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Studying the ten years variability of *Octopus vulgaris* in Senegalese waters using generalized additive model (GAM)

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Abstract
In the Senegalese upwelling ecosystem, *Octopus vulgaris* population shows high seasonal and interannual variability. Simple regression methods have been applied to investigate how octopus abundance is related to environmental change. However, the precision of such models is still unclear due to the non-linear character of the relationships. This work applied generalized additive model (GAM) to investigate ten years (1996-2005) variability of octopus recruitment in the Senegalese waters. The semi-parametric smooth function and Poisson distribution were used to build the models. The variables included in the models were sea surface temperature (SST and time (Month and Year). We show that GAM is more useful and relevant in investigating the complex relationships between octopus recruitment and SST at seasonal and interannual scales than classical regression techniques, by offering the best fits. We demonstrated that high octopus recruitment occurred at water temperature range between 17.5 and 18 °C.

Keywords: Generalized additive model; *Octopus vulgaris*, Senegalese waters, SST

Introduction

Octopus vulgaris is today one of the most targeted species in Senegal because of its commercial value. Its main fishing area is located to the south of Dakar, near of Mbour (Fig. 1). The resource shows marked interannual and seasonal variability in catches [4], a phenomenon commonly exhibited by most fisheries involving short-lived species, and which reflects changes in local abundance [22]. High levels of abundance were first observed during the summer of 1986. Exploitation started that year, and in subsequent years, catches varied considerably, from <5 000 tonnes (t) to 15 000 t, and reaching a peak of nearly 45 000 t during the summer of 1999 [4, 7].

Previous studies suggested that annual variability of octopus catch was somewhat the results of environmental changes. Annual variation in abundance and recruitment of octopus has been attributed to the variations of environmental conditions [9; 10, 17]. Most studies linking octopus abundance to environmental changes were based on traditional regression techniques [1, 2, 3, 4, 5, 9, 10, 20, 21].

However, the likely non-linear nature of the relationships would suggest the use of models which are able to take into account such character, as generalized additive model (GAM). More information would be obtained by using GAMs than traditional regression techniques for exploring the complex relationships between marine resources and environmental and temporal parameters. In this work, we aimed to better illustrate the abundance of octopus as function of environmental over time using generalized additive model (GAM).

Materials and methods

Biological data

The total catch in weight of octopuses fished monthly during January 1996 to December 2005 in Senegal was provided by the Oceanographic Research Centre of Dakar-Thiaroye (CRODT, Centre de Recherche Océanographiques de Dakar-Thiaroye) in addition to the relative catches from artisanal and industrial fisheries for that same period.

Octopus age was determined using the growth equation [8], and a catch-at-age table was created from the landing-by-size data [13]. This table was used to generate a catch-by-age

Matrix, assuming a stable growth pattern. Then, monthly recruitment of 5-month-old individuals was estimated for 1996-2005 period, through age-structured virtual population analysis (VPA) [21].

Environmental data

The environmental predictor variables used for this analysis were sea surface temperature (SST, °C). SST data were obtained from the Pathfinder V5.0 sensor (day and night images; 4.4 km resolution). Data covered the time period between January 1996 and December 2005. SST were averaged from 13°5 N to 14°5 N and from the coast to the 200-m isobaths, the octopus stock area (Fig.1).

Sea surface temperature is an environmental factor which is most often used in investigations of relationships between the environment and fish behavior and abundance [14]. Change in temperature as small as 0.1 °C can be perceived by many fish species [15]. Temperature can affect fish in many different ways by affecting the rates of metabolic processes and thus modify their activity level. Temperature influences marine species at different stages of their life cycles, for instance, during spawning, and at the development and survival of the eggs and larvae, as well as influencing distribution, aggregation, migration and schooling behavior of juveniles and adults [11; 16, 19].

Data analysis

The generalized additive model (GAM) was used to investigate the associations between SST, month and year, and octopus recruitment. It allow to depict the complex relationships between species and their environment [25].

GAM is described as a generalization of ordinary linear models [24]. In these models the linear predictors are related to the response variables via a link function that extends the use of the regression models beyond non-Gamma response variables. GAM uses data-driven functions, such as splines and local regression, which have superior performance relative to the polynomial functions used in linear models. The semi-parametric smooth functions (s) were used to fit the interactions between the predictors (SST, month and year) and the dependent variable, octopus recruitment. The link function used in this case is Gamma, because the most significant results were obtained with it after test.

