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## Characterization and monitoring of potential fishing areas in the exclusive economic zone of Senegal by the method of multicriteria analysis: Contribution of remote sensing and GIS

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### Abstract

Nowadays, the high frequency and the synoptic nature of the earth observation data are a compulsory tool for a global understanding of the functioning of the earth and more particularly of the ocean. Remote sensing data were utilized in this study to relate the biophysical features of the ocean to the catches of coastal pelagic fish in the Exclusive Economic Zone (EEZ) in Senegal from 2003 to 2017. The adopted procedure was, on the one hand; the multi-criteria analysis from the biophysical parameters which will give an idea on the availability on the coastal pelagic species in the exclusive economic zones in Senegal. The multi-criteria analysis by weighting made it possible to have a map of the availability of coastal pelagic species from 2003 to 2017 in the EEZ in Senegal. It enable to distinguish three zones of availability: the high availability of species which is observed during the cold season, the average availability taking place in both seasons, and the low availability occurring during the hot season but more concentrated in the south.

**Keywords:** Sea surface temperature (SST), Chlorophyll-a concentration (Chl-a), MODIS data, Small pelagic species, Senegal EEZ

### 1. Introduction

Senegal is one of the countries of the Northwest African sub-region with the highest catches. Coastal pelagic resources constitute more than 70% of the catches made in the Senegalese Exclusive Economic Zone (EEZ), mainly through artisanal fishing. The quality and diversity of these resources in Senegalese waters are due to several environmental factors, such as the variation in the abundance of phytoplankton and the upwelling of deep cold waters loaded with mineral salts, called the upwelling phenomenon. This physical and biological variability, as well as the light conditions, strongly influence the primary production. The latter, essentially linked to the development of phytoplankton, supports the whole food chain up to the exploited species and explains part of the spatio-temporal variability (Diankha *et al.*, 2017) [1].

The Exclusive Economic Zone (EEZ) of Senegal is characterized by a well-defined upwelling rich in nutrients, which sustains one of the highest productive ecosystem in the world. Small pelagic stocks constitute the bulk (tonnage) of all fish landings and are the most significant marine resources. Small pelagic species, composed mainly of small pelagics, are the main source of animal protein for the majority of the population. The fish consumption of about 25 kg/year/inhabitant surpasses the world average of 12 kg/year/in habitant and that of the rest of Africa, at 8.2 kg/year/in habitant (Lazar *et al.*, 2014) [2].

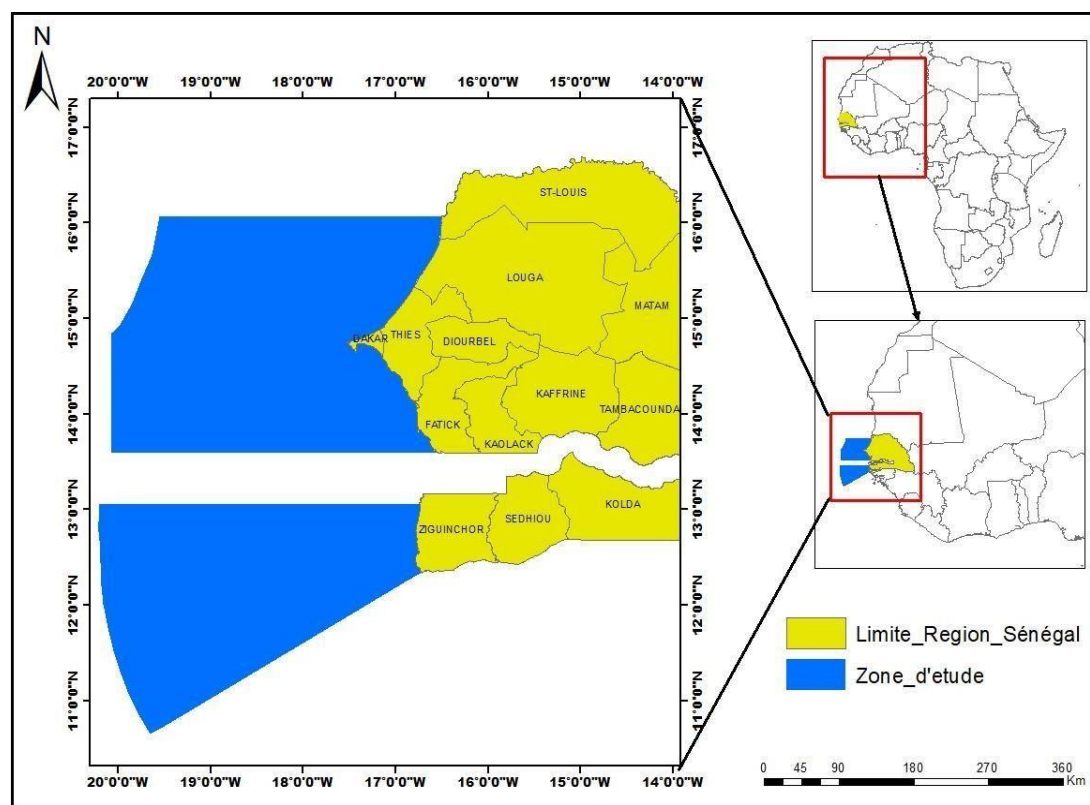
This marine resource is vital for coastal populations dependent on artisanal fishing for their income and food security, such as in coastal West Africa. The Senegalese upwelling is marked by great seasonal and interannual variability thought to have effects on small pelagic fish (Bakun, 1996) [3]; (Cury and Roy, 1987) [4]; (Fréon, 1991) [5]; (Fréon and Mendoza, 2003) [6]. Advances in satellite remote sensing of environmental perturbations have become important in understanding variations of ocean productivity and small pelagic fish catches.

