Aquat. Living Resour. 17, 107–117 (2004)

DOI: 10.1051/alr:2004021
www.edpsciences.org/alr

Aquatic
Living
Resources

Parameters estimates from various models as "sets of indicators" or "sets for indication" in a data driven approach

Francis Laloë[a]

UMR 063 C3ED (IRD-UVSQ) IRD, BP 64501, 34394 Montpellier Cedex 5, France

Received 26 January 2004; Accepted 11 May 2004

Abstract – A parameter of a model becomes a decision support indicator if it is used as an argument of a decision function. This implies consideration of a wider model than the initial one and to acknowledge its complexity. It is also necessary to include the estimation of parameters in indication theory and to consider a data driven approach. Data analysis leads us to provide sets of indicators. With reference to the statistical concept of sufficiency (Fisher 1925), such a set may also be considered as a set for indication, equivalent to the original data for any subsequent purpose of indication. From the same data set, several models may be built providing different sets for indication. None of them can be considered as the best; this depends both on the context (e.g. fishing practices) and on the addressed questions. No model must be chosen to the exclusion of alternatives: an illustration is given with models in relation to a catch-effort data set, with a case study on Senegalese small scale fisheries.

Key words: Model / Parameter / Set of indicators / Set for indication / Estimation / Sufficient statistic / Data driven approach / Fisheries system dynamics

Résumé – Estimations de paramètres selon divers modèles comme « jeux d'indicateurs » ou « jeux indicateurs » dans une approche guidée par les données. Un paramètre d'un modèle devient un indicateur d'aide à la décision lorsqu'il est utilisé comme argument d'une fonction de décision. Cela implique de le considérer au sein d'un modèle plus large que le précédent et de reconnaître la complexité du système étudié. Il est également nécessaire d'inclure l'estimation dans la théorie de l'indication et de considérer une approche fondée sur les données. L'analyse des données conduit à produire des jeux d'indicateurs. En référence au concept statistique d'exhaustivité (Fisher 1925), un tel jeu peut également être vu comme « jeu indicateur » équivalent aux données initiales pour toute production ultérieure d'indication. A partir d'un même jeu de données, plusieurs modèles peuvent être construits conduisant à des jeux indicateurs différents. Il n'est pas possible de dire quel serait le meilleur ; cela dépend à la fois du contexte (nature des pratiques de pêche en particulier) et des questions auxquelles on cherche à répondre. Le danger est de privilégier un modèle à l'exlusion des autres. Avec un cas d'étude relatif à la pêche artisanale au Sénégal, cette discussion est illustrée par des modèles associés à des données de capture et d'effort.

1 Introduction

One apparently obvious aspect of the relation between social demand and scientific knowledge is the quality of the answer from scientific studies to this social demand. It is commonly stated that this answer must take into account the available scientific knowledge and that it must be clear. To gather these two qualities is far from being easy: a difference between the representations of two "objects" from a given scientific viewpoint must not necessarily lead to different "social" answers. Alternatively, "socially different" objects may appear equivalent according to one given scientific representation. Referring to the definition proposed by G. Bateson (quoted by Bougnoux 1993, p. 227), one information is "a difference that makes a difference", indicating that one information from one viewpoint is not necessarily one information from another. This is otherwise "complicated" because there is not only one scientific viewpoint and because one can find in the social demand many different questions and expectations.

We first consider in this paper indicators as particular formulations of the parameters of a given "scientific model". Any scientific representation of a fisheries exploitation includes a certain number of parameters (prices, costs, numbers of jobs, carrying capacities, growth rates, catchabilities etc.). Each of these parameters is defined with a given meaning. Functions of these parameters may be proposed as indicators, having themselves definitions and clearer senses as elements of answers to others questions. Therefore, the transition from parameter toward indicator leads us to consider a wider context than the

[a] Corresponding author: laloe@mpl.ird.fr

initial one and leads us to acknowledge explicitly the complexity of a system.

