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A biomass production model with environmental effect : application to the shrimp fishery in Senegal

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ABSTRACT

This scientific technical report stands in the Working Package 3 "*Stock Assessment Methods and Analysis Tools*" of the ISTAM European project (http://projet-istam.org). The work package WP3 aims at improving the stock assessment methods, with a particular emphasis to models developed in data poor environment and for short lived species.

The present work presents an application of the Biomass Production Model for the stock assessment of Senegalese shrimps (*Penaeus notialis*).

Exploitation of the white shrimps (*Penaeus notialis*) by trawlers recently became a major fishing activity in several Western African countries. In Senegal, two stocks are intensely exploited: the north one around Saint-Louis and the Roxo-Bijagos stock in the south (the largest stock). Life cycle of shrimps is very short and recruitment is usually considered highly dependant of the upwelling intensity. Thus, fisheries management has to take into account diagnosis based on stocks assessment, but also to adapt to environmental variability.

The aims of this work are to understand and quantify the respective part of fishing and environmental effects on abundance of the Senegalese shrimps stocks and to establish a diagnosis on the stocks status and to estimate MSYs depending on environmental conditions.

Using a surplus production model which includes a additional effect of environment, we analysed changes in abundance of two main shrimps stocks of Senegal, over the past 10 years. We showed that the northern stock is still underexploited and that the driving force of abundance and catch is the upwelling intensity; conversely, the southern stock is strongly over-exploited and less affected by the environmental variability.

Key words: Western Africa, coastal upwelling, chlorophyll index, *Penaeus notialis*, variability of catches, Stock assessment

CONTENTS

1. INTRODUCTION

Exploitation of the white shrimp *Penaeus notialis* (Perez-Farfante, 1967) by specialized trawlers is one of the main marine activities for many coastal countries of West Africa. It constitutes the main species of Penaeidae exploited along the African west coasts. The species lives on muddy bottoms, from the coast to 65 m depth. In Senegalese waters, two stocks are intensely exploited, the north one around Saint-Louis and the Roxo-Bijagos stock in the south (Fig. 1) (the largest stock). The harvest from the south has annually varied and decreased over the study period (1740 t in 1996 to 685 t in 2005), while the harvest from north has been less than 1000 t year-1 without any trend.

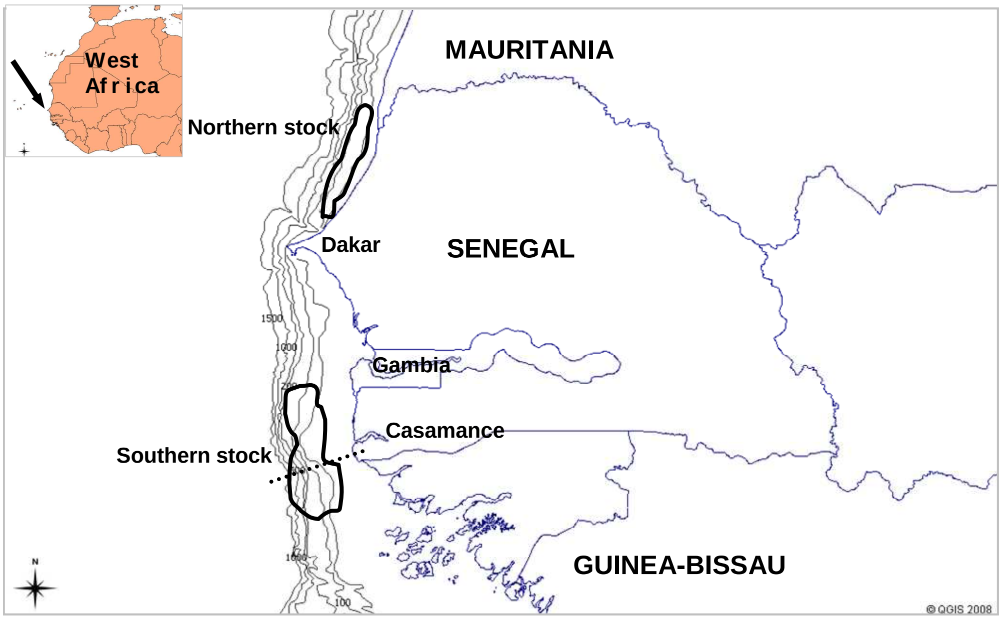

Figure 1: Localisation of the white shrimp fishing grounds in Senegalese waters

White shrimp stocks have been exploited since the end of 1960 (Lhomme, 1981; Caverivière and Thiam, 2002). Shrimps stocks present rapid and instable dynamics. Their potential of production varies very hard from one year to other one.

Modelling and understanding shrimps exploitation is a challenge for a series of reasons: shrimp distribution and abundance are influenced by environmental variation (Caverivière and Rabarison, 1997; Lhomme, 2001; Caverivière and Razafindrakoto, 2007), rapid growth and short life cycle. Life cycle of shrimps is very short and recruitment is usually considered highly dependant of the upwelling intensity. Thus, fisheries management has to take into account diagnosis based on stocks assessment, but also to adapt to environmental variability.