The MGCV package in the software R (version 3.2.3) was used. This software (R) is a free software programming language and a software environment for statistical computing and graphics widely used for data analysis.

The dependent variable, octopus recruitment is modelled as the additive sum of unspecified non-parametric functions of hypothesized covariates and their interaction.

Results

The scatterplots (Fig. 2) suggest that in the area of octopus catch:

a. High octopus recruitment appeared to be associated with upwelling season during 1996-2005 period.
b. The pattern of the relationship between octopus recruitment and year were not clear. The most important octopus recruitment was observed in 1999 and 2002.
c. The largest octopus recruitment (65.23%) was apparently observed in SST ranges between 17 to 22 °C.

The patterns of single effect of the covariates are shown (Fig. The general structure through the year is quite clear, with a maximum effect in upwelling months which decreases progressively toward warm season months, whose effect is negative. Regarding the effect of year, it shows significant and variables patterns from a year to another (Fig. 3b). Its higher and positive effects occurred in 1999 and 2002. As for the relationship between SST and octopus recruitment, it consists of positive effect on recruitment at temperature below 24 °C and negative above 24 °C (Fig. 3c).

The patterns of the interaction between SST and temporal variable (month and year) are illustrated (Fig. 4). It is found that the effect of SST on octopus recruitment highly differs from a month to another and year to year. Its higher effect through the year is observed between December and June (Fig. 4a). The most important effect of SST occurred when at temperature between 17 and 18 °C, and this cold water was observed in March. Regarding the interannual effect of SST on octopus recruitment, the highest was recorded in 1999 at SST ranges between 17.5 and 18 °C (Fig. 4b). Significant effect of SST was also observed in 2002.

The results of the individual and the combined effects of the covariates on octopus recruitment are summarized in table 1. All the variable and their interactions are significant at 99.99% level. Looking after the percentage of the explained deviance of single variable, month, year and SST explain, 27.9%, 55.9% and 52.9% of the variability of octopus recruitment, respectively. The combined effect of SST and year, exhibited the highest explained deviance, 86.4%, almost the double deviance of its interaction with month (48% of the total deviance).

Table 1: Significance values (p-values, % of the explained deviance and AIC) of the covariate effects on octopus recruitment. Level of significance was set to 0.05.

Covariates	Degree of Significance		AIC		% of explained deviance	
	GAM	GLM	GAM	GLM	GAM	GLM
Month	<2e-16 ***	<2e-16 ***	622690810	693292580	27.9	19.7
Year	<2e-16 ***	<2e-16 ***	381063591	851325172	55.9	1.4
SST	<2e-16 ***	<2e-16 ***	406775127	517743637	52.9	40
SST/Month interaction	<2e-16 ***	<2e-16 ***	448552675	507163548	48	41.2
SST/Year interaction	<2e-16 ***	<2e-16 ***	116975820	507017974	86.4	41.2

Discussion

The link between environmental variables and distribution and abundance of octopus using simple linear models has been demonstrated by several authors. Caballero *et al*. (2010) applying simple linear model, found that the variability of SST through the year was the major responsible for octopus abundance off the Canary Islands. In Senegalese waters, based on simple correlation and linear model, it was found that octopus recruitment is linked to SST [20, 21]. However, the complexity of such interaction due to the non-linear population dynamics response [18], raises questions about the appropriateness of applying such model to investigate the link between marine resources and environmental parameters.

This study exhibited the non-linear pattern of the relationship between SST and octopus abundance at seasonal and interannual scales. It is showed that highest octopus recruitment occurred in upwelling season when water temperature is between 17.5 and 18 °C. Higher octopus recruitment was recorded in 1999 and 2002, because in both years, water temperature were around 18 °C during the cold season (Fig. 5). This study demonstrated the ability and effectiveness of GAM to investigate the complex relationship between octopus recruitment and upwelling intensity. It pointed out that GAM is more efficient than generalized linear model (GLM) in table 1. The results from GAM are more significant than those from GLM. Even if both models are very significant, the explained deviance and the Akaike information criterion (AIC) of GAM origin are the most important and lowest, respectively. It is worth highlighting that model with the lowest AIC values, is statistically the most significant.