We then present indicators as useful information on the various components of a fisheries exploitation system. Such presentations acknowledge the complexity of the system; they also lead us to establish large lists of indicators which can be difficult to collect in one single representation.

We then consider the topic through a data driven approach. Analysis of a data set leads us to build a model, which can be used with a fitting procedure (e.g. least squares) to produce a "treatment" of the data. This treatment results in a statistic, a set of functions of the data, estimates of the parameters of the model. We may then use the model with these estimated values for exploratory analysis, whose results will be functions of the data. Such an approach may be to some extent generic if it is applied to a data set obtained through usual survey designs (e.g. catch-effort data obtained from stratified sampling designs).

We finally consider that an overall goal may not (only) be to search for a finite "complete list" of indicators, which would mean that we search for a perfect knowledge of the information needs of everyone involved in the system. More "modestly", from the available knowledge of the system and available data, the goal may be to search for an "indicator set" (or a "set for indication"), i.e. a set of functions of these data which are as far as possible equivalent to the original set of data for any subsequent purpose of indication. This can be directly related to the concept of a sufficient statistic (Fisher 1925). For illustration of this context, we present an example with various models and a catch-effort data set from a stratified sampling design for small scale fishery in Senegal.

2 Indicators from a given theoretical representation: Schaefer's model and MSY as a basic example

The parameters of the well-known Schaefer's model (Schaefer 1954) are r, K and q (growth, carrying capacity and catchability) in the equation:

$$\mathrm{d}B_t/\mathrm{d}t = rB_t(1 - B_t/K) - qf_tB_t.$$

These parameters can be estimated from data, time series of yields and efforts (see for example Pella and Tomlinson 1969; Hilborn and Walters 1992). These estimates, combined with the time series of efforts, can be used to estimate the mortality $F_t = qf_t$ at time t. They also permit the estimation of the biomass B_t at one given time t. The functions $rK/4$ and $r/(2q)$ correspond to the MSY and f_{MSY}, Maximum Sustainable Yield and level of effort leading to this yield if it is maintained constant. From a scientific viewpoint on the dynamics of a population, r, K and q have clear definitions. MSY and f_{MSY} do not provide any further information since they are exactly known from the r, K and q values. MSY and f_{MSY} may be useful because they present the information in a different way. We should therefore consider a broader context than the initial one (Schaefer's equation) for which the K, q and r parameters were defined. It is necessary to identify viewpoints for which knowledge of the values of MSY and f_{MSY} makes sense and particularly, according to these values, what decisions will be taken, by whom and according to which objective.

Considered this way, a parameter becomes an indicator, an element of a statement in a broader context than the one of the initial model. This can be for example the context of the scientific appraisal where a scientific statement is integrated into the dynamic of a decision process (Roqueplo 1997). If one considers the dynamism of a decision process, some indicators must naturally be qualified as "decision support". A simple tool to verify that a parameter presents this quality is to check that different values (estimates) of this parameter lead to different decisions. As a difference making a difference, the indicator is really an information according to the definition of Bateson.

Visual representation can be used to illustrate how a parameter or a set of parameters can be used as an indicator. For example, Serchuck et al. (1997) present, on a graph whose coordinates are the levels (F_t and B_t) of mortality and biomass at time t, the various areas for which a "decision" should or should not be necessary in order to achieve a sustainability objective. Garcia (2000) and Mace (2001) also present this example. Such a presentation can be used in the context of viability theory (Béné et al. 2001) according to the decisions that can really be taken to identify the areas for which solutions (available decisions on mortality levels) exist or not in order to achieve a given objective.