The small pelagics are the most abundant fish stocks in the CCLME area, and they are mostly shared by several coastal states. They occupy a fundamental place in the upwelling ecosystem because of their intermediate position in the trophic chain and their abundance. The small pelagic stocks exhibit strong natural variations in abundance. These species may control both the abundance of the zooplankton that they eat ("topdown" control) and the abundance of their predators ("bottomup" control) according to the situation (Bakun, 1996) [3].

## 2. Materials and Methods

### 2.1 Study Area: Senegal has an exclusive economic zone

(EEZ) 718 km long that extends over nearly 159,000 km<sup>2</sup> (Greenpeace, 2012). In surface area, Senegal's maritime territory ranks 85th in the world and 24th in Africa. It is divided into two large areas: the Great Coast, which extends from the mouth of the Senegal River in the north to the Cape Verde peninsula, and the Little Coast, which extends from the Cape Verde peninsula to the Sine Saloum in the south including Casamance (Figure 1). Indeed, there is a clear ecological disparity between the Petite-Côte and the Grande-Côte, both in terms of the direct influence of the upwelling and the enrichment processes that result from it (Demarcq *et al.*, 1991) [7].



**Fig 1:** Study area of the Senegal has an exclusive economic zone (EEZ)

### 2.2. Satellite Data

The biophysical parameters (chlorophyll-a, sea surface temperature) used in this study come from the MODIS Aqua sensor which will allow to determine the ocean color. The wind data from ERA-Interim is a dataset that will allow the calculation of the upwelling index and the turbulence index to characterize their phenomenon. The landing data of coastal pelagic species from the Senegalese Directorate of Marine Fisheries will allow an analysis of the relationships between the biophysical parameters of the ocean and the species studied.

### 2.3. Method

For a better protection of fisheries, the management of fishing areas is necessary for a sustainable development of marine and coastal areas. The realization of such a management requires the use of modern tools of analysis and spatial modeling such as geographic information systems (GIS). It is presented as a multi-criteria spatial analysis tool. The spatial analysis option of GIS can indeed allow the spatialization and aggregation of different oceanographic factors essential to the analysis and modeling of optimal ecological conditions of

fisheries (Kassi, 2012) [8].

The aim of this analysis is to develop maps of availability of pelagic species in the Senegalese exclusive economic zone for a given period and to consider forecasts for the coming years. For this study, a data set of chlorophyll concentration, surface temperature, upwelling index and turbulence index was used for a 15-year period from 2003 to 2017.

The first 10 years of data from 2003 to 2012 were used for model design and the last 5 years of data from 2013 to 2017 for validation. To do this work, several steps were followed:

- Determination of the parameters to be used
- Modeling the data
- Production of results
- Validation of the results

#### 2.3.1 Determination of Criteria

For this study, the four ocean biophysical parameters (chlorophyll-a, surface temperature, coastal upwelling index and turbulence index) were used because of their strong influence on the availability of coastal pelagic species. Pelagic fish stock data from the same period.

### 2.3.2 Data Modeling

The modeling consists of the evaluation, classification and aggregation of the parameters that directly influence the coastal pelagic species in the exclusive economic zone of Senegal, but also the determination of the favorable fishing areas during the whole year.

Each parameter determined will be evaluated and classified according to its influence on the availability of pelagic species from 2003 to 2012. The classes "Poor, good, very good" were

used for the evaluation.

### 2.3.3 Assessment and Classification of Parameters

#### 2.3.3.1 Chlorophyll-A Concentration and Coastal Pelagic Fish Stocks

The chlorophyll-a concentration map was generated from the chlorophyll pigment concentration data recorded by the MODIS -Aqua satellite from 2003 to 2017 (Table 1).

**Table 1:** Chla assessment and stock quantity

Chla	Evaluation of Chla	Availability class of species	Quantity of fish
<2	Low	Bad	< 250000
2 à 2.5	Average	Good	250000 à 280000
> 2.5	Strong	Very good	>280000

#### 2.3.3.2 Sea Surface Temperature and Coastal Pelagic Fish Stock:

The surface temperature map was generated from the

data recorded by the MODIS-Aqua satellite from 2003 to 2017 (Table 2).

**Table 2:** Evaluation of surface temperature and stock quantity

TSM	Evaluation of SSM	Availability class of species	Quantity of fish
< 24 °C	Low	Very good	>280000
24 °C à 25 °C	Average	Good	250000 à 280000
> 25°C	Strong	Bad	< 250000

#### 2.3.3.3 Coastal Upwelling Index and Coastal Pelagic Fish Stock

The analysis of the calculated upwelling index shows that

throughout the year periods of high upwelling intensity correspond to very high landings and periods of low upwelling intensity correspond to low landings (Table 3).