Previous studies have suggested that short-lived species such as octopus are characterized by a strong sensitivity to environmental conditions [1, 6, 9]. According to Jouffre *et al*. (2000), octopus is very sensitive to the fluctuations of upwelling intensities in breeding areas. And temperature mostly influences the first life stage of octopus, mainly on the growth of octopus larvae and juveniles, and acts also on the survival of octopus paralarvae [1, 12]

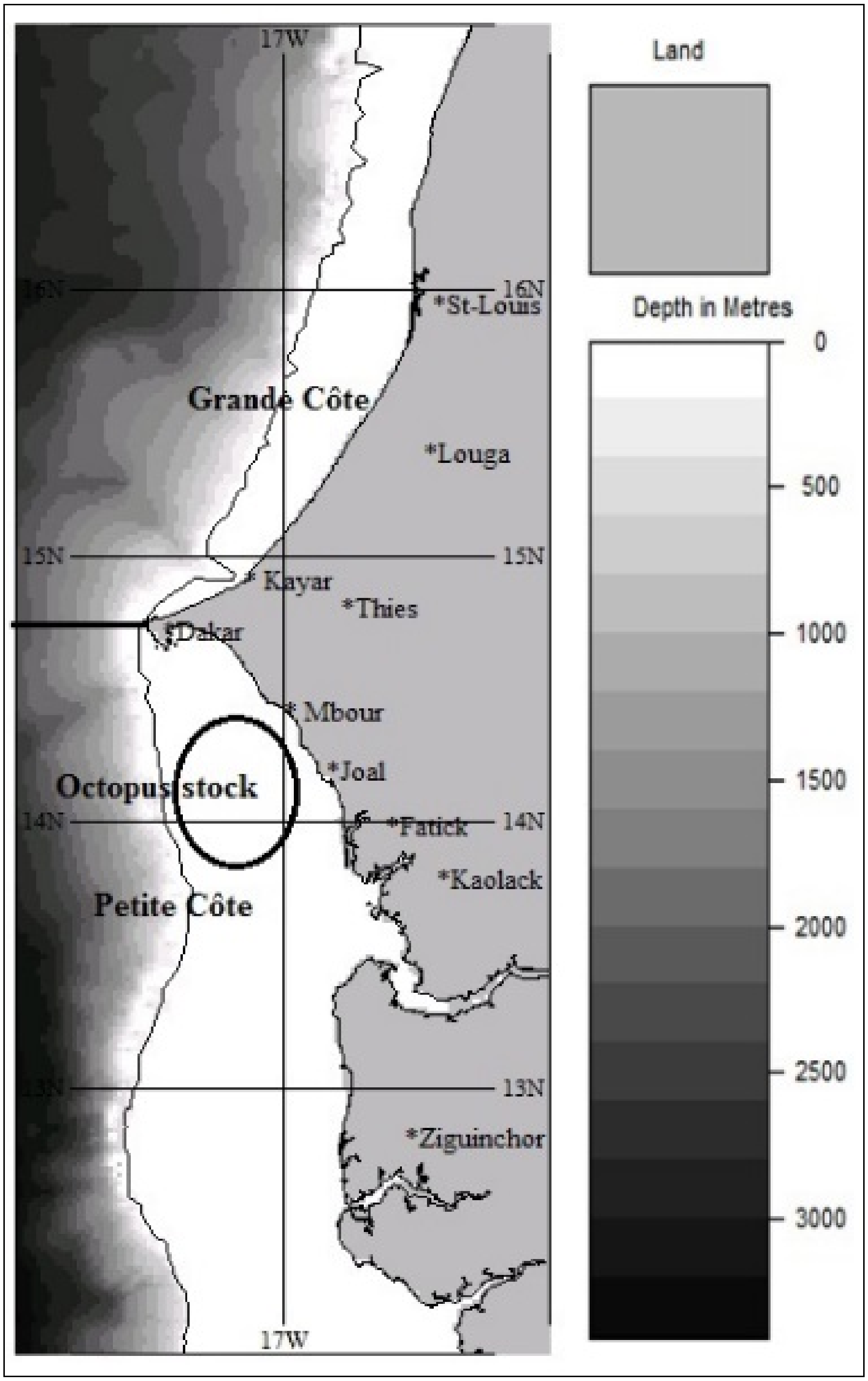

Fig 1: Localization of the main octopus fishing ground in Senegalese waters. The black line represents the 200 m isobaths.