The variation of the decision according to a variation of the indicator value can also be illustrated with the derivative of the decision as a function of which the indicator is an argument (note that the mathematical term of argument of a function f to name x in the equation $y = f(..., x, ...)$ appears very well adapted in the present case):

$$\lim_{\varepsilon \to 0} \frac{D(..., x + \varepsilon, ...) - D(..., x, ...)}{(x + \varepsilon) - x}.$$

This highlights two very important aspects. First, x is not necessarily the only argument(s) of the decision. Second, and may be more important, this equation is made up of three elements, a ratio, its numerator and its denominator. There is here a paradox because each of these elements can lead us to identify scientific research questions, but this quality has been considered up to here for the denominator only. The two other aspects have only been introduced to describe the transition of x from a parameter toward an indicator in the decision making domain. The widening of the domain of the potential questions for research is justified by considerations for the application of the research. In addition, some of the questions that can appear in this context may be not recognized by anyone of the single disciplines of research involved in a research program. If so, they may be considered as "orphan". For example (Laloë 1999) such a question deals with the part due to the decisions of the fishers in the variability of the impact of the actions they operate on the resource: for natural sciences this variability makes difficult to assess the state of the resource under study and, for social sciences, the impact of activity is of no direct interest. Those questions may be especially fundamental if they emerge as a need for applicability of the research; their adoption may impose a better identification of the role of disciplines in the field of sciences of information (Laloë 1999).

3 Acknowledging complexity

If one considers x as a parameter of an exploited population dynamics model, its status as a decision support indicator is to be a parameter of a new model connecting the initial one with a second describing the decision. The initial population dynamics model becomes one element of this whole. This means that the transition of the parameter toward the indicator implies a decision of complexity, according to the following definition proposed by Legay (1997), who considers complex:

> "a system, the nature of which changes when it looses one of its elements".

However, the population dynamics model remains present and necessary, with its formula, its parameters, their meanings and the data used to estimate them. If the interpretations change in a broader context, the formulae remain present. This paradox disappears if one considers that a model is not defined by a formula but by the interpretation of this formula. Therefore, several models may be defined with the same formula according to the following definition (Wagner 2002): "The models of a formula are the interpretations that make it true".

In order to put in concrete form this decision of complexity, it is necessary to identify decision functions. This implies identification of a decision-maker, a formulation of the parameters of the "scientific" model as argument(s) of the decision function and explicit clarity for this function to include some other arguments. It is necessary to identify the pursued objective, and what may be used in the initial "scientific model" to describe this objective. This complexity further increases if one admits that there may be several decision-makers, with possibly contradictory objectives, and that they do not necessarily extract the same arguments from the parameters of the initial scientific model...

Coming back to the Schaefer's model as an example of the initial scientific model, the parameters are r, K and q. They may be formulated as MSY, F_{MSY} and F_t, arguments of one decision function $D(\cdots, MSY, F_{MSY}, F_t, \cdots)$ at the current time t. It is now commonly stated and admitted that this context "as a whole" is not at all satisfactory. There are countless numbers of criticisms, for example relating to:

- the quality of the scientific model as a representation of the dynamics of a population, (equation, definition of the resource as a unique entity, impact of other sources of variation...);
- the quality of the estimates of the parameters of the model with available data;
- the quality of *MSY* as sufficient for a complete identification of the objective;
- the quality of F_{MSY} (or f_{MSY}) as control;
- the decision-maker's power (and even his existence) to fix mortality to a given level;
- ...

Cury and Cayré (2001) present the evolution of "*MSY*" in the last 50 years. They indicate that the existence of maximum sustainable yield has been present since the fifties (Beverton and Holt 1957), but that 20 years later this idea was questioned in a drastic way by the famous "epitaph to the concept of maximum sustained yield" of Larkin (1977). This was followed later by a discussion on the objective of the management as the one proposed by Pitcher and Pauly (1998) who consider sustainability as a deceptive goal and argue that rebuilding ecosystems should be the over-riding goal of new fisheries management approaches.

