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Perspectives

A System of Indicators for Sustainability: An Example from the Senegalese Fisheries

DJIGA THIAO
Centre de Recherches Océanographiques de Dakar-Thiaroye
FRANCIS LALOË
Institut de Recherche pour le Développement

Abstract *In most coastal countries the fisheries sector satisfies multiple socioeconomic needs. This is especially the case in many coastal developing countries where fisheries represent a substantial source of food, jobs, and income. However, fisheries exert strong pressures on marine resources with threats to their sustainability. The context of overexploitation of marine resources is combined with a great diversity of stakeholders intervening in the governance of the fisheries. Thus, a better understanding of the challenges fisheries face is essential to enact management policies to ensure sustainability. Through a case study of the Senegalese fisheries, this article develops quantitative indicators of social, economic, and ecological states of the fisheries. Standardized principal components analysis combined with the Hodrick-Prescott filter is used to assess trends in the indicators. These indicators can contribute to an adaptive management framework in a context of multiple management objectives with diverse stakeholders and uncertainty.*

Key words Indicators, fisheries, sustainability, adaptive management.

JEL Classification Code Q22.

Introduction

The exploitation of marine resources is a significant source of economic and social development. According to FAO (1999), fishing is an important worldwide activity that contributes to the subsistence of hundreds of millions of people. But fishing also supports livelihoods and foreign exchange of developing countries (Smith *et al.* 2010). Overfishing of many stocks combined with the deterioration of marine ecosystems threatens the sustainability of the world fisheries, which have to be rationally managed in order to maintain their contribution to human well being (FAO 1995; FAO 1999). This article develops indicators of sustainability that aim to support effective management with an application to fisheries in Senegal.

Djiga Thiao is a researcher, Centre de Recherches Océanographiques de Dakar-Thiaroye (CRODT)/ISRA PO Box 2241, Dakar, Senegal (email: d_thiao@yahoo.fr). Francis Laloë is a researcher, Institut de Recherche pour le Développement (IRD), UMR-GRED 220 (Gouvernance, Risques, Environnement Développement), 911 av. Agropolis, BP 64501 34 394 Montpellier Cedex 5, France (email: laloe@mpl.ird.fr).
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A system of indicators can contribute to adaptive management by providing practical, updated measures of the multiple dimensions of fisheries sustainability. Adaptive management of natural resources is essential due to the fact there are many uncertainties that jeopardize the effectiveness of current policies (Ruddle and Hickey 2008). In the fisheries sector, the functioning of marine ecosystems is so complex that available knowledge is not generally sufficient and accurate enough to provide all suitable answers. By ignoring uncertainties, management policies can cause more environmental degradation, loss of ecological services, and economic and social instabilities (Walters 1986; Walters and Holling 1990). Therefore, the paradigm of adaptive management is based on the simple principle that any result (success or failure) of a management policy should serve to improve the strategy. It explicitly recognizes the existence of uncertainties and gaps of knowledge about the functioning of complex systems and the policies to manage them (Lee 1993). Through monitoring by a system of indicators, newly acquired knowledge should help incorporate necessary modifications into the management plan.

Scientists and policy makers are calling for indicators to promote sustainable fisheries management. The FAO directives for responsible fisheries (FAO 1995) state that systematic recourse to indicators should be encouraged as a means of reinforcing the understanding of the situation and the trends of the various dimensions of the fisheries. The need for indicators was also stressed in 2004 in Paris during an international symposium on "quantitative ecosystem indicators for fisheries management" (Cury and Christensen 2005). Moreover, a working group comprised of a large number of experts from different countries has recently been established through the Indiseas project (www.indiseas.org). This projects aims to develop a comparative framework by selecting and analyzing various ecological indicators (Shin and Shannon 2010; Shin *et al.* 2010). This project is also extending its approach to other aspects of fisheries, such as human and environmental dimensions. Increased interest of the scientific community is mainly due to the difficulty in selecting indicators that reflect the situation and challenges of fisheries. In addition, scientists are also eager to provide appropriate tools for communication, decision-making, and management (Degnbol 2005; Livingston *et al.* 2005; Rice and Rochet 2005; Rochet and Rice 2005; Laloë 2007; Shin and Shannon 2010).

Senegal provides a useful case study because fisheries play an important role in the economy and food security. Further, the case illustrates some of the generic challenges of indicator development. Overexploitation of marine resources has become a great concern among stakeholders (managers, scientists, NGOs, fishers, and consumers) who seek to develop rational management of these resources (Thiao 2009). In this context, our article aims to improve understanding of the complex interactions between the ecological and socioeconomic dimensions of the fisheries. The idea is to analyze Senegalese fisheries as a case study to develop a framework to provide a system of indicators based on diverse available data (Laloë 2004; Laloë 2007).