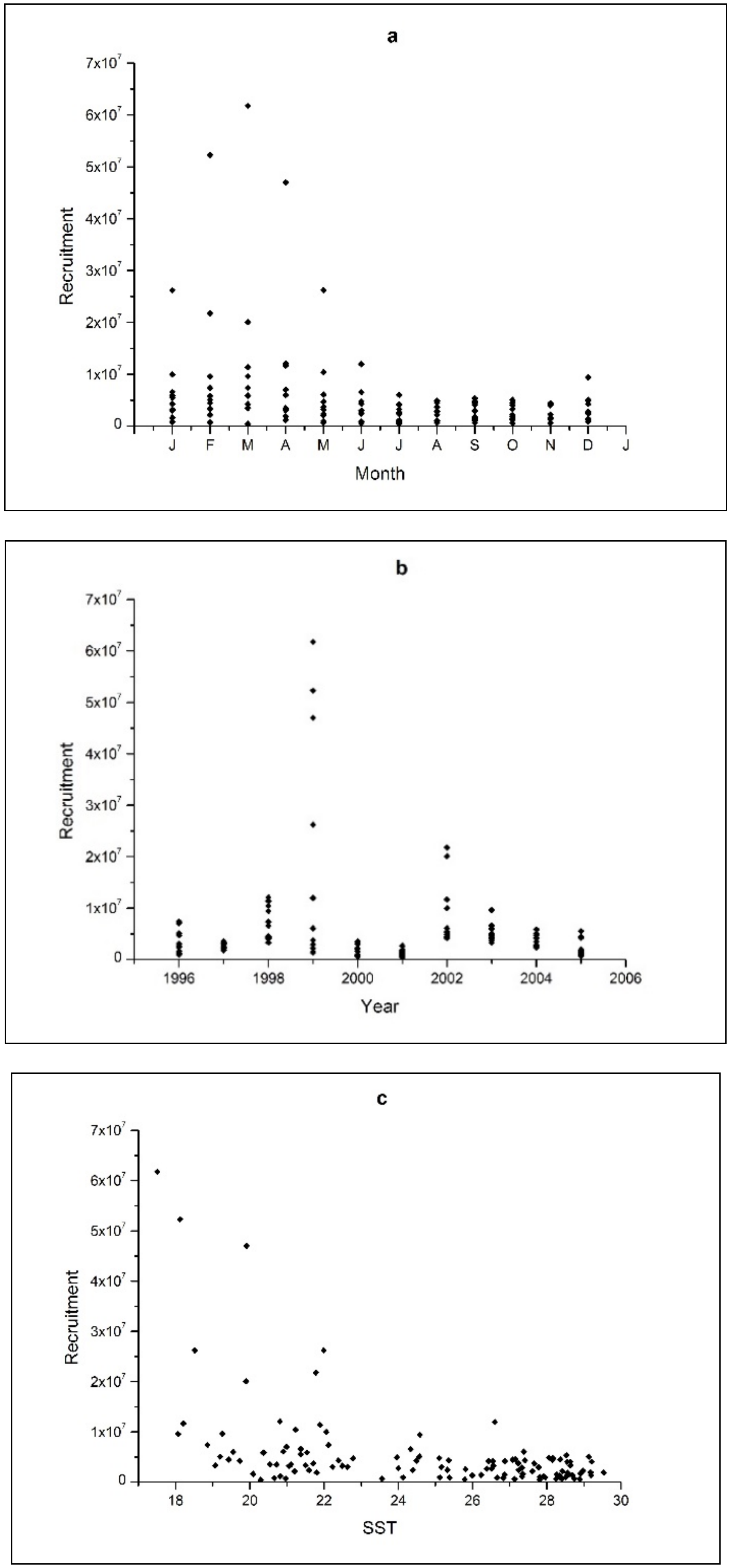

Fig 2: Scatterplot showing the relationship between octopus recruitment, SST, Month and Year (1996-2005)