Therefore, fisheries catch and effort data have been analyzed with surplus production models including an additional effect of environment (e.g. Fox, 1970; Freon, 1991).

The first aim is to study abundance of the shrimps stock: seasonal pattern and interannual variation in abundance. The second aim is to understand and quantify the respective part of fishing and environmental effects on abundance of the Senegalese shrimps stocks and the third, to establish a diagnosis on the stocks status and to estimate MSYs depending on environmental conditions.

2. MATERIALS AND METHODS

2. 1. Data

2.1.1. Abundance indices

The CPUE data were expressed as shrimp catch in kilograms per day fishing. Databases, provided by the Centre of Oceanographic Research of Dakar-Thiaroye (CRODT) and data collected from Sopasen industry were registered by trawlers operating in the Senegalese ZEE.

The catch per unit effort (CPUE) is calculated from the catch (Y in kilograms) of Senegalese trawlers and fishing effort (E in number of day fishing) by fishing year, month, area and mean engine power of fishing boat as following expression:

$$CPUE_{y,m,z,f} = \frac{Y_{y,m,z,f}}{E_{y,m,z,f}}$$

where y refers to year, m to month, z to area, f to fleet (boats with the same engine power class).

Generalized linear modelling (GLM) techniques were applied to these CPUEs to obtain an index of relative abundance (adjusted cpue) independent of changes in spatial fishing patterns and the spatial distribution of the resource, but assuming stability in fleet composition through the study period. Indeed, basic cpue is influenced by several (significant) factors: the heterogeneous spatial distribution of the fleet and of the resource, and the different technical characteristics of boats. Therefore, the factors taken into account in GLM process are: year, month, fishing area and mean engine power of fishing boat.

The index of abundance is expressed as fellow:

$$\ln CPUE_{y,m,z,f} = \ln IA_{y,z} + \ln .d_m + \ln P_f + \ln \varepsilon_{y,m,z,f}$$

where IAy,z is the effect of combined factor fishing year and area that can be interpreted as a annual abundance index by fishing area (adjusted cpue), d_m the effect of the factor month, Pf the effect of the factor engine power-class, and εy,m,z,f is the normally distributed residual variation.

Gaussian error-model, to fit the distribution of residuals, was chosen according to goodness of fit of statistics models.

2.1.2. Environmental variables

Predictive models based on environmental factors typically depend on one or two driving variables, which presumably control the survival of earlier life stages. For example, penaeids are subtropical species whose range extends into warm temperate waters, but temperatures below 18-20◦C are suboptimal for growth (Witzell and Allen, 1982) and may have a measurable effect on production if temperature drops below 20◦C for a large part of the year (Staples *et al*., 1985).

Seasonal climatology of sea surface temperature and sea surface chlorophyll, given by SeaWiFS sensor shows seasonal dynamics of the coastal upwelling, with a maximum in winter. The local enrichment, which is maximum in winter, is clearly visible using biomass index derived from phytoplankton density (mg/m^3). Two environmental variables, upwelling and primary production indices (Fig. 2) were incorporated in the predictive models as possible predictor variables. The values for all environmental variables were used in the predictive models as monthly averages. Both, the fishing effort and environmental variables were found from previous studies (Lhomme and Garcia, 1984) to impact shrimp catch rates of the west coast trawl fishery of Senegal. These two environmental indices are alternatively tested in the model. The one is measuring the coastal upwelling intensity (Fig. 2a) from wind speeds provided by the SeaWiFS database; the other is related to the primary production (Fig. 2b) derived from satellite infrared images of chlorophyll a (NOA database, http://las.pfeg.noaa.gov).