**Table 3:** Evaluation of the upwelling index and the quantity of stocks.

CUI	Evolution of CUI	Availability class of species	Quantity of fish
< 1900	Low	Bad	< 250000
1900 à 2000	Average	Good	250000 à 280000
> 2000	Strong	Very good	>280000

#### 2.3.3.4 Turbulence Index and Coastal Pelagic Fish Stock

The turbulence index allows us to say that periods of high turbulence correspond to the amount of coastal pelagic fish stock that is very low and periods of low turbulence

correspond to the amount of coastal pelagic fish stock that is very high. The table below shows the evaluation of the turbulence index in relation to the landings of coastal pelagic fish (Table 4).

**Table 4:** Evaluation of the turbulence index and stock quantity

TI	Evaluation TI	Availability class of species	Quantity of fish
< -60	Low	Very good	>280000
-60 à -50	Average	Good	280000 à 250000
> -50	Strong	Bad	< 250000

**2.3.4 Development of A Map of the parameters:** During the first ten years from 2003 to 2012. This representation allows the calculation of the correlation coefficient as a function of stock quantity for each parameter, but also to determine their weights on the coastal pelagic species (Table 5).

#### 2.3.5 Association of the different classes with the weights

For the determination of the weights of the different variables, the curves of variation of the stock quantity and the different criteria were represented.

**Table 5:** Correlation coefficient and the weight of the parameters on the quantity of stock.

Criteria	Correlation coefficient	Weight of criteria
Chla	0.2649	0.48225
TSM	0.001	0.00183
IU	0.1303	0.23721
IT	0.1531	0.27871
Total	0.5493	1

#### 2.3.6 Merging the Variables

This part allows the fusion of the four parameters to develop a synthesis map of the period of availability of coastal pelagic

species in the Senegalese exclusive economic zone.

In this study, the aggregation method by weighting was used and is widely used in many works (Kassi, 2012)<sup>[8]</sup>; (Saley,

2003) [9]; (Jourda *et al.* 2002) [10]; (Kouamé, 2007) [11]. Weighting consists of multiplying each parameter by its weight.

**2.3.6.1 Productivity Indicator (I<sub>1</sub>)**

The parameters, chlorophyll-a concentration and sea surface temperature were crossed to obtain the productivity indicator map.

$$I_1 = (Chla * P_{chla}) + (SSM * P_{SSM}) \text{ (Kassi, 2012) [8]}$$

With

- Chla = Chlorophyll-a concentration
- P<sub>chla</sub> = Weight of chlorophyll concentration
- SST = Sea Surface Temperature
- P<sub>SSM</sub> = Sea Surface Temperature Weight

**2.3.6.2 Planktonic Abundance Indicator (I<sub>2</sub>)**

The fusion of the coastal upwelling index and the turbulence index gives the planktonic food abundance indicator map. Indeed the winds that induce turbulence are often at the origin of the upwelling thus driving the presence of planktonic food in the marine environment (Kassi, 2012) [8]. The upwelling equation is as follows:

$$I_2 = (CUI * PCUI) + (TI * PTI) \text{ (Kassi, 2012) [8]}$$

With

- TI = Turbulence index
- PCUI = Upwelling index weight
- CUI = Coastal Upwelling index
- PTI = Turbulence index weight

**2.3.7 Availability Map**

The fusion of the productivity and planktonic abundance indicators allows to obtain the invalid availability map of the species. For this, the sum of the equations of the productivity indicator and the planktonic food abundance indicator gives the global equation,

$$AM = I_1 + I_2$$

$$AM = (Chla * P_{chla}) + (SSM * P_{SSM}) + (CUI * PCUI) + (TI * PTI)$$

**2.3.8 Validation Map**

To develop the final species availability map, the fusion of all four parameters of the last five years from 2013 to 2017 was done, but the fishing data are not considered in the development of the validation map. Here we reason in terms of the area of availability covered for each year.

**3. Results**

**3.1. Relationship between parameters and stock quantity from 2003 to 2012:** The variations of coastal pelagic fish stocks according to the parameters allow to see the relationships between the parameters and the availability of coastal pelagic fish in the exclusive economic zone of Senegal. These annual variations will allow to discriminate the influence of each parameter on the species. Variations in stock quantity and chlorophyll-a concentration as a function of year show that stock quantity increases as chlorophyll-a increases except for the year 2006 when there is a high chlorophyll concentration and a decrease in stock quantity. Variations in stock quantity and surface temperature as a function of years from 2003 to 2012 show that surface temperature varies from year to year between 23 °C and 26 °C. During the years 2005 and 2010, high temperatures and a decrease in the amount of stocks below 250,000 tons are observed. In 2003, 2007 and 2012, low values of temperature below 25°C and a very large amount of stocks above 270,000 tons are observed. For the representation of the variation of the upwelling index and the quantity of stocks, it is observed that the evolution of the curve of the variation of stocks follows that of the upwelling index except for 2006 and 2009 where the high intensities of upwelling correspond to medium quantities of stocks. The variation curves of the turbulence index and the quantity of stocks show that during the years 2005, 2006 and 2010 the strong turbulence of the water column corresponds to low quantities of stocks and in 2004, 2007, 2009 and 2011 we observe weak turbulence of the water column corresponding to high quantities of stock of coastal pelagic species.



**Fig 2:** Relationship between parameters (Chla, SST, TI and CUI) and stock quantity from 2003 to 2012

### 3.2 Species Availability Criterion

The maps represent the spatio-temporal variation of the different variables (chlorophyll-a, sea surface temperature, upwelling and turbulence) from 2003 to 2017.