Material and Methods

From the Dataset to the System of Indicators

The sustainable development paradigm requires considering ecological, economic, and social dimensions together. Therefore, it implies the use of relevant information on different fisheries characteristics. This situation is also often characterized by conflicts and controversies between stakeholders (managers, scientists, NGOs, fishers, and consumers) who have different objectives and points of view. Our objective is to provide a synthesis of available data that can be used by stakeholders to address multiple issues and better communicate. Hence, there are two important elements to consider in order to help these stakeholders have the best possible overview on the state of the fisheries, objectives, and constraints. First, there are various data collected through several methods conducted by different institutions. Second, a multidimensional statistical function of these data should involve a list of parameters to estimate. Such a list should evolve because the needed information cannot be completely and definitely known. That would imply an implicit assumption of perfect knowledge of the behavior of the system with perfect knowledge of the information needs of any given stakeholder. Taking these two elements into account, the available data should be synthesized in order to achieve the following purpose as stated by Fisher (1922): "The object of statistical methods is the reduction of data. A quantity of data, which usually by its mere bulk is incapable of entering the mind, is to be replaced by relatively few quantities which shall adequately represent the whole, or which, in other words, shall contain as much as possible, ideally, the whole of the relevant information contained in the original data". The "relatively few quantities" must be both a list of indicators and, as much as possible, equivalent to the original set of data for any further indication purpose. This statement is in reference to the quality of a sufficient statistic as defined by Fisher (1925): "When a sufficient statistic exists, it is equivalent, for all subsequent purposes of estimation, to the original set of data from which it was derived." According to Fisher's view, a synthesis of available data can be expressed as a set of parameter estimates that may have their own meaning (*e.g.*, a catch estimate is useful for someone interested specifically in catches) and can be used to provide information about something else as well. This may be related to the definition of information given by Bateson (1970) "a difference that makes a difference". In other words, two different estimates of a catch (combined with estimates of other parameters) may lead to different estimates of the health of the ecosystem with a certain decision for fisheries management. Therefore, as an argument of a decision function, a catch estimate becomes an indicator for decision-making support (Laloë 2004).

In the specific case of fisheries management, it is essential to have a coherent and synthesized set of data including various dimensions and aspects of those fisheries. This set of data is what we call "system of indicators." In an ideal case, the system of indicators should be a sufficient statistic derived from the entire set of available data. However, such a purpose is impossible because that would theoretically imply that the likelihood of those data as a function of parameters is known. According to Fisher (1922) the suitable synthesis "shall contain as much as possible […] the relevant information contained in the original data." Hence, arbitrary choices have to be made to achieve that purpose by considering a framework based on a "state of the art."

Data Description and Origin

The first category of selected indicators is related to fishing pressure. It corresponds to fishing effort and catch, respectively, measuring the intensity of fishing activities and the level of extracted biomass from the marine ecosystems. Data related to fishing effort are selected by taking into account the main fishing gears of the artisanal and industrial fisheries. In the case of artisanal fisheries, the effort corresponds to the total number of trips by canoes using hand line, ring net, or gillnet. The artisanal catch is aggregated according to three types of resources (pelagic fish, demersal fish, and other species such as cephalopods, mollusks, and crustaceans). For the industrial fisheries, the bottom trawl fleet has been considered. In this case, fishing effort is expressed in terms of number of days at sea and the corresponding catch. All the data mentioned above come from the database of the Senegalese Oceanographic Research Centre of Dakar-Thiaroye (Thiao 2009).

The ecological state is analyzed through three groups of indicators related to the abundance and length of the main target species and the trophic level of the total catch. Fish length is attracting increasing attention of fisheries economists and not just biologists (Macher and Boncoeur 2010). Catch per unit of effort (CPUE) is chosen to represent the abundance index of seven main species: round sardinella (*Sardinella aurita*), Madeiran sardinella (*Sardinella maderensis*), red pandora (*Pagellus bellottii*), bluespotted seabream (*Sparus caeruleostictus*), white grouper (*Epinephelus aeneus*), sole (*Cynoglossus spp.*), *and Cymbium spp.*, which is the most important mollusk in the Senegalese fisheries. Most of these species are currently characterized by high levels of overexploitation (FAO 2007a). From 1985 to 2005 these species constitute 67% of the annual total catch, with a mean of 350,000 tonnes per year. However, this proportion reaches 70% during the five last years of the period, where the annual total catch is about 450,000 tonnes. Moreover, while *Pagellus bellottii, Sparus caeruleotictus, Epinephelus aeneus*, and *Cynoglossus spp.*, whose high prices are almost out of reach for the Senegalese households, are essentially exported to the developed countries, *Sardinella aurita* and *Sardinella madarensis* constitute the main seafood products in local markets. These two species, which are still landed in great quantities (about 270,000 tonnes per year), contribute significantly to satisfy the internal demand of the Senegalese population. Seventy five percent of the animal protein in the Senegalese diet is provided by marine resources, at about 25 kg per capita. Mainly targeted by ring nets with the largest artisanal fishing canoes containing an average of about 30 fishers per trip, *Sardinella* and *Cymbium spp.* are the most important products targeted along the Senegalese coast. Hence, they significantly contribute to employment, providing income to thousands of people along the Senegalese coast.

Because of the lack of regular scientific surveys, CPUE is the only available time series that serve to analyze the abundance of the exploited species in the Senegalese fisheries (FAO 2007a). The principle is based on the classical hypothesis that CPUE is proportional to abundance through the catchability coefficient. However, great concern has been raised by Maunder *et al.* (2006) about this hypothesis due to the fact that catchability, which is supposed to be constant over time, is likely to change through variability of some factors such as efficiency of the fleet, species targeted, environmental conditions, and dynamics of the population or fishing fleet. Therefore, the CPUE of a given species should be seen as simple proxies of the abundance index of the stock. To ensure that the CPUE best represents the proxies of the abundance index, a specific gear for each species that targets it is chosen. Thus, while pelagic fish, such as *Sardinella aurita* and *Sardinella madarensis*, are essentially caught by ring net, *Pagellus bellottii*, *Sparus caeruleotictus*, and *Epinephelus aeneus* are locally targeted by hand line. Concerning *Cynoglossus spp.* and *Cymbium spp.*, gillnet is the main gear that is used by fishers. For all the species mentioned above, the mean length of the catch is calculated, except for *Cynoglossus spp.* and *Cymbium spp.* for which length data are not available. Data used for CPUE and length are also from the database of the Oceanographic Research Centre of Dakar-Thiaroye. The mean trophic level of the catch is calculated using 130 species clearly identified in the catch (Thiao 2009). Except for some cephalopod and crustacean species for which additional data are provided by Laurans *et al.* (2004) through gut contents, data about trophic levels are extracted from Fishbase (www.fishbase.org; Froese and Pauly 2000). The formula below (1) is used to estimate the mean trophic level of the catch:

$$\overline{TL_t} = \frac{\sum_{i=1}^{N} Y_{it} TL_i}{\sum_{i=1}^{N} Y_{it}}, \tag{1}$$

where Y_{it} corresponds to the total catch for a given species i at year t, and TL_i is its trophic level. N is the total number of species taken into account (here $N = 130$).