But this rejection is "pure and simple" and as such may be excessive in the context of an intrinsically complex problem. This complexity is erased here while proceeding to a certain number of *identifications*: the decision, $F_{\text{future}} = F_{MSY}$ or $f_{\text{future}} = F_{MSY} = r/2q$, is an identity function of one element of the list of indicators. In the same way the objective, catches equal to $MSY = rK/4$ is also an identity function of one element of the list of indicators. There is no flexibility in the articulation between the decision, the objective and the parameter. In addition, parameters, objectives and decisions are enterely defined from the model in use... This leads us to restrict the social demand as a set of expectations to which an arbitrary and reductionist model can provide exact answers. Note that this must not lead to reject the model and its parameters. This criticism can be made against any model whatever its quality may be. For example we may consider that an ecosystem approach can be preferable to an approach in which the resource is described by an unique quantity. Models of ecosystem are available (for example Ecopath and Ecosim, Walters et al. 1997). But as for the "*MSY* context" this approach becomes open to the same criticism if it is associated to an objective entirely described by the model, as presented in the article "Rebuilding ecosystems, not sustainability, as the proper goal of fishery management" (Pitcher and Pauly 1998).

If we come back to complexity, the criticisms become much less straightforward, and the history of the *MSY* may be presented in a different way. For example, Mace (2001) considers transitions in the definition of *MSY*, with one first stage where *MSY* is seen as a fixed amount that could be taken each year indefinitely. *MSY* is then seen in a second stage as a maximum Yield average (or an approximation of it)... the following stage being to consider F_{MSY} as a limit to be avoided rather than a target... This sequence makes clear the recognitions of the stochastic aspect of the studied phenomenon, of the problems of indicator estimation and of the fact that the objective is not necessarily an optimum expressed as some particular function of parameters of the used model. This leads Mace (2001) to answer the "*MSY* epitaph" of Larkin (1977) with a "*MSY* reborn" telling among other things that "*MSY* as a cause, it's the focus of many laws". All of this may perhaps finally be summarized with a definition of *MSY* probably due to J. Gulland[1]

> Maximum sustainable yield (*MSY*: "A quantity that has been shown by biologists not to exist, and by economists to be misleading if it did exist. The key to modern fisheries management".

[1] This quote is given by R. Hilborn (1994) in the preface of a book of Daniel Pauly: Gulland once sent me a "Confidential" briefing document that he (or an anonymous colleague) had prepared for private circulation. In the document a number of fisheries terms were defined...

4 Indicators as a general question

We have presented up to here the context of a scientific theoretical model, examining how its parameters can be used (formulated) as indicators in a wider context. Another way to proceed is to approach the topic directly from a wide viewpoint on governance and sustainable development, searching for pertinent indicators of a fisheries exploitation system. The contributions made in this context acknowledge the complexity of the addressed question. The indicators are relative to several components of the system, considering its natural, economic and social components and distinguishing indicators relative to the objectives, to the control variables, to the state of the system etc (see for example Garcia and Staples 2000; Riley 2001; Pitcher and Preikshot 2001). This is justified if the aim is to improve the capacity of management, which means we should link indicators between components of the system: "to be useful, indicators of sustainable development need to link the natural production and economic dimensions of fisheries activity" (anonymous 2002). Large lists of indicators are proposed, for which relationships with scientific knowledge become difficult to establish. This can be illustrated from a scientific viewpoint, in a particular domain, by the state of the art for definitions of the indicators (see for example Rochet and Trenkel 2003 for a presentation of the indicators of the impact of fishing on an ecosystem).

While thinking about an indicator as a potentially useful source of information, we can consider again the question of *MSY* in the following words: can one indeed pretend that no one would be interested, in one way or another, in an evaluation of the expectation of the maximum quantity of fish that could be produced in a stationary[2] process by a fishery... even acknowledging that this is conditional on the maintenance of the present "way of fishing" and on the maintenance of environmental conditions, etc. etc.? If some actors are not indifferent to it and if they use it, this evaluates the information, not necessarily as an objective, but may be merely as an argument in a discussion with other actors...

Models such as Schaefer's may be used to compute such an estimate but the model and the estimate no longer have the same meaning, becoming elements of a system which may be considered as part of "a construct with arbitrarily defined boundaries for discourse about complex phenomena to emphasise wholeness, inter-relationships and emergent properties" (Röling 1994). These systems must permit dialog between actors and they should be built in order to fulfil this objective (O'Connor 1999).