#### 3.2.1 Chlorophyll-A

In general, chlorophyll concentrations are found between the shore and the open ocean. Low chlorophyll concentrations are observed offshore throughout the study period.

The spatio-temporal variation of chl-a shows that during the period from 2003 to 2017 the highest concentrations of chl-a are located on the coast with values above 3 ug/l. During the years 2004, 2007, 2010, 2012, 2014 and 2017, the high concentrations of chl-a are located south of the Cape Verde Peninsula. The average concentrations are observed on the coast north of the Cape Verde peninsula during the years 2004, 2007, 2010, 2012, 2014 and 2017.

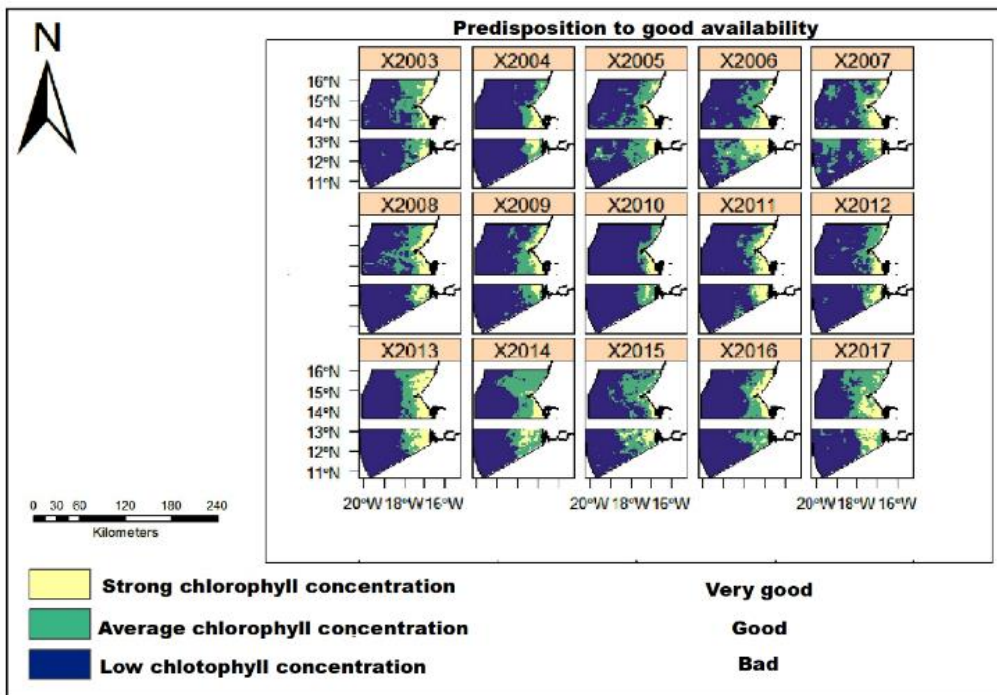


Fig 3: Chlorophyll concentration criteria from 2003 to 2017

#### 3.2.2. Sea Surface Temperature

In the general case, low temperatures are located in the south on the open sea of the exclusive economic zone. During this period from 2003 to 2017, low temperatures are observed in the north of the exclusive economic zone of Senegal and

along the coast. In 2005, cold waters covered a large part of the area from north to south. The average temperatures are located off the EEZ and more frequent on the northern part.

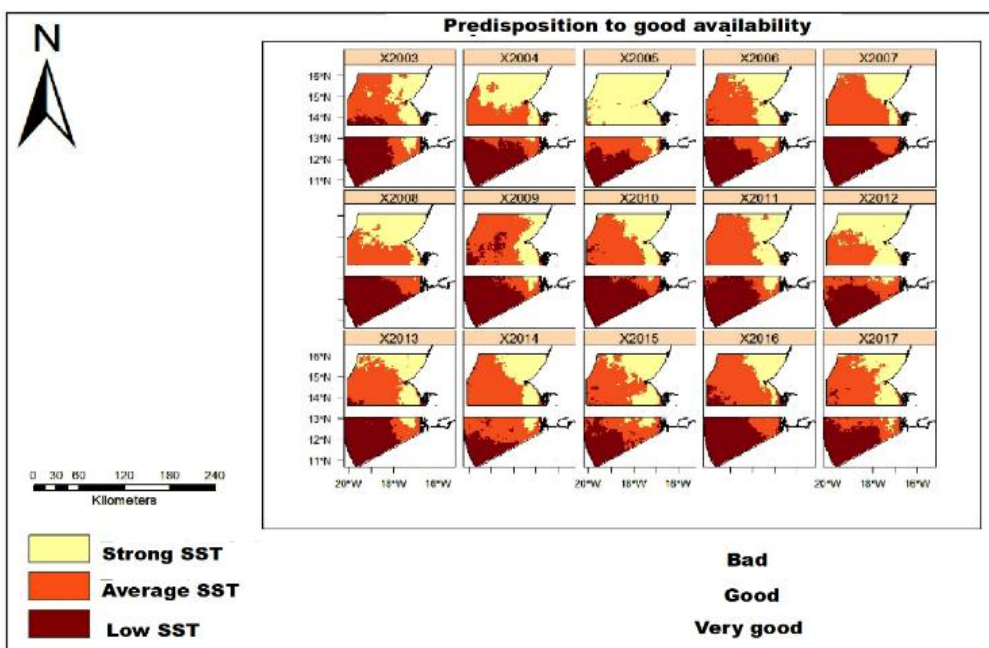


Fig 4: Sea surface temperature criterion from 2003 to 2017

### 3.2.3 Upwelling

Generally speaking, the weak upwelling intensities are located on the southern coast of the EEZ and cover the entire Casamance area.