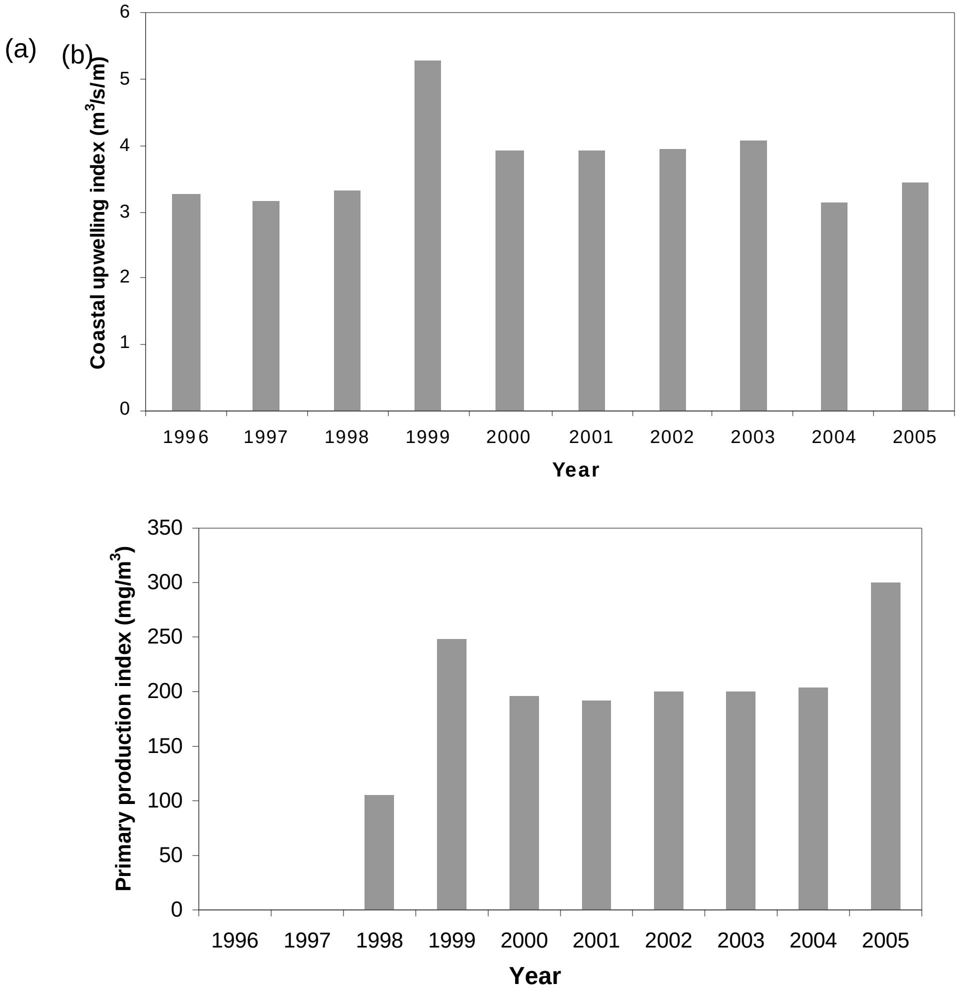

Figure 2: Environmental variables used in the models: (a) Coastal upwelling (northern stock) and (b) primary production (southern stock)

Coastal upwelling index (m3/s/m), obtained from the site of the division of environmental research (ERD Upwelling and Environmental Index Products) is calculated according to the Ekman's theory of transport of masses of surface water by the wind and rotation of the earth. Series came out, is monthly and goes from January, 1967 till March, 2007, for two points corresponding to shrimps stocks areas. Chlorophyll index obtained corresponds to the wind effort of north or northeast direction divided by the Coriolis parameter, which is a function of rotation and latitude of the earth.

Chlorophyll a concentration data come from historical data of the sensor SeaWiFS, download from the site of NASA (http://daac.gsfc.nasa.gov), with a frequency of 8 days. The average spatial resolution of the data was 4,5 km and monthly images of surface chlorophyll a concentration were generated by simple averaging, similar to Demarcq *et al.* (2003). The chlorophyll indices constitute monthly mean concentration of chlorophyll a (mg/m3) between the coast until 1 mg/m3. Data are available between September, 1997 and November, 2005 and cover all western African zone (10 °N - 36 °N).

2.2. Fox surplus production model including an environmental variable

Surplus production models are simple models for harvesting without age and the surplus production is the rate at which individuals can be removed from a population without change in population size. Surplus production models assume that a population's capacity to increase is a function of population density, and that population density will not change if members are removed at the same rate as the population's capacity for increase (Jensen, 2005). The abundance index used in the surplus production model including the effect of environment is the Index of abundance derived from the cpue of a selected homogenous fleet (industrial fishing). Derived from these indices and from total catches (Y), theoretical fishing efforts (E) are calculated as follow:

$$E_y = \frac{Y_y}{IA_y}$$

where y refers to year.

In a first step, a Fox model without environment effect was adjusted. It is expressed as:

$$IA_y = b \times e^{a \times E_y}$$

where a and b are parameters.

Two types of surplus production models with effect of environment (Fréon, 1991), based on Fox model, are tested. They translate an environment effect on the recruitment and so, on abundance. Fox Models are fitted to the 1996 to 2005 time series and express the abundance (AI) of each stock as a function of the fishing effort (E) and the environmental index (V), (Fréon, 1991; Fréon et al., 1992).

The first corresponds to a linear effect of upwelling index.

$$AI = (a + V^b) \times e^{c \times E} \qquad (1)$$

where a, b and c are parameters.

Second corresponds to a non-linear effect.

$$AI = (a \times V^b) \times e^{c \times E} \qquad (2)$$

These models are adjusted on Excel, on the whole available series, from 1996 to 2005.

3. RESULTS

Both models give similar results. However the best results are obtained with model 2. As a result, only the second model is presented here.