5 Estimation – and data – as a theoretical component of indication

As an element of a theoretical model, a parameter is defined in a theoretical way. This remains true if it is used as an argument of a decision function, in a theoretical decision model. The form of this function will depend on the quality of the available knowledge on the real value of the indicator. It is commonly stated that an indicator must be computable but generally, we only have an estimate. Therefore an indicator must theoretically be considered both as a parameter of a theoretical model (e.g. $rK/4$ in Schaefer's one) and as an estimate i.e. the value of a function of available data. This function is an estimator, i.e. a random variable whose quality must be assessed with parameters (e.g. standard errors). For example, depending on this assessment, the principle of precaution will be more or less taken into consideration. In the same way, the paper of Rochet and Trenkel (2003), providing a review of indicators which can measure the impact of fishing, becomes much more meaningful with its twin (Trenkel and Rochet 2003) dealing with estimation of these indicators with currently available data.

5.1 Indicators as data functions and the concept of the sufficient statistic (Fisher 1925)

This may lead us to consider indicators as data functions and to adopt a viewpoint on available data. The question then becomes: given an available data set, which are the data functions that may be useful, i.e. which provide answers to questions addressed by someone involved in the system? It is a priori quite evident that such functions will be found for some questions, and will not for many other ones. Hence, from a set of usual questions we may consider which of them may or may not be answered.

For example if we consider an usual cath-effort data set with the Schaefer's model, we may provide more or less precise answer to any question on biomass time series for a given effort time series... We may in addition provide more or less precise answer to any further question on some function of this biomass (CPUE, Yields, revenues...), but we cannot provide answer on the impact of the change of the price of one species on the effort time series...

If we choose a model with its parameters for the description of the dynamics of an exploited resource, we assume that the state of the resource is a function of those parameters whose values are estimated by fitting the model to available data. As said above the set of parameter estimates is a set of functions of these data, i.e. a (general) statistic (or synthesis). From these data and model, and whatever the question, the answer will then be a function of this statistic.

Therefore, this statistic should be able to provide all the information present in the data. If so, this statistic is said to be sufficient, according to the definition given by Fisher (1925):

> [a sufficient statistic] is equivalent for all subsequent purpose of estimation to the original data from which it was derived.

In statistical theory, this idea is made concrete throughout a quite simple formula known as the "factorisation criterion" (see for example Arnold 1988):

Suppose that a data set $\{x_1, x_2, ...x_n\}$ is a realization of one random variable whose distribution has a parameter θ with some dimension. The likelihood of the data set is

[2] Stationary means here that the distribution of the random variable of which the catch is a realisation does not depend on time. If stationarity cannot be assumed indefinitely (Fromentin and Ravier 2001), it can be considered for a given finite time, which may be (or not) acceptable in the context of the decision process...

$f(x_1, x_2, ...x_n; \theta)$. A statistic $T(x_1, x_2, ...x_n)$ is sufficient if and only if $f(x_1, x_2, ...x_n; \theta) = g(T(x_1, x_2, ...x_n); \theta) \times h(x_1, x_2, ...x_n)$. This means that, conditional on the value of $T(x_1, x_2, ...x_n)$ the likelihood of a data set does not depend on the parameter θ. Therefore, the differences between data sets $\{x_1, x_2, ...x_n\}$ and $\{x'_1, x'_2, ...x'_n\}$ for which $T(x_1, x_2, ...x_n) = T(x'_1, x'_2, ...x'_n)$ make no difference to what we can estimate about and from θ. From Bateson's definition, there is no information on these differences.

We have now two definitions of the parameter of a model, which means that we have two different models, even if we give them the same name. They are (i) the parameter of the exploited population dynamics model (e.g. r, K, q with Schaefer's one) and (ii) the parameter of the distribution of the random variable for which the data used for estimation purposes are a realization.