The space-time variation of the upwelling index shows that

the strong intensities are located to the north and offshore of the EEZ. The strong upwelling intensities are more important in 2004, 2006, 2010, 2016 and 2017. The average upwelling intensity is observed along the coast and gradually increases towards the open sea in the south.

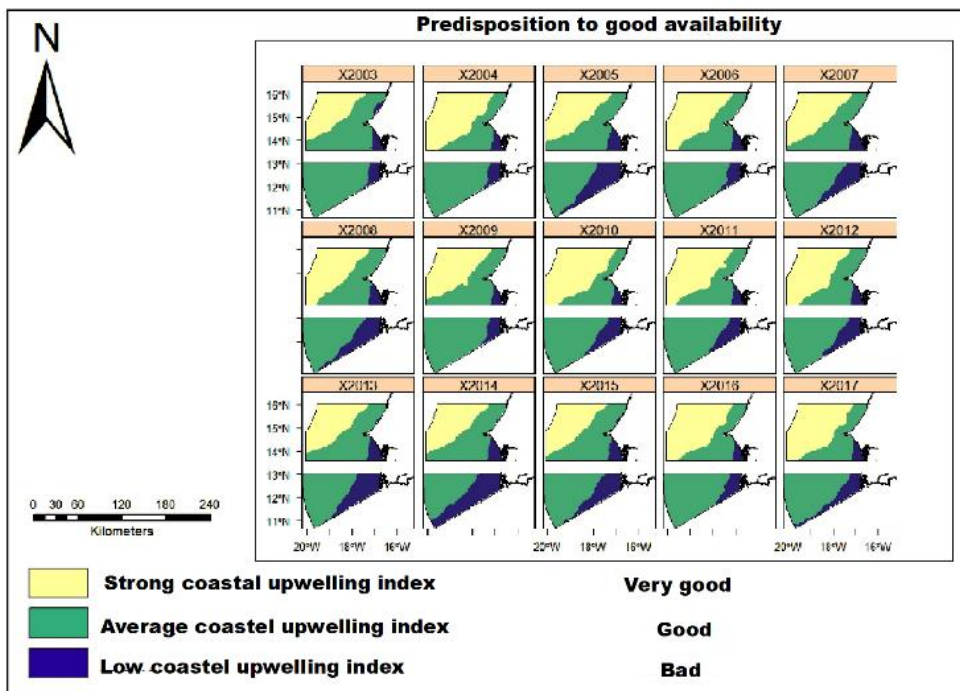


Fig 5: Upwelling index criteria from 2003 to 2017

### 3.2.4 Turbulence

Generally speaking, low and medium turbulence was observed at the coast throughout the period.

The spatio-temporal variation of the turbulence index shows that the strong turbulence of the waters is observed offshore to the north. In 2003, 2005, 2008, 2012, 2013, 2014, and 2015,

the strong turbulence covers a small part of the EEZ to the north. Medium turbulence is observed in the North on the coast and gradually decreases in the South towards the open sea. The weak turbulence covers the southern coast of the EEZ. During the years 2003, 2013 and 2015, low turbulence was observed along the entire coast.

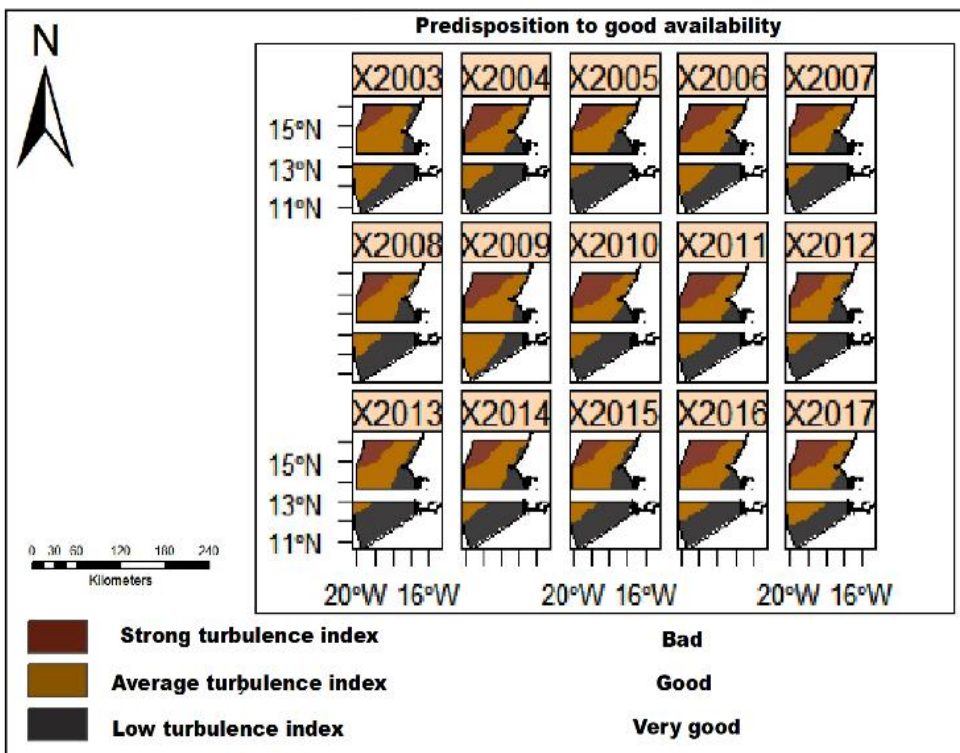


Fig 6: Turbulence index criteria from 2003 to 2017

### 3.3 Variable Fusion MAP

The results obtained represent the spatio-temporal variation of productivity and planktonic food abundance indicators in the Senegalese exclusive economic zone.