Fishbase is a huge online database containing a great diversity of information on worldwide fish species. It is the only one in which trophic level data are available for almost all identified fish species. In order to extract specific trophic levels related to the species of the Senegalese waters, a query was made in the Fishbase Species Ecology Matrix. This query, which led us to the life history data on all fish species of Senegal, was implemented through the Fishbase search tool (http://www.fishbase.org/search.php), where it is possible to select the data of a specific country. For all of these species, the values of the trophic level for which standard errors are also indicated have been estimated from either food data or diet data (www.fishbase.org; Froese and Pauly 2000).

The socioeconomic state of the fisheries is analyzed through some indicators related to the role of the fisheries sector in terms of satisfaction of the main economic and social needs. Thus, for any given target species, *i*, the formula below (2) is used to estimate what we call the economic yield, EY_i, by multiplying the mean ex-vessel price, P_i, by the abundance index, AI_i, represented by the CPUE. It is important to mention here that the monetary unit is expressed in FCFA (Franc CFA), which is the currency of Senegal and seven other West African countries. There is a fixed exchange rate between the Euro and FCFA (1 Euro = 655.957 FCFA).

$$EY_i = P_i * AI_i. \tag{2}$$

This indicator corresponds to the average gross revenue per unit of effort of a given target species. Therefore, it is different from fishing profit because it does not take into account fishing costs for which time series are not available. The total gross domestic product (GDP in FCFA) of the fisheries sector is also used as an economic indicator. It is estimated by the National Agency of Demography and Statistics of Senegal (www.ansd.sn). Moreover, the amount of currency (in $US) provided through imports is also considered in this category of economic indicators. This indicator is extracted from the FAO database accessible through the universal software for fishery statistical time series FishStat Plus (FAO 2007b). Regarding social aspects, the importance of job creation is taken into account through the number of people directly working in the fisheries sector. As another social indicator, average consumption per capita of fisheries products, which reflects the role of the fisheries in terms of food security, is also considered. This indicator is estimated by dividing the total consumption of fresh seafood products by the total Senegalese population. Data related to total consumption are provided by the Direction of Marine Fisheries, while the total population time series is available through the census and estimations regularly done by the National Agency of Demography and Statistics (www.ansd.sn).

Table 1 shows the main characteristics of the selected indicators. The objective is not to provide an exhaustive set of indicators. Therefore, taking into account the availability and relevance of the data required to describe the sustainability of the Senegalese fisheries, a list of basic indicators is proposed to demonstrate the necessity and strategy to simultaneously consider both ecological and socioeconomic dimensions in fisheries management policies. This list has integrated some elements recommended by the FAO directive on indicators for sustainable development of marine fisheries (FAO 1999). It also contains many variables considered in the RAPFISH tool for comparative evaluation of fisheries sustainability (Pitcher and Preikshot 2001).

Standardized PCA to Describe Multivariate Correlations

This article uses Principal Component Analysis (PCA) to describe high-dimensional data in just a few dimensions (Ringner 2008; Pessel and Balmat 2008; Abdi and Williams 2010). The reduction procedure consists of determining the directions (called principal components) where the cloud of values is more extended. From a geometric point of view, the principle of PCA is the projection of the data along the directions where they vary the most. These directions are determined by the eigenvectors of the covariance matrix corresponding to the highest eigenvalues.

Table 1
List of Selected Indicators to Analyze Fisheries Sustainability

Category	Code	Label	Unit
Fishing pressure	effhdl	Fishing effort of the hand lines fleet	Trips
	effgnt	Fishing effort of the gillnets fleet	Trips
	effrnt	Fishing effort of the ring nets fleet	Trips
	effbtr	Fishing effort of the bottom trawl fleet	Days
	catpel	Catch of pelagic fish by artisanal fisheries	Tonnes
	catdem	Catch of demersal fish by artisanal fisheries	Tonnes
	catoth	Catch of other species by artisanal fisheries	Tonnes
	catbtr	Total catch of bottom trawl fisheries	Tonnes
Fisheries socioeconomic state	eysaur	Economic yield of *Sardinella aurita*	FCFA/trip
	eysmad	Economic yield of *Sardinella madarensis*	FCFA/trip
	eypbel	Economic yield of *Pagellus bellottii*	FCFA/trip
	eyscae	Economic yield of *Sparus caeruleotictus*	FCFA/trip
	eyeaen	Economic yield of *Epinephelus aeneus*	FCFA/trip
	gdp	Fisheries GDP	10^9 FCFA
	curr	Currencies provided through exports	$US
	empl	Number of direct jobs in the fisheries	10^3 persons
	cons	Per capita consumption of fresh seafood products	Kg/person
Fisheries ecological state	aisaur	Abundance index of *Sardinella aurita*	Kg/trip
	aismad	Abundance index of *Sardinella madarensis*	Kg/trip
	aipbel	Abundance index of *Pagellus bellottii*	Kg/trip
	aiscae	Abundance index of *Sparus caeruleotictus*	Kg/trip
	aieaen	Abundance index of *Epinephelus aeneus*	Kg/trip
	aicymb	Abundance index of *Cymbium spp.*	Kg/trip
	aicyng	Abundance index of *Cynoglossus spp.*	Kg/trip
	lgsaur	Mean length of *Sardinella aurita*	Centimeter
	lgsmad	Mean length of *Sardinella madarensis*	Centimeter
	lgpbel	Mean length of *Pagellus bellottii*	Centimeter
	lgscae	Mean length of *Sparus caeruleotictus*	Centimeter
	lgeaen	Mean length of *Epinephelus aeneus*	Centimeter
	TL	Mean trophic level of total catch	Level

