectifiee - initialisation en R
```

```
MAT_F2<-MAT_C/MAT_CTOT
R_init<-929926  #Valeur issue de Bertignac, 1987
F_pseudo_rectif(R_init)

# VPA rectifiée - initialisation en FT
FT<-0.2
R_init<-MAT_N[1]
optimize(F_pseudo_rectif_global,interval=c(R_init/10,R_init*10))$minimum  # La valeur de recrutement initial est supposee se trouver dans un intervalle de valeurs autour du recrutement estimé par la methode de POPE
MAT_N2      #Effectifs aux ages estimes par la methode de VPA rectifiee
MAT_F2      #Mortalite par peche aux ages estimee par la methode de VPA rectifiee
MAT_Q

N<-MAT_N2
F<-apply(MAT_F2,1,sum)
F

##################################################
################## Graphiques  ##################
##################################################

#Visualiser les données d'entrée
#png(filename = "inputs-bar.png", width = 480, height = 600,pointsize = 12, bg = "white", res = NA, restoreConsole = TRUE)
opar<-par()
par(mar=c(4.2,4,0.2,1))
par(mfrow=c(2,1))
#par(mgp = c(3.1,0.5,0))
ageclass<-seq(2,19, by = 1)
plot(x = ageclass, y = MAT_C[,1], xlab = "Age", ylab = "Catch (numbers)", type = "l")
lines(x = ageclass, y = MAT_C[,2], type = "l", lty = 3)
lines(x = ageclass, y = MAT_C[,3], type = "l", lty = 5)
lines(x = ageclass, y = MAT_C[,4], type = "l", lty = 6)
text(x = 2.3, y = 46000, "(a)", cex=1.1)
textlgd<-c("Longliners", "Pelagic trawlers", "Small coastal fishing", "Misc.")
legend(x = 13, y = 49000, legend = textlgd, lty = c(1,3,5,6), bty = "n", y.intersp = 1.4, cex = 0.7)
annee<-seq(1985,1968,by=-1)
plot(x=annee, y = MAT_Eff[,1], xlab = "Years", ylab = "Relative fishing effort", type = "l", ylim = c(0,3600))
lines(x = annee, y = MAT_Eff[,2], type = "l", lty = 3)
lines(x = annee, y = MAT_Eff[,3], type = "l", lty = 5)
lines(x = annee, y = MAT_Eff[,4], type = "l", lty = 6)
text(x = 1968.5, y = 3400, "(b)", cex = 1.1)
textlgd<-c("Longliners", "Pelagic trawlers", "Small coastal fishing", "Misc.")
legend(x = 1970, y = 3600, legend = textlgd, lty = c(1,3,5,6), bty = "n", y.intersp = 1.4, cex = 0.7)
par(opar)
#dev.off()

# Graphiques pour visualiser les résultats
F<-apply(MAT_F2,1,sum)
N<-MAT_N2
#png(filename = "outputs-bar.png", width = 480, height = 600,pointsize = 12, bg = "white", res = NA, restoreConsole = TRUE)
opar<-par()
```

```
par(mar=c(2,4.5,0,2))
par(mfrow=c(3,1))
par(mgp = c(3.3,0.5,0))
plot(MAT_CTOT, xaxt = "n", xlab = "", ylab = "Total catches", type = "b", pch = 17, cex.lab = 1.3)
axis(1,at=c(5,10,15),tick = TRUE, labels = FALSE)
text(x=17.5,y=65000,"(a)",cex=1.1)
plot(F, xaxt = "n", xlab = "", ylab = "Fishing mortality", type = "b", pch = 17, cex.lab = 1.3)
axis(1,at=c(5,10,15),tick = TRUE, labels = FALSE)
text(x=1.2,y=0.47,"(b)",cex=1.1)
par(mar=c(5,4.5,0,2))
plot(N, xlab = "Age", ylab = "Fish numbers", type = "b", pch = 17, cex.lab = 1.3)
text(x=17.5,y=1050000,"(c)")
par(opar)
#dev.off()

# Analyse de sensibilite
varFT<-seq(0.2,1,by=0.2)
matF3<-matrix(NA, nrow = age, ncol = length(varFT))
R_init<-rep(NA,length(varFT))
for (i in 1:length(varFT)) {
VPA_Pope(varFT[i])
R_init[i]<-MAT_N[1]
FT<-varFT[i]
optimize(F_pseudo_rectif_global, interval=c(R_init[i]/10,R_init[i]*10))$minimum
for (j in 1:age)
if (nb_flot < 2)
          {
          matF3[j,i]<-MAT_F2[j,]
          }
else

          {
          matF3[j,i]<-apply(MAT_F2[j,],1,sum)
          }
                  }

#png(filename = "sens-bar.png", width = 480, height = 480,pointsize = 12, bg = "white", res = NA, restoreConsole = TRUE)
opar<-par()
par(mar=c(4.5,4,0.2,2))
plot(matF3[,1], xlab = "Age", ylab = "Fishing mortality", type = "l", ylim = c(0,1.2))
for (i in 2:length(varFT))
    {
    lines(matF3[,i], type = "l")
    }
par(opar)
#dev.off()

# Diagnostic de rendement par recrue (Y/R)
F<-apply(MAT_F2,1,sum)
mf<-seq(0, 2, by=0.1)
N4<-matrix(NA, nrow = age, ncol = length(mf))
Y4<-matrix(NA, nrow = age, ncol = length(mf))
MAT_Wtot<-read.table("poids-bar.txt", header = TRUE, quote = "\t")
MAT_W<-apply(MAT_Wtot[,-1],1,mean)
N4[1,]<-1
```

```
for (i in 1:length(mf))

        {for (j in 2:age)
        {
        N4[j,i]<-N4[j-1,i]*exp(-mf[i]*F[j-1]-MAT_M[j-1])
        }
        }

for (i in 1:length(mf))

        {for (j in 1:age-1)
        {
        Y4[j,i]<-MAT_W[j]*(mf[i]*F[j]/(mf[i]*F[j]+MAT_M[j]))*N4[j,i]*(1-exp(-mf[i]*F[j]-MAT_M[j]))
        }
        }

for (i in 1:length(mf))
        {
        Y4[age,i]<-MAT_W[age]*(mf[i]*F[age]/(mf[i]*F[age]+MAT_M[age]))*N4[age,i]      #
Prendre en compte les captures accumulées dans le groupe +
        }

Ytot<-apply(Y4,2,sum)

#png(filename = "YperR-bar.png", width = 480, height = 400,pointsize = 12, bg = "white", res
= NA, restoreConsole = TRUE)
opar<-par()
par(mar=c(4.5,4,0.2,2))
plot(mf,Ytot, xlab = "Effort multiplier", ylab = "Yield per recruit", type = "l")
par(opar)
#dev.off()
```