3.1. Abundance index

White shrimps are almost off-loaded in every tide and occurrence is therefore close to 1. Hence, Gaussian model is used to estimate the annual abundance indices. The model explains 43.29% of the deviance (Table 1). In the model, there is an interaction effect between the year and the fishing area. The two shrimps stocks do not evolve in an identical way in the course of time. The yearly effect explains the largest part of the total deviance (17%). It is followed by the monthly effect, which explains 10.3% of the total deviance. This explains the existence of strong interannual and seasonal variations of the abundance of shrimps stocks.

Table 1: CPUE GLM modelling of national industrial fisheries: structure of conserved models and statistical results - Gaussian model: CPUE white shrimp ~ year * area + month + fishing boat

	Df	Deviance	Resid. Df	Resid. Dev	% Deviance	P(>|Chi|)
NULL			1049	1671.72		
Year	10	284.43	1039	1387.29	17.01	4.68E-59
Area	1	16.94	1038	1370.34	1.01	2.19E-05
Month	11	172.54	1027	1197.81	10.32	1.96E-33
Fishing boat	9	155.55	1018	1042.26	9.30	5.56E-31
Year : area	10	94.38	1008	947.88	5.65	4.60E-17

For the northern stock, the index levels varied considerably between years, but no clear trend is apparent (Fig. 3). The maximum abundance was observed in 1999-2001 and the minimum in 1997. Annual abundance varied between years by a factor of 4.

For the southern stock, yearly indices indicated also high variability in stock abundance but the abundance has been reduced by 4-fold over the past 10 years (Fig. 3).

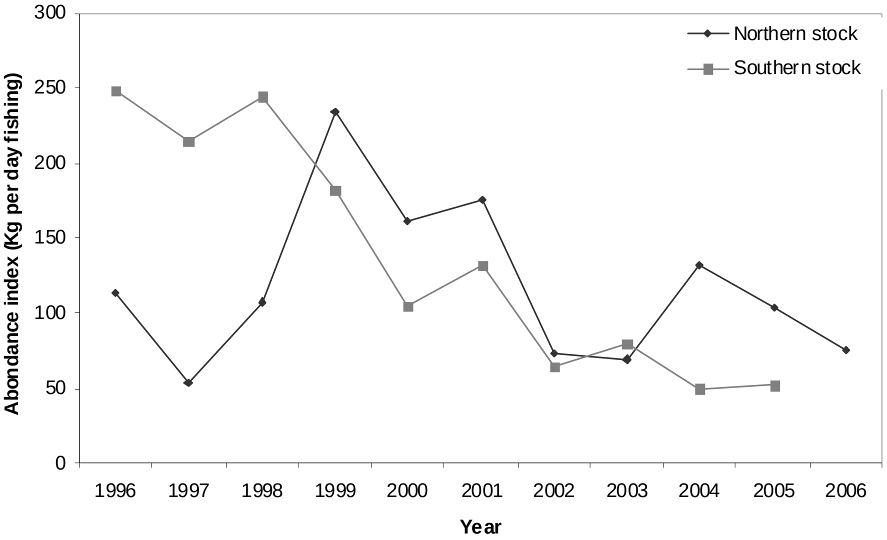

Figure 3: Abundance indices of Penaeus notialis estimated from industrial data for both stocks from 1996 to 2005

3.2. Catches

In Senegal, annual shrimp landings ranged from 2476 metric tons (t) (1996) to 1204 t (2005), decreasing significantly over the 1996-2005 period, and especially during the latest two years. The decrease mostly affected the southern stock where landings were divided by almost three between 1998 and 2005. Conversely, catches on the Northern stock exhibited a high year-to-year variability, but no clear trend (Fig. 4).

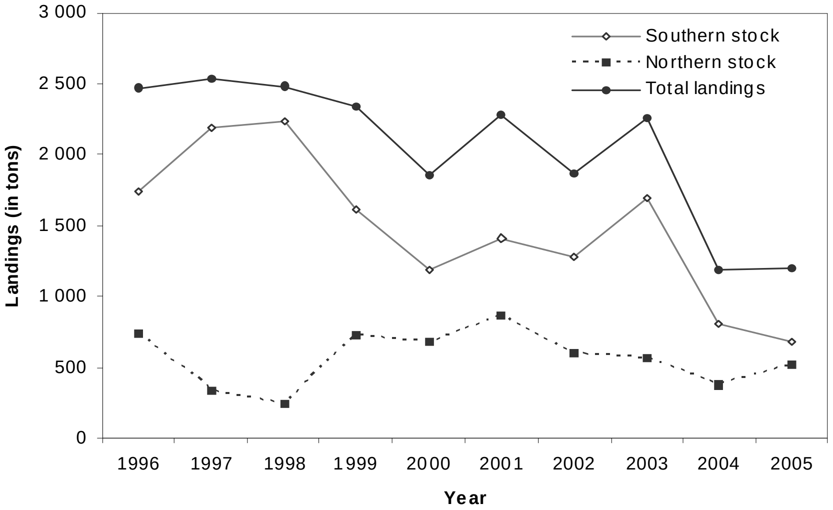

Figure 4: Catch trends for Senegalese shrimps (Penaeus notialis) for the period 1996 to 2005

3.3. Northern stock

For the northern stock, the model based on the index of upwelling intensity explains 64.9% of the year-to-year variability (Table 2).