The effectiveness of the basic PCA method depends on the major assumption of Gaussian data. In general, a correlation matrix is recommended over a covariance matrix when variances are rather extreme or due to a common source of fluctuations, and particularly when different measurement units are used for different variables. Hence, in the case of heterogeneous data, single PCA is weakened by the units used to measure the original variables as well as the range of their values. To improve the effectiveness of the PCA, it is recommended to normalize the original variables. An alternative solution is to apply a Standardized Principal Component Analysis (SPCA), a common standardization method that was implemented in this article to transform all the data into z-scores with zero mean and unit standard deviation (Pessel and Balmat 2008). Therefore, for any given indicator, I, the standardization value at any time, t, is obtained through this formula (3):

$$I_t' = \frac{I_t - \mu}{\sigma}, \tag{3}$$

where μ and σ are the mean and standard deviation of I_t, respectively.

The normalization further reduces the spreading of the data and hence the noisy dimensions. SPCA equalizes dissimilar variations in the data set by using a correlation matrix instead of a covariance matrix. Therefore it facilitates the description and interpretation of the relationships between variables through a unitary correlation circle. In the case of this article, which tackles a time series data set, each principal component constitutes a time series summarizing the evolution of the indicators correlated with it.

Hodrick-Prescott Filter to Estimate Trends

There are many methods to estimate the trend of a given time series. In this article, we apply the Hodrick-Prescott filter to establish the trends of the indicators (Hodrick and Prescott 1980). This nonparametric smoothing method, which does not require any assumption on the distribution properties of the time series, is usually applied to estimate long-term trends of macroeconomic indicators (Razzak 1997; Kaiser and Maravall 1999; Gòmez and Bengoechea 2000). In order to estimate the trend, T_t, of a given indicator, I_t, the Hodrick and Prescott filter was applied by solving the minimization problem below (4):

$$Min\left[\sum_{t=1}^{n}(I_t - T_t)^2 + \lambda\sum_{t=2}^{n-1}[(T_{t+1} - T_t) - (T_t - T_{t-1})]^2\right], \tag{4}$$

where n is the total number of time units of the time series (in particular the number of years). For very high value of λ, the estimated trend is almost linear, but smoothing residuals are very important. On the other hand, very low values of λ yield trends that are almost similar to the initial time series. Hence, the suitable value of λ results from a compromise between the need to estimate linear trends and the concern of adjusting the extreme values of the time series. This flexibility is an important advantage of the HP filter method.

Mann-Kendall Test to Describe the Trends

A Mann-Kendall test (Mann 1945; Kendall 1975) is used to evaluate the significance and direction of monotonic trends that can be linear or nonlinear (Onoz and Bayazit 2003; Sheng and Chunyuan 2004). It is a nonparametric test that is not affected by extreme values (outliers). The principle of this method, whose algorithm is described below, consists of comparing all the values of the trend, T. Therefore, for $i < j$ the statistic of the test is calculated as indicated below:

$$S = \sum_{i=1}^{n-1}\sum_{j=i+1}^{n} s_{ij} \qquad \text{with} \qquad s_{ij} = \begin{cases} +1 & if\ T_i > T_j \\ 0 & if\ T_i = T_j \\ -1 & if\ T_i < T_j \end{cases}. \tag{5}$$

In practice, the test is performed by using the standardized statistic:

$$Z = \begin{cases} \dfrac{S-1}{\sigma_S} & if\ S > 0 \\ 0 & if\ S = 0 \\ \dfrac{S+1}{\sigma_S} & if\ S < 0 \end{cases} \qquad \text{with} \qquad \sigma_s = \sqrt{\frac{n(n-1)(2n+5)}{18}}. \tag{6}$$

This standardized statistic follows the standard normal distribution. If $|Z| \geq u\alpha_{/2}$, the null hypothesis is rejected and the presence of a significant monotonic trend can be admitted. A threshold of $\alpha/2$ equal to 5% is retained for all tests made in this article. Once a significant trend is statistically confirmed by the test, its direction is given by the sign of Z. If $Z < 0$ the trend is decreasing, and for $Z > 0$ the trend is increasing. A robust estimation of its slope can be made using the formula below (7) proposed by Sen (1968):

$$\beta = Median\left(\frac{T_j - T_i}{j-i}\right). \tag{7}$$

Visualization of the Fisheries Sustainability Profile

The main goal of the system of indicators is to visualize the profile of the fisheries in terms of sustainability. Because of the diversity and heterogeneity of the various indicators, it is essential to standardize them in order to be able to represent them together in a single scale. The choice of a standardization method is often arbitrary. However, it is preferable that the reference values used in the standardization method reflect the objectives of the societal response (situations to reach or to avoid). But in most cases, such reference levels are not available and cannot even be defined. In the case of the Senegalese fisheries for which an integrated set of reference levels taking into account the different dimensions of the sustainability has never been defined, the choice of an empirical standardization is a solution. With this method, the reference levels of a given indicator correspond to the minimum and maximum values recorded in the time series (Munda 2005). Thus, the standardized values of the indicator range from 0% (corresponding to the minimum) to 100% for the maximum. All the standardized values are calculated with the following formula:

$$I_t' = \frac{I_t - I_{t\min}}{I_{\max} - I_{t\min}}. \tag{8}$$

I_t and I_t' represent the original and the standardized values, respectively, of a given indicator at time t. I_{min} and I_{max} are the minimum and maximum recorded values of the time series. It is important to mention that in this empirical method, the reference levels (min and max) do not often reflect societal objectives. They correspond to the thresholds that show the best and worst situations reached by the indicators during the whole period.