#### 3.3.1 Productivity Indicator

In general, low productivity is observed between latitudes 14°N and 11°N in the offshore EEZ.

The fusion of the chlorophyll-a and sea surface temperature parameters allows us to obtain the productivity indicator map. This productivity map gives an idea of the distribution of species in the Senegalese exclusive economic zone. On this

map we distinguish three types of productivity: high productivity, medium productivity and low productivity. During this period from 2003 to 2012, the high productivity is located along the entire coast between longitudes -17°W and -18.5°W. This is due to high chlorophyll-a concentration and low sea surface temperature at the coast. In 2003, 2005 and 2008 high productivity was observed offshore up to longitude -19°W in 2005. Average productivity was observed northward to latitude 13°N in 2004, 2006, 2007, 2008 and 2011. In 2003 it was between the coast and the open sea from 14°N, and in 2005 it reached 12°N.

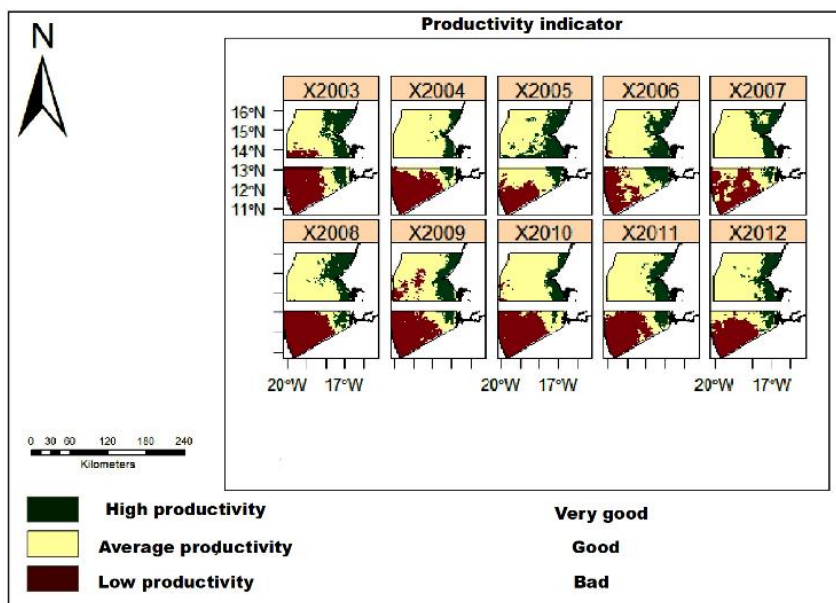


Fig 7: Productivity indicator in the exclusive economic zone of Senegal

#### 3.3.2 Planktonic Abundance Indicator

In general, average abundances are observed on the coast and increase progressively towards the open sea until latitude 13.5°N, where they cover the entire open sea in the southern part. The low abundances are located on the coast to the south from latitude 14.5°N and gradually increase towards longitude 20°W in 2005, 2007, 2008, 2010 and 2012. In 2003, 2004, 2006, 2009 and 2011, the highs are between longitudes -16.5°W and -18°W.

The fusion of the parameters of the coastal upwelling index

and the turbulence index gives an idea of the spatial distribution of plankton abundance in the exclusive economic zone of Senegal. Three classes were observed: low planktonic abundance, medium planktonic abundance and high planktonic abundance.

During the period from 2003 to 2012, the high abundances are located offshore between latitudes 16°N and 13.5°N except in 2003 and 2005 when the latitude does not exceed 14°N. They are also located between longitudes -17°W and -20°W throughout the area.

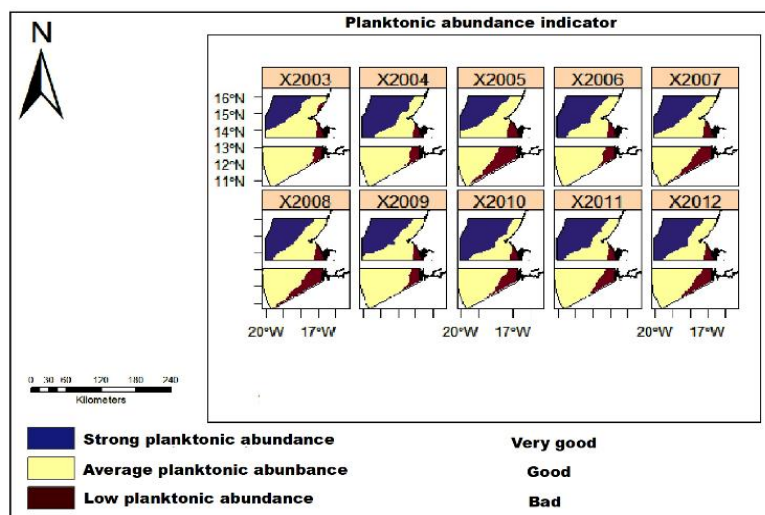


Fig 8: Plankton abundance indicator map

### 3.4 Species Availability Map

The result of the species availability is the fusion of the maps of productivity indicator and planktonic food abundance indicator from 2003 to 2012.