Compared with a simple model (Fox model without environmental effect), considering environment significantly improves the prediction. The corrected R^2 between observed index of abundance derived from GLM and predicts based on the Freon model tacking into account either the Coastal Upwelling Index (CUI), changes from 0.18 to 0.65 (Table 2). The model with effect of environment definitely gives an account of values of abundance raised during 1999 and 2001 of very intense upwelling, and a sensitive fall in 1997-1998, years of upwelling not much marked.

Table 2: Variance explained by the various models: corrected R^2 between observed Index of abundance and predicts based on the Fox model (without environmental effect) or based on the Fréon model (tacking into account either the Coastal Upwelling Index (CUI), or Primary Production Index (PPI)

	Northern stock			Southern stock		
	AI Fox	AI (CUI)	AI PPI	AI Fox	AI (CUI)	AI PPI
Corrected R^2	0.177	0.649	0.435	0.707	0.656	0.752

Fishing effort and abundance fluctuates over the period without any clear trends (Fig. 5a), and the stock seems to be close to the full exploitation. The abundance of the stock mainly depends on the coastal upwelling index, which explains 47.2% of the total variance.

The model shows that the level of production greatly depends on environmental conditions (Fig. 5b). MSY for instance varies from 300 to 900 tons for respectively the lower and the upper values of the observed interval of yearly upwelling indices (Fig. 5c). Moreover, the environmental model does not change the diagnosis of full exploitation (Table 3).

Table 3: Parameters estimated and estimated quantities for the Fox and Freon surplus production models applied to northern shrimp stock of Senegal

Parameters	Fox model	Fréon model (CUI = 3.74 $m^3/s/m$)
a	-0.000147	34.59
b	238	1.43
c		-0.73
MSY (in tons)	597	608
mEmsy	1.4	1.4
Emsy	6980	6980
Y2005./MSY	0.869	0.853