Thus, this kind of empirical standardization is a useful statistical step that enables us to easily visualize and describe the general profile of the fisheries through a radar plot, also known as a web chart or kite diagram (Pitcher and Preikshot 2001; Munda 2005). However, because reference levels are not available *a priori*, results should be interpreted with caution.

Results of the Analysis of the System of Indicators

Interactions between Fisheries Development and Ecosystem Health

The histogram of the eigenvalues (figure 1) shows that the first three components (*C1*, *C2,* and *C3*) summarize 71% of the total variability of the set of indicators. With 44% of the total variability, the first component, *C1*, is a good summary of the global evolution of most of the indicators. Through this component there is a clear opposition between two groups of indicators. The first group, which is constituted by increasing indicators, is negatively correlated with *C1*. Those indicators are also strongly correlated between them. This group represents development of the fisheries characterized by an increase in fishing pressure, which has positive socioeconomic impacts. Those socioeconomic impacts are perceptible through the increase of some indicators, such as gross fishing revenue (economic yields), fisheries GDP, exports, number of jobs, and consumption per capita of seafood products. The second group, which is positively correlated with *C1*, represents the indicators whose trends are decreasing. It corresponds to the ecological state indicators. The decrease of these indicators reflects a progressive degradation of ecosystem health resulting from sustained fishing pressure over the last two decades. Therefore, ecological deterioration is highlighted by the worsening of the CPUE (abundance index), in particular for the demersal fish species, the mean length, and the mean trophic level of the catch. The two other components (*C2* and *C3*) summarize the evolution of the other indicators whose trends are not monotonic. Indeed, *C2* represents indicators that are relatively stable, such as the mean length of *Pagellus bellottii*, while *C3* describes parabolic situations (the case of the mean length of *Sardinella aurita* and the CPUE of *Sardinella aurita* and *Sparus caeruleotictus*).

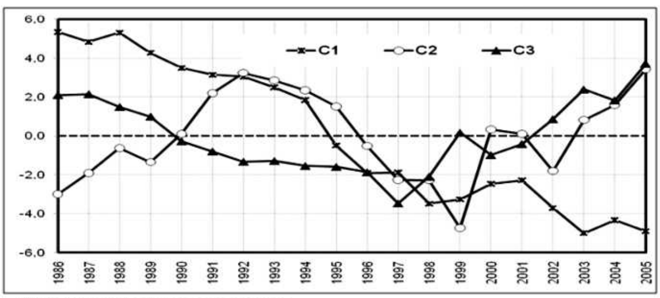
The negative correlations between the two main groups of indicators reflect the long-term conflicting interactions between the ecological and socioeconomic dimensions of the fisheries. This is the consequence of the antagonism between the health of the marine ecosystem and the development of the fisheries through the intensification of the fishing activities to satisfy the increasing socioeconomic objectives. Therefore, the dilemma between conservation and exploitation of natural resources is the real problem faced in the fisheries sustainable management policies. The objective of maintaining a minimal stock of natural resources for intergenerational needs is related to multiple dynamic factors. Thus sustainable management of fisheries should guarantee a dynamic coviability between ecological and socioeconomic systems (Le Fur *et al.* 1999; Cury *et al.* 2005).

Lessons from the Indicator Trends

All the fishing pressure indicators show increasing trends, except the catch of the bottom trawl fleet that is decreasing by –518 tonnes per year (figure 2). Fishing effort of the hand line and gillnet fleets is characterized by a large increase with an annual average growth, reaching 18,676 and 12,236 trips per year, respectively. However, fishing effort of those two fishing fleets was relatively stable at the end of the 1990s. The slope of the fishing effort of the ring net fleet is less significant, but remains considerable (+770 trips per year). Moreover, instead of stabilizing, the effort of the ring net fleet exhibited continuous growth during the entire period 1986–2005. With an annual growth of 3,177 days per year, the trend of the bottom trawl fleet's fishing effort is characterized by two steps. From the beginning of the period until the end of the 1990s the increase is high. Then, after reaching its highest level of around 300,000 days, the fishing effort of the bottom trawl fleet began decreasing.

COMPONENTS	EIGEN VALUE	PERCENT OF INERTIA	CUMULATED PERCENT	
1	13.1124	43.71	43.71	***
2	4.8758	16.25	59.96	********************************
3	3.2967	10.99	70.95	**********************
4	2.1709	7.24	78.19	***************
5	1.6450	5.48	83.67	************
6	1.1027	3.68	87.35	*******
7	0.9530	3.18	90.52	******
8	0.5377	1.79	92.31	****
9	0.4808	1.60	93.92	***
10	0.4059	1.35	95.27	***
11	0.3712	1.24	96.51	***
12	0.2875	0.96	97.47	**
13	0.2533	0.84	98.31	**
14	0.1800	0.60	98.91	**
15	0.1301	0.43	99.34	*
16	0.0979	0.33	99.67	*
17	0.0540	0.18	99.85	*
18	0.0314	0.10	99.95	*
19	0.0136	0.05	100.00	*
20	0.0000	0.00	100.00	*