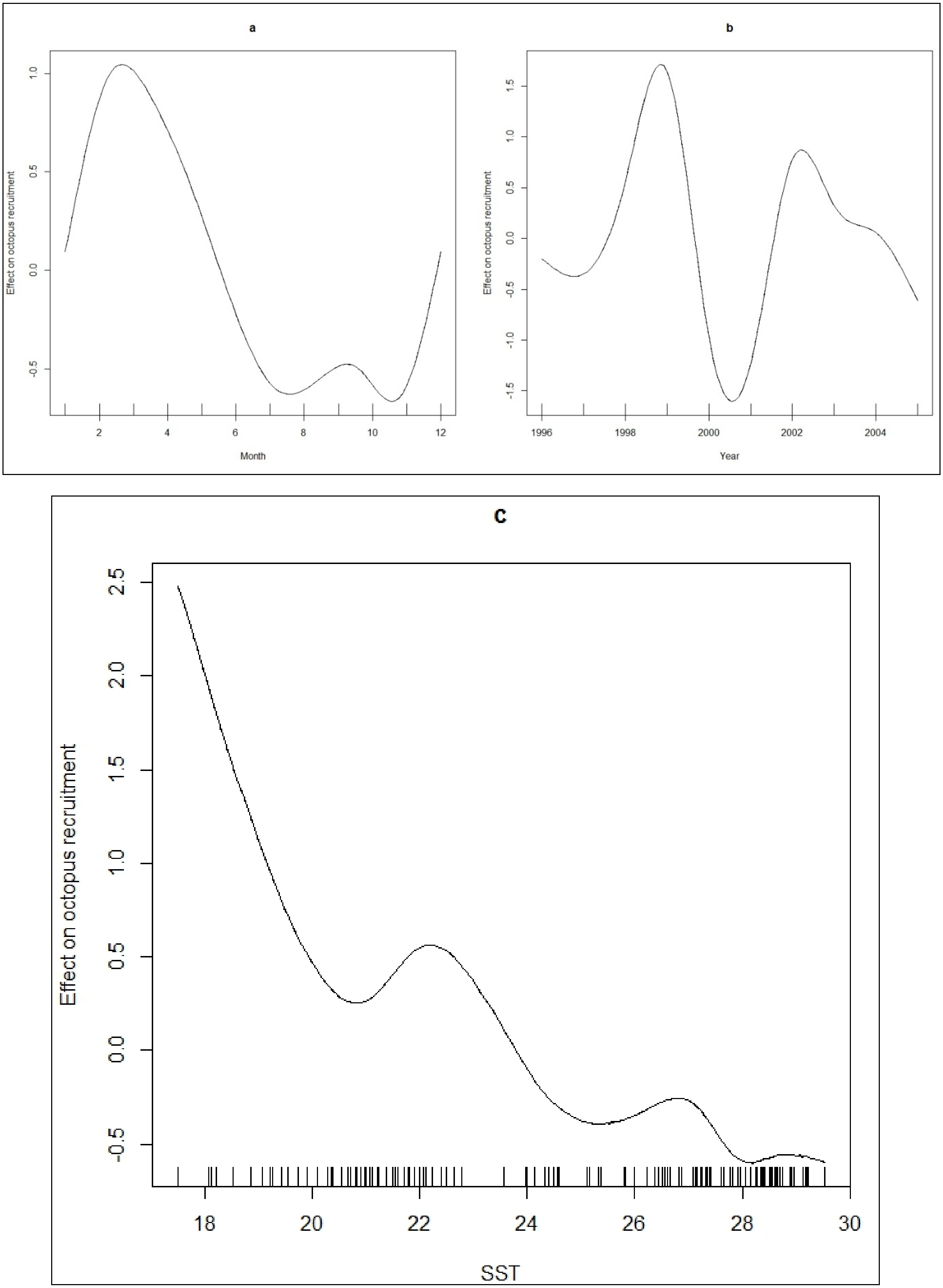

Fig 3: GAMs-derived effect of SST, Month and

Year.