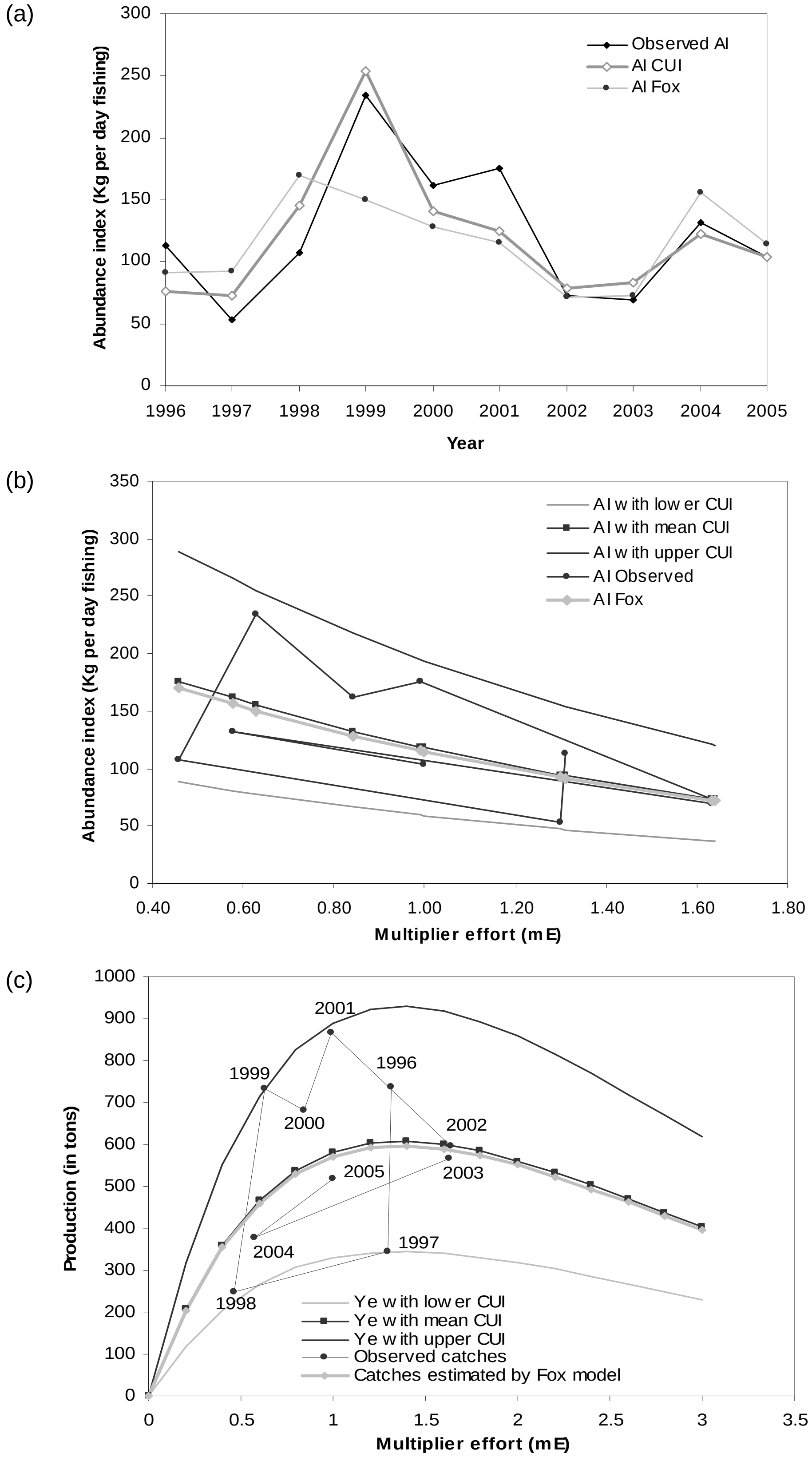

Figure 5 : Northern shrimp stock of Senegal: (a) catch per unit of effort (CPUE) observed and predicted based on Fox model (without environmental effect) or based on the Fréon model (tacking into account either the Coastal Upwelling Index (CUI) from 1996 to 2005, (b) exponential-exponential production model based on time series of catch per unit of effort (CPUE), of estimated effective fishing effort (E) and upwelling index (V), (c) exponential-exponential production model based on time series of catches, of estimated effective fishing effort (E) and upwelling index (V)

3.4. Southern stock

For the southern stock, the best fit is observed using the primary production index (corrected $R^2 = 0.75$) (Table 4). Compared with a simple model (Fox model without environmental effect), considering environment improves the prediction. The corrected R^2 between observed index of abundance derived from GLM and predicts based on the Freon model tacking into account either the primary production index, passes so from 0.71 to 0.75 (Table 2).

Table 4: Parameters estimated and estimated quantities for the Fox and Fréon surplus production models applied to southern shrimp stock of Senegal

Parameters	Fox model	Fréon model (PPI=205.63 mg/m3)
a	-2.339	12570.293
b	985.866	-0.615
c		-1.545
MSY (in tons)	2021	1473
mE_{msy}	0.4	0.6
E_{msy}	5225	7838
Y_{2005}./MSY	0.3388	0.4624

Fishing effort strongly increased during the period, while the abundance has been reduced by 4-fold over the past 10 years (Fig. 6a). The stock is nowadays significantly overfished whatever the environment could be (Fig. 6b, 6c). Compared to E_{MSY}, the surplus of fishing effort for 2004-2005 is estimated equal to 64%, independently of the upwelling intensity. The loss of production compared to MSY is equal to 63%.

Nevertheless, upwelling intensity explains 4% of the variance and results in significant changes in predicted catches. MSY for instance varies from 1600 to 1900 tons for respectively the lower and the upper values of the observed interval of yearly upwelling indices. So, from one year to the next, the fishing may exhibit strong changes, in terms of fishing effort and especially captures, which can be explained by the interannual variations of the upwelling intensity.