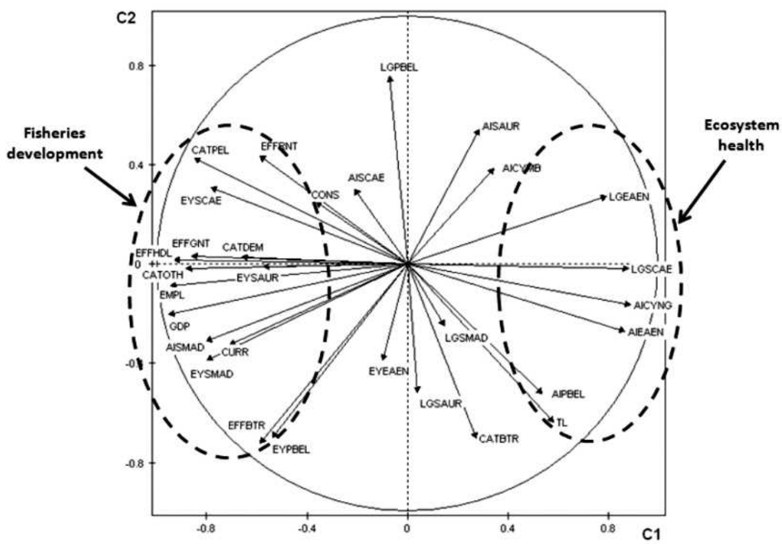
(a) Eigenvalues and relative inertia of the components



(b) Evolution of the first three components

Indicators	Correlation indicators- components		
	C1	C2	C3
EFFHDL	-0.93	0.02	-0.10
EFFGNT	-0.86	0.03	-0.27
EFFRNT	-0.59	0.44	0.16
EFFBTR	-0.59	-0.72	-0.19
CATPEL	-0.85	0.43	0.08
CATDEM	-0.66	0.03	0.48
CATOTH	-0.88	-0.02	0.24
CATBTR	0.28	-0.70	-0.03
AISAUR	0.29	0.54	-0.71
AISMAD	-0.80	-0.31	0.25
AIPBEL	0.54	-0.52	0.51
AISCAE	-0.21	0.30	0.66
AIEAEN	0.87	-0.27	0.24
AICYMB	0.34	0.39	-0.22
AICYNG	0.89	-0.16	0.20
LGSAUR	0.04	-0.52	-0.65
LGSMAD	0.15	-0.25	-0.51
LGPBEL	-0.07	0.76	0.21
LGSCAE	0.88	-0.02	-0.11
LGEAEN	0.80	0.28	-0.01
TL	0.58	-0.63	0.33
EYSAUR	-0.57	-0.01	-0.55
EYSMAD	-0.80	-0.39	0.05
EYPBEL	-0.54	-0.70	0.07
EYSCAE	-0.78	0.31	0.38
EYEAEN	-0.10	-0.39	-0.05
GDP	-0.95	-0.20	0.03
CURR	-0.71	-0.33	-0.10
EMPL	-0.95	-0.09	-0.15
CONS	-0.37	0.25	-0.33

(c) Matrice of correlations between indicators and three first components



(d) Circle of correlation in the plan (C1,C2)

Figure 1. Multivariate Correlations between Indicators

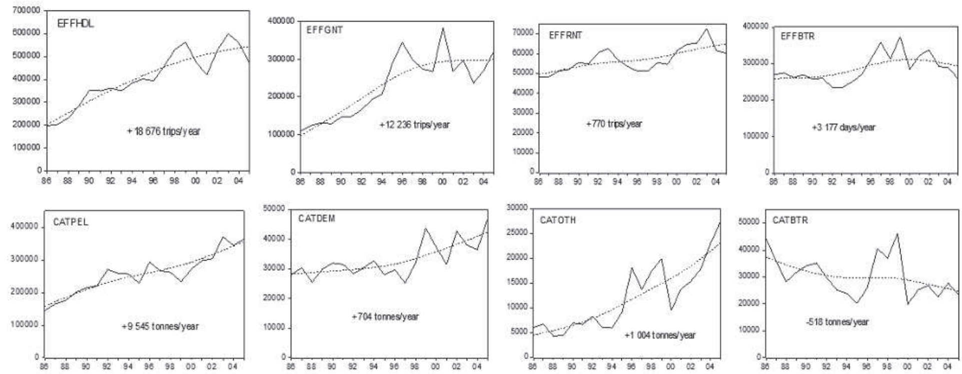


Figure 2. Time Series (solid line) and Trends (dashed line) of Fishing Pressure Indicators

Contrary to the bottom trawl fleet, whose catch is decreasing, the trends of the artisanal fisheries catch are increasing over the entire period. Thus, for the pelagic fish species, the slope of the catch is very high (+9,545 tonnes per year). After being relatively stable, the catch of demersal fish species has increased considerably since the second half of the 1990s. Given the scarcity of most of the demersal fish species, this recent increase is due to the exploitation of new target species, such as *Arius spp.* (Thiao 2009).

The socioeconomic indicators are all characterized by increasing trends (figure 3). However, at the beginning of the period, the levels of those indicators were very low and relatively stable until the beginning of the 1990s. Moreover, in 1994 a 50% devaluation of the national currency positively impacted the prices of most of the species, particularly for those whose catch is export-oriented. Thus, the average gross revenue per unit of effort (economic yields) of *Sardinella aurita* and *Sardinella madarensis* are characterized by significant growth from 1986 to 2005 (+5,602 FCFA and +5,476 FCFA per year, respectively). For *Pagellus bellottii*, the growth rate was less significant (+150 FCFA per year). However, except *Epinephelus aeneus*, for which the trend is relatively stationary over the whole period with few fluctuations, the economic yields of the main species are stable and even decreasing since the end of the 1990s. The specific situation of *Epinephelus aeneus* is due to its higher price that compensates for the strong decrease of its CPUE. The slopes of the trends of the GDP and the exports are positive and important (+3 billion FCFA per year and +4,982 US$ per year, respectively). The number of new jobs per year is around 1,400. It is important to note that with approximately 60,000 fishers currently, the artisanal fisheries sub-sector is the main jobs provider. Per capita consumption of seafood products is also increasing moderately (+0.1 kg/person per year). It has been rather stable since the end of the 1990s. The stability in and decrease of the trends of many socioeconomic indicators during recent years may reflect the negative impacts of long-term deterioration of ecosystem health.