In general, the exclusive economic zone of Senegal is covered by high and medium species availability.

The high availabilities are located on the north coast and offshore during the whole period from 2003 to 2012. The high availabilities cover almost the entire northern part of the Senegalese exclusive economic zone. They are located between latitudes 16°N and 12°N and longitudes -20°W and

17°W. The average availability is observed from the coast, in the south from latitude 14°N and

The average availabilities are observed from the coast, to the south from latitude 14°N where they increase progressively towards the open sea until 11°N. Over the entire period, average availabilities cover the entire latitude of 13°N and 11°N. Average availabilities are also observed in the north near the coast in all years.

Low availabilities are found in the south between latitude 12°N and 11°N and longitude -17.5°W and 18°W in 2010, 2011, 2012 and 19°W in 2005, 2007 and 2008.

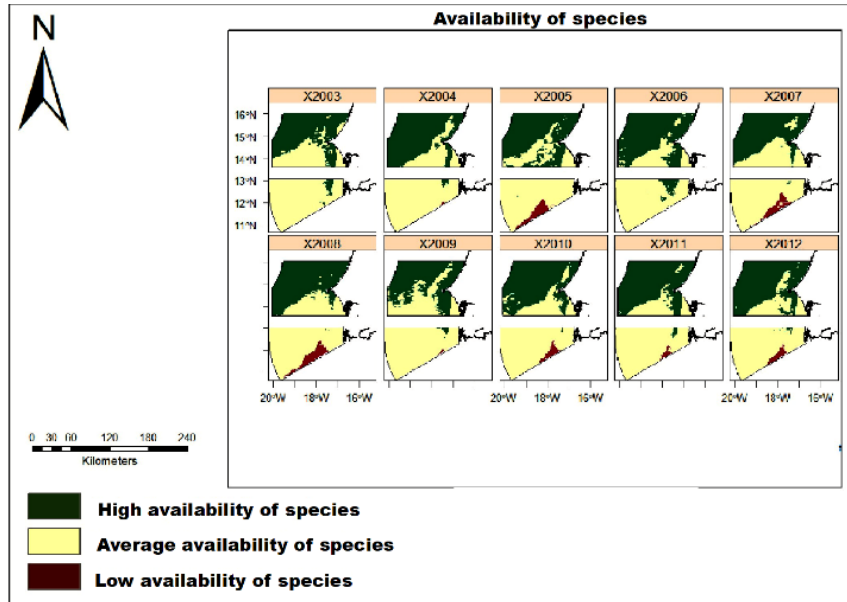


Fig 9: Species availability map

### 3.5 Validation of Results

The validation of species shows high availability during the cold season in the Senegalese exclusive economic zone for the period 2013 to 2017.

The species availability validation map from 2013 to 2017 shows that, in 2013, 2014 and 2016, the high availability is located in the north on the coast and offshore between latitudes 16°N and 13.5°N. In 2015 and 2017 the high

availability continues to latitude 12.5°N. High availabilities are observed between longitudes -17°W and -20°W. Average productivities are observed between latitude 14°N and 11°N in 2013, 2014, 2015 and 2016 and between longitude -17°W and -20°W. In 2017 average productivity is observed from latitude 13.5°N offshore and 12.5°N toward the coast. The low productivity covers a small part of the area and is located southwards towards the open sea.

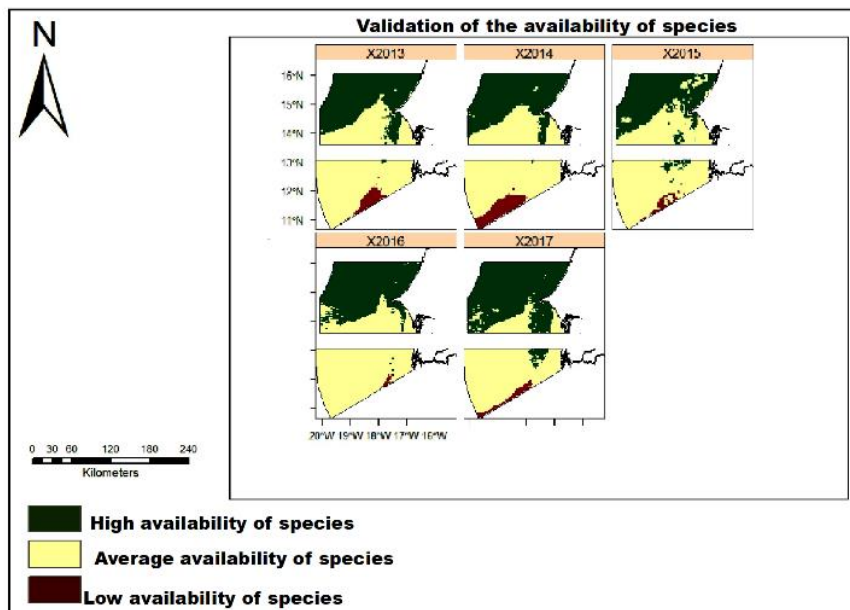


Fig 10: Species availability validation map from 2013 to 2017



The area occupied by these three classes of species availability during the five years is presented in the table below.