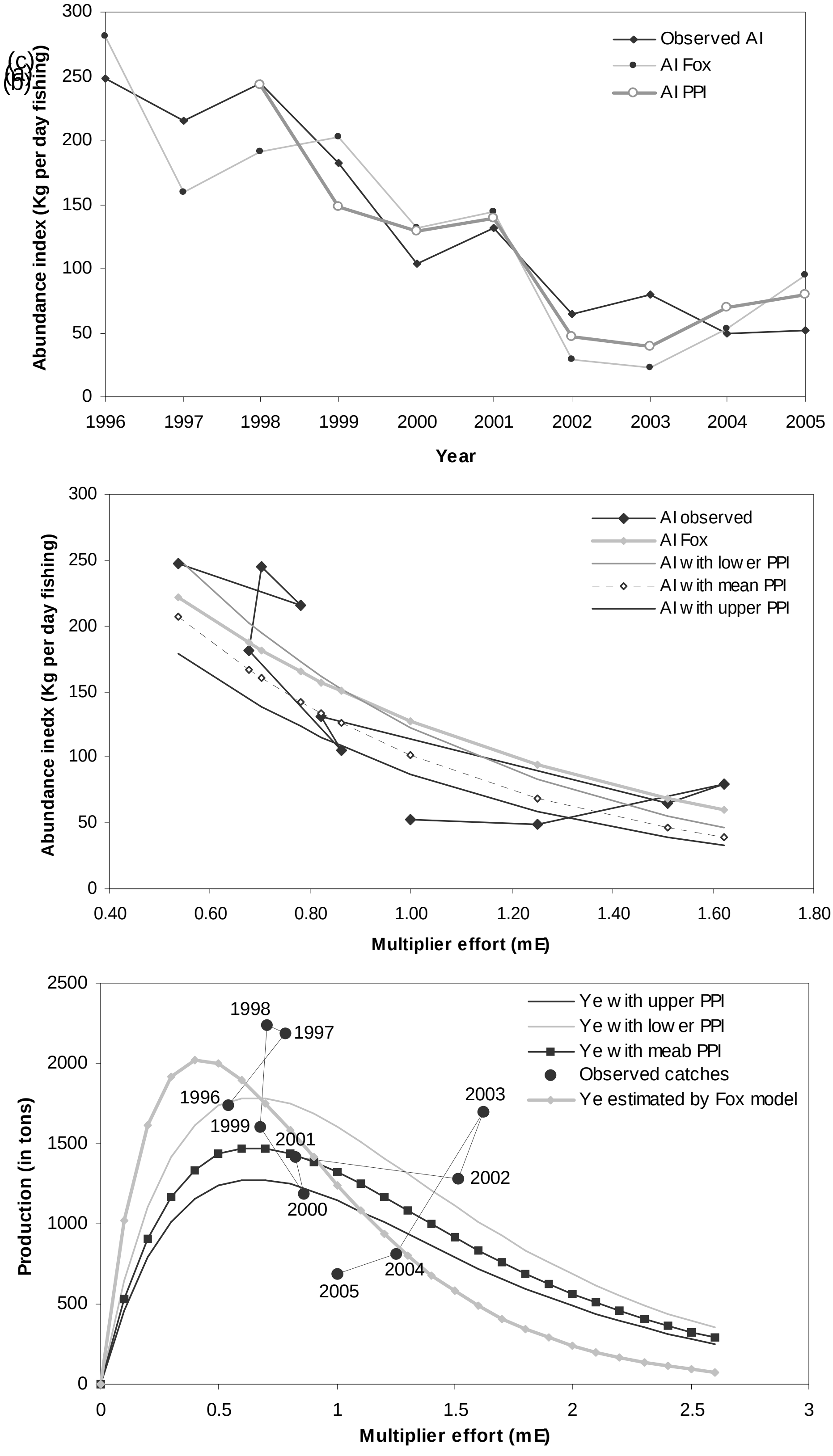

Figure 6: Southern shrimp stock of Senegal: (a) catch per unit of effort (CPUE) observed and predicted by an exponential-exponential production model of the time series of the estimated effective fishing effort and primary production index from 1996 to 2005, (b) exponential-exponential production model based on time series of catch per unit of effort (CPUE), of estimated effective fishing effort (E) and primary production index (V), (c) exponential-exponential production model based on time series of catches, of estimated effective fishing effort (E) and upwelling index (V)

4. DISCUSSION AND CONCLUSION

In Senegal, no relation was put in an obvious place between outputs or catches and the coastal upwelling index, contrary to what was noticed for other Peneidae stocks in other regions (Freon *et al*., 1992).

The total fishing effort applied to demersal resources, already important in Senegal at the beginning of 1980s was multiplied by 2,5 (Gascuel *et al*., 2004), thus, drawing away in the course of the last three decades, environmental changes in the composition of the marine populations. In fact, many fish stocks collapsed to the advantage of other species in shorter life, such as octopuses and shrimps. This is one of the essential results drawn from studies conducted by the project; Fisheries Information and Analysis System (FIAS, 2005). For example, it was shown that the fishery had reduced the biomass of emblematic species (Thiof, Pageot), about by a factor of 10 (Gascuel *et a*l., 2004). In effect, a surplus production model with effect of environment (abundance of fish) was consequently tested. Results show that the main stocks of fish exploited and shrimps stock in the south of the country were subjected to the same evolution (diminution of their abundance).

In general, penaeid shrimp have short life cycle, rapid growth, and high rates of natural mortality associated with the early stages (Garcia and Le Reste, 1986; Hendrickx, 1995).

Some studies have shown that penaeid recruitment and population dynamics are strongly influenced by a wide range of physical mechanisms that affect the migration of planktonic stages (larvae and postlarvae) from spawning grounds in the open ocean to coastal nursery areas (Garcia and Le Reste, 1986). As for phytoplankton food during the first stages of marine life, then for detritus food before even their return from the zones of mangrove swamp neighbouring, Freon *et al*. (1992) assume that they are sensitive to the fluctuations of the upwelling.