Most of the trends of the ecological indicators are characterized by negative slopes (figure 4). This decrease is more perceptible for the CPUE of *Epinephelus aeneus* and *Pagellus bellottii* (–0.4 kg/trip and –0.5 kg/trip per year, respectively) and the mean length of *Epinephelus aeneus* (–0.9 cm per year). With an annual decrease of 2.9 kg/trip, the trend of the CPUE of *Cymbium spp.* is characterized by two steps. Before the beginning of the 1990s, the CPUE experienced rapid growth. After reaching a maximum level around 230 kg/trip, the CPUE began declining in the second half of the 1990s. This pattern is similar to the CPUE and mean length of *Sardinella aurita*. Despite the fact that the trends of these two indicators are not statistically significant (non-monotonic), it is clear that since the middle of the 1990s the case of *Sardinella aurita* is deteriorating. For

Pagellus bellottii, the mean length is stable at approximately 20 cm. The trophic level of the total catch is also decreasing (–0.006 per year). From 1985 to 2005, the mean trophic level has lost about 0.20 units, which is probably not negligible in terms of ecological functioning of the marine ecosystem. Although the trophic data extracted from FishBase are characterized by uncertainty, this indicator suggests that trophodynamic top-down changes may have occurred in the Senegalese marine ecosystems (Laurans *et al.* 2004; Bundy *et al.* 2010).

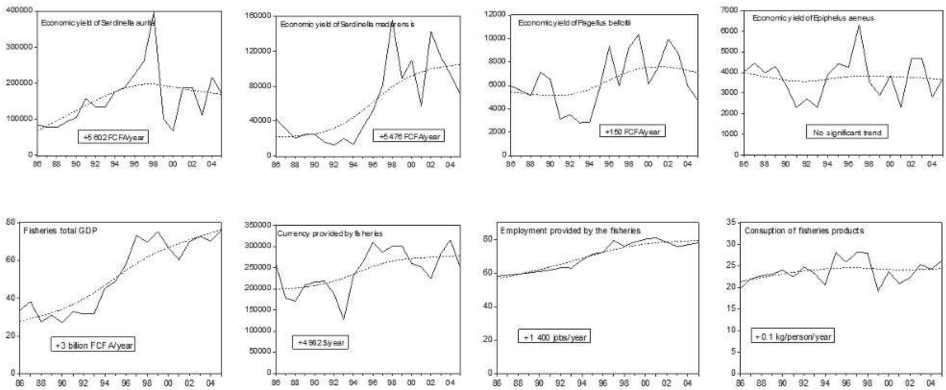


Figure 3. Time Series (solid line) and Trends (dashed line) of Socioeconomic State Indicators

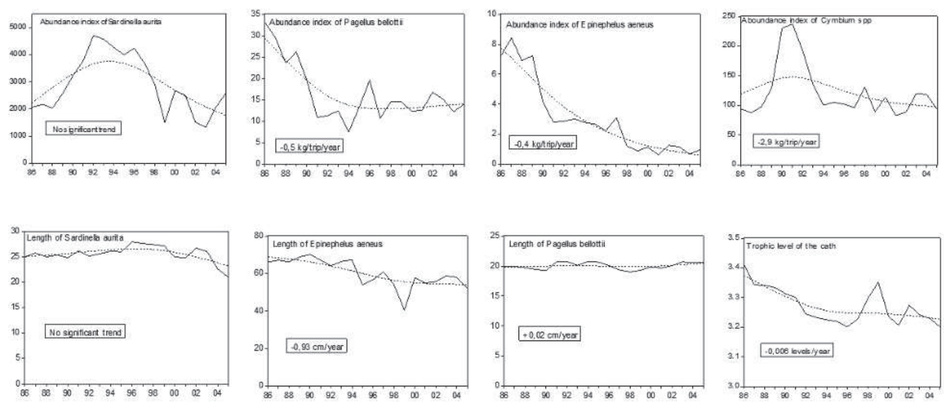


Figure 4. Time Series (solid line) and Trends (dashed line) of the Ecological State Indicators

Overview of the Fisheries Sustainability Profile

The visualization of the global sustainability profile through five web charts (figure 5) reveals that considerable changes have progressively affected the main dimensions of the fisheries (fishing pressure; ecological and socioeconomic condition). Thus, in 1986 the standardized values of the ecological indicators, which are between 80 and 100%, show a rather good ecological situation. However, during the following years the ecological states (abundance index, mean length, and mean trophic level) were globally worsening, while fishing pressure and socioeconomic indicators have progressively evolved towards higher levels. In 1995 the fisheries sustainability profile was in relative balance between the different categories of indicators. Five years later the profile is characterized by a clear deterioration of the ecological state. Thus, in 2000, except the abundance index of *Sardinella aurita* and *Sardinella madarensis* whose standardized values hardly reach 50%, the ecological state is at a very low level (standardized values less than 25%). In contrast, most of the socioeconomic indicators are improved, with standardized values beyond 50%.