In 2013, medium availability occupies more than half of the area with 58%, high availability covers 38% of the area and low availability covers a small portion 3.3%. In 2014, average productivity covers more than half of the area with 55.9%, high productivity covers 38.4% of the area, and low productivity covers 6.5%. In 2015 average productivity is

very large and covers 61.5% of the area, high productivity occupies 36.9% and low productivity occupies a small part 1.6%. In 2016 average productivity covers a large portion 58.4%, high productivity occupies 41.2% and low productivity occupies a very small portion of the area 0.4%. In 2017, high productivity occupies more than half of the area with 51.4%, medium productivity follows with 48.4% and low productivity with a very small area 0.2% (Table 6).

**Table 6:** Statistics of the area occupied by availabilities from 2013 to 2017

Availability classes in%	Years				
	2013	2014	2015	2016	2017
Strong	38%	38,4%	36,9%	41,2%	51,4%
Average	58%	55,9%	61,5%	58,4%	48,4%
Low	3,3%	6,5%	1,6%	0,4%	0,2%

The fishing data of these five years 2013, 2014, 2015, 2016 and 2017 show that the quantity of stocks of coastal pelagic species is strong in 2016 and 2017 more than 300000 tons. In 2013 and 2015, the quantity of stocks is more or less important with about 280,000 tons. In 2014, the quantity of stocks is low with 255386 tons.

This comparison allows to validate the four criteria studied (chlorophyll, sea surface temperature, upwelling and water turbulence) and to make reliable the results on the areas of availability of pelagic species in the exclusive economic zone of Senegal.

#### 4. Discussion

The analysis of the spatial distribution of the four studied parameters (chlorophyll, surface temperature, upwelling and turbulence) allows us to study their variability from one year to another.

During the years when the strong and medium upwelling intensity covers the costernal zone, the surface temperature is very low and the chlorophyll concentration is high. During this same period, turbulence is low to moderate. However, the upwelling ecosystem is very dynamic and shows high interannual variability at all spatial and temporal scales. In these ecosystems, pelagic species are dominant in biomass, mainly coastal species, whose population dynamics are often linked to the very high physical variability of the upwelling (Jehid, 2016) [12]. Understanding the mechanisms linking environmental fluctuations to the recruitment of these species is one of the major challenges of fisheries in Senegal.

In Senegal, the questions posed by the high variability of fishery species and their exploitation make it necessary to approach both the fishery and its environment.

In this study, the multi-criteria analysis allowed the identification of areas of high, medium and low availability of coastal pelagic species in the exclusive economic zone of Senegal.

The productivity obtained allows us to say that for high concentrations of chlorophyll and low surface temperature, the productivity is high. When the concentration is medium, the productivity is medium with low or medium temperatures. When the concentration is low, the productivity is low with average or strong temperatures.

The planktonic abundance obtained shows that upwelling drives planktonic food abundance in the marine environment. For areas of high upwelling intensity, planktonic food abundance is high even if turbulence is high. When upwelling intensity is medium, planktonic food abundance is medium

with strong to medium turbulence. When the upwelling intensity is low, the abundance is low with low or medium turbulence in the water column.

Chlorophyll concentration and the upwelling phenomenon are essential for species availability. Indeed, the upwelling of deep cold water to the surface always carries with it nutrients from the sea floor (Kassi 2012) [8]. These nutrients transported to the surface by the upwelling, contribute to the development of phytoplankton, whose concentration in chlorophyll-a measures the abundance, hence the high productivity of the environment. Consequently, a high availability of species is observed.

Environmental parameters (chlorophyll-a, sea surface temperature, upwelling and turbulence) play a key role on the recruitment of species. In 2017, it is noted that the high availability occupies more than half (51.33%) of the exclusive economic zone of Senegal corresponds to the largest amount of stocks (304054.75 tons) during the validation period (2013 to 2017). In 2014, the low productivity covers a very important part compared to the other years of the validation period and the quantity of stocks is the lowest (255386.36 tons) during the whole period. According to these results, it can be said that the fluctuation of the environmental conditions greatly affects the fishery, especially the coastal pelagic species in the exclusive economic zone of Senegal, hence the importance of a continuous monitoring of the environment for a more rational management of the stocks.

#### 5. Conclusion

The multi-criteria analysis allows us to say that the chlorophyll-a concentration, the sea surface temperature, the upwelling index and the turbulence index are criteria that allowed us to characterize the availability of species in the Senegalese exclusive economic zone. Remote sensing of the ocean is one of the most useful missions for society for both scientific research and operational activities. These results have provided new knowledge on the biophysical parameters of the ocean in the exclusive economic zone of Senegal and their relationship with the landings of coastal pelagic fish. These results make it possible to draw up operational maps for the identification of potential fishing areas, thus allowing the fishermen to work more efficiently and save fuel. This is certainly not to encourage overfishing, but rather to provide practical means to ensure sustainable management and more efficient fishing. Areas of high upwelling intensity correspond to areas that regularly record high chlorophyll-a concentrations and low ocean surface temperature values and

correspond to areas that are constantly populated by pelagic resources.

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