Survival during the first stages of development is highly associated with abiotic variables (Díaz-Ochoa *et al*., 2008) such as salinity or rainfall (Le Reste, 1992, for *Penaeus notialis* in Casamance estuary). In addition, sea surface temperature may regulate both juvenile shrimp growth and adult shrimps yields (e.g. Penaeus duorarum off Caroline (USA) during the two colder weeks in the year: Hettler, 1992; *Litopenaeus vannamei* off northern Peru, during years with and without El Niño: Mendo and Tam, 1993). Another important abiotic variable for determining penaeid shrimp abundance is freshwater input (Lhomme, 2001). Rainfall was negatively correlated with *P. notialis* juvenile abundance in the Casamance estuary, southeast of Senegal (Le Reste, 1982, 1992; Lhomme and Garcia, 1984) and *Litopenaeus setiferus* juvenile abundance in the Terminos Lagoon, southwest Gulf of Mexico (Gracia, 1989). Runoff was positively associated with catches of *Metapenaeus macleayi* and *Fenneropenaeus merguiensis* in southeast Queensland, Australia (Loneragan and Bunn, 1999), whereas Diop *et al*. (2007) found a negative association between the abundance of juvenile *Litopenaeus setiferus* and both river discharge and cumulative wetland loss in Louisiana. The extent of suitable nursery habitats such as mangroves has also been considered crucial for determining penaeid shrimp abundance (a negative effect associated with mangrove loss), for instance for *Fenneropenaeus merguiensis* in northern Australia (Vance et al., 1990) and Malaysia (Loneragan *et a*l., 2005) and for nine penaeid species off the Philippines (Primavera, 1998). In addition, recruitment success has been associated with physical transport mechanisms such as tides (e.g. Criales *et al.,* 2005 for *Farfantepenaeus duorarum* in Florida Bay, USA), meander rings (e.g. Criales and Lee, 1995; Criales *et a*l., 2003 also for *Farfantepenaeus duorarum* off Florida), and the direction of subtidal currents for entering the nurseries (e.g. for *Litopenaeus setiferus* postlarvae in Georgia, USA; Wenner *et al*., 2005).

The resource shows marked interannual variability in catches, a phenomenon common to most fisheries of short-lived species, reflecting changes in local abundance.

Our analyses represent a first attempt to identify relationships between variability in shrimp landings in both stocks and factors influencing these landings. The results show that the northern stock is still underexploited or fully exploited and that the driving force of abundance and catch is the upwelling intensity; conversely, the southern stock is strongly over-exploited and less affected by the environmental variability. In the north of Senegal, the seasonal upwelling is highly variable from year to year and constitutes the major factor determining this productivity. In the South, hydrodynamic processes seem to dominate and determine the primary production.

Several studies have analyzed the association between precipitation, primary productivity, coastal upwelling index and the recruitment of other penaeid shrimp.

For example, between 1969 and 1994 in the south of the Gulf of Mexico (Campeche Sound), the migration of the shrimp *Farfantepenaeus duorarum* towards the nursery areas was correlated with the rainy season, primary productivity, and oceanic circulation patterns, whereas periods with peak juvenile recruitment in the fishing areas were affected by rain, river runoff, and winds from the north (Ramirez-Rodriguez et al., 2003).

The area, off the Senegalese coast, was described by Roy (1989), as environmentally affected by oceanographic processes such as upwelling during November-May, in turn, is closely related to atmospheric dynamics determined by the seasonal changes in the Trades Winds direction associated with the latitudinal migrations of the ITCZ. The Senegalese ecosystem does not constitute a homogeneous system on the two sides of Cap-Vert peninsula (Roy, 1989). According to speed and direction of wind, the upwelling intensity and mineral salts bringing show important difference on both sides of the peninsula. Upwelling in the two regions will be comparable in period of strong trade wind. On the contrary, in weak trade wind period, the predominant winds are orientated northwest-north. Resurgence and mineral salts bringing will be more important in the south region (Roy, 1989).

Therefore, Northeast Trades are associated with a generalized increase in primary production at the end of the year and the beginning of the following year (Roy, 1989). In the north of Senegal, the upwelling intensity (inferred from variations in wind speed) has been linked to white shrimp production. A similar relationship was also proposed for the Colombian shrimp fishery, lagged 4-6 months (Forsbergh, 1969) and In Panama, but the landing statistics are lagged 3 months (Díaz-Ochoa *et al*., 2008).

Our results show that the oceanographic conditions for the regional circulation around the West African coasts, associated with global and regional climate regimes, can influence the population dynamics of white shrimps. This is especially true for recruitment, which seems to be enhanced during high upwelling intensity periods (in winter). In combination with the effects of fishing exploitation, resulting in a decreasing trend in yield of species, this environmental influence could be the basis of interannual fluctuations observed in landings of these and other important resources in the area (e.g. *Sardinella sp.* and *Octopus vulgaris*), most with similar periodicity (Freon *et al*., 1992; Olivier, 1993 and Carbonell *et a*l., 1999; Laurans *et al*., 2002).

For this case (case studies of ITAM project), we will attempt to make estimates of biomasses (stock) and of activity levels (actual fishing efforts), by taking care to adapt the assessment tools to the data characteristics (scientific/commercial CPUE, short-lived species, uncertainties about the CPUE, activity in numbers of strata for the small-scale fisheries or in catches for each identified boat for the industrial fisheries, etc) and the variability of environment.

The key to the fisheries management of exploited shrimps is the variability of their recruitment, the environment and the ability of the fisheries to adapt quickly.

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