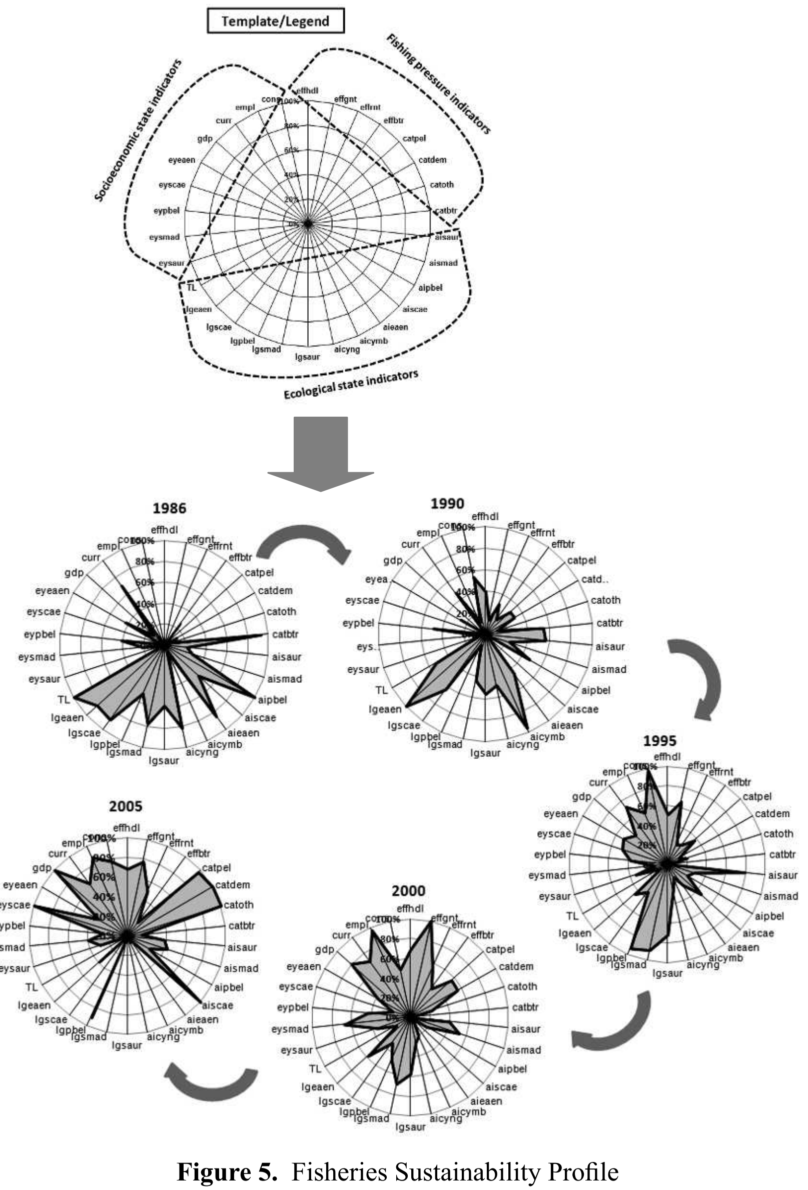


Figure 5. Fisheries Sustainability Profile

In 2005 the ecological state was clearly bad, except regarding the relative improvement of the CPUE of *Sparus caeruleotictus* and the mean length of *Pagellus bellottii*. Over the same period several socioeconomic indicators reached high levels. However, the gross revenue per unit of effort (economic yield) of some species exhibited low levels compared to their situation in 1995. This particular situation resulted from the general decrease of the CPUE of the main target species, which is no longer compensated for by increases in prices. Globally, it is clear that despite the importance of the fisheries, sustained fishing pressure has resulted in harmful ecological degradation and a worsening socioeconomic crisis.

Conclusion

Economists are now beginning to explore tradeoffs among economic, social, and ecological goals in bioeconomic models (Péreau *et al.* 2012). A system of indicators is useful to improve the understanding of the socioeconomic and ecological interactions and challenges of sustainable fisheries management. The analysis of some indicators illustrates the complexity of major changes in the Senegalese fisheries. Fishing activities help to satisfy socioeconomic needs, but they also place considerable pressure with long-term harmful ecological consequences that may involve socioeconomic loss. However, this case study demonstrates that ecological and socioeconomic factors do not move in the same direction simultaneously. When ecological states showed signs of deterioration, most socioeconomic indicators were still increasing. This lag is due to the fact that during the 1990s there was considerable, sustained fishing pressure combined with high prices that compensated for ecological loss and maintained human benefits. It is also consistent with the lagged adjustment process in Vernon Smith's dynamic open access model of the fishery (Smith 1969). However, during the end of the 1990s, trends of the socioeconomic indicators became generally stable and even decreased. Therefore, an effective management policy should seek to regulate fishing pressure before ecosystem health begins to show signs of decline and potential future socioeconomic crisis.

In order to mitigate conflicting interactions and ensure sustainability, fisheries management must strike a balance between human needs and ecosystem health. Being able to provide a global overview of the fisheries sector, a system of indicators is a useful tool for sustainability by encouraging dialogue and participative governance in a context of multiple objectives, constraints, and uncertainties. It can facilitate comprehension and collective identification of problems in order to guarantee consensus and acceptability that are necessary to improve management policies. However, in order to satisfy the managers' demand of information, indicators provided by scientists require heterogeneous data that are not always available. Some caution is also in order because indicators that are not grounded in bioeconomics and institutional context have the potential to be misleading. For example, there is considerable controversy over catch trends as an indicator of fishery collapse (Branch *et al.* 2011). Therefore, a system of indicators for sustainability should be considered as an integrated tool for adaptive management.

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