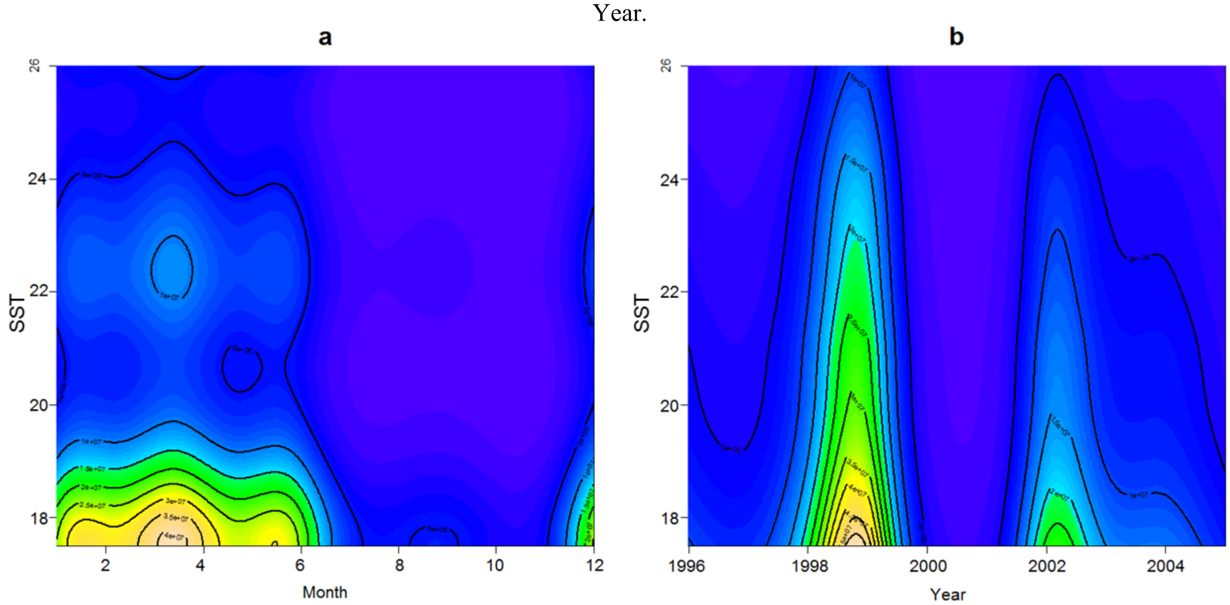

Fig 4: GAMs-derived effect SST/Month, SST/Year interactions on octopus recruitment (1996-2005).

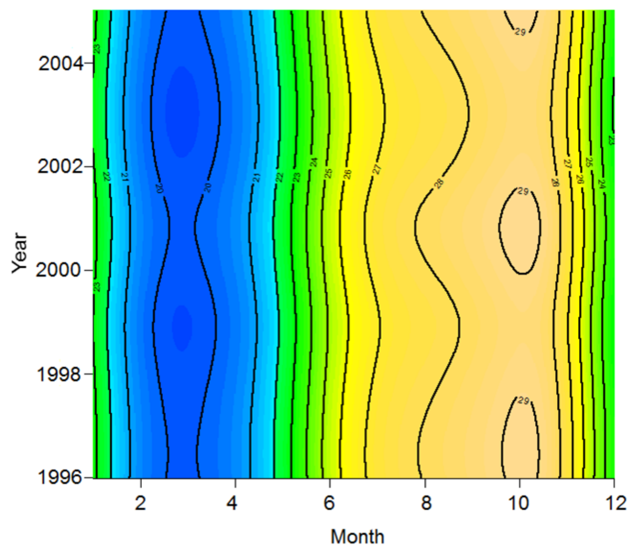

Fig 5: GAMs-derived effect Month/Year interaction on SST (1996-2005)

Conclusion

In summary, GAMs provided more precise information on the existing relationships between dynamic of octopus population and upwelling intensity in Senegalese waters than classical regression techniques. Ecological mechanisms without requiring their explicit definition could be due to the significant statistical relationships between octopus recruitment and SST [23]. GAMs also showed that the non-linear combination of SST, month and year describes better their influences in octopus recruitment than their analysis in isolation. As all models, GAMs present limitations as well. The additive models are currently suffering from a lack of available statistic interference procedure and a lack of a formal parameter of goodness of the fit making more complicated de interpretation of the output.

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