These two definitions may to some extent be superimposed if the set of estimates of the parameter of the population dynamics model is also a sufficient statistic. As far as possible, experimental designs are built in order to reach such a superimposition. This is achieved if the collected data may be assumed to be a sample from a gaussian linear model $Y = X\beta + \varepsilon$ where $X\beta$ is the expectation of Y, and where ε are gaussian, independent residuals with equal variance σ^2: in this case $\hat{\theta} = \{\hat{\beta}, \widehat{\sigma^2}\}$, least squares estimates of β and the estimated residual mean squares, is a sufficient statistic. This statistic is minimal since it is no more sufficient if we remove one of its elements. In fisheries analysis, models are not linear and, as we study time series, residuals cannot be assumed independent. Each of these two properties makes it impossible to assume that least squares estimates of β and the estimated residual mean squares provide a sufficient statistic. But this statistic may be considered "as minimally sufficient as possible". If so, it can be related to an equivalence relation on the sample space where two samples are equivalent if they lead to the same estimated values. The partition of the sample space (the possible data sets) defined by this equivalence relation is "as minimally sufficient as possible", this partition is unique and makes clear "what is important" (See Arnold 1988 for a rigorous presentation of minimal sufficient statistics and minimal sufficient partitions).

With such an assumption, this statistic may be viewed as one formulation of the set for indication *derived from the data set. It may provide a list of indicators, but the important result is that any further indicator from this data set will be a function of the elements of this statistic.*

As said above, the statistical quality of the set of parameter estimates depends strongly on the sampling design used for data collection. We shall consider this question in the context of catch-effort surveys: data on activity and results of commercial fishing units are collected with a sampling design which cannot be considered as a controlled experimental design (as is done for scientific surveys using a scientific vessel). The "experimental design" is at least partially decided by fishing units (choice of target species, fishing gears, fishing areas...), and the quality of the superimposition will depend on the nature of these decisions.

6 An illustration with catch-effort data analysis

The aim of catch effort surveys is to provide estimates of time series of fishing activity and catches, which will be used for the estimation of the parameters of exploited population dynamics models. The general equation of such a model is:

$$E(Y_t) = g_{\theta_1}(y_{t-}, f_t, z_t). \tag{1}$$

Where $E(Y_t)$ is the expectation of catches at time t, g_{θ_1} is a function with parameter θ_1. The arguments y_{t-}, f_t and z_t represent previous fishing results, fishing activity and some elements of the "environment". The dimensions of Y_t, θ_1, y_{t-}, f_t and z_t may be greater than one. For the first step, the fishing effort is estimated as a time series f_t. Then, conditional[3] upon the f_t time series, estimates of the parameter θ_1 of the model are obtained, for example using a least squares criterion of the differences between observed and fitted catches (see for example Hilborn and Walters 1992). With such an approach, the definition of f_t as an argument representing the impact of fishing activity mainly results from the definition chosen to represent the resource. For example, it is one fishing effort in the case of a one-stock surplus production model. In the case of a multi-components resource (e.g. Ecopath and Ecosim models, Walters et al. 1997), this variable is a set of yields or mortalities per component.

The estimates of the parameter θ_1 could be obtained by searching which values $\widehat{\theta_1}$ of θ_1 maximize the likelihood of the observed Y with given f:

$$\mathcal{L}(Y; \theta_1|_f).$$

We shall call hereafter this formula the *"conditional dynamic model"*. The set of estimated values $\widehat{\theta_1}$ is used as a set for indication: for any purpose of estimation the contribution of the original data set is provided as a function of $\widehat{\theta_1}$ only. This would be entirely justified if the set of estimated values was a sufficient statistic but, as said above this objective cannot be achieved. However, with more or less realistic assumptions on the distribution of Y_t we consider that the usual least squares estimate of θ_1 (including the residual sum of squares) provides an "as sufficient as possible" statistic.

The criterion to be minimized may be:

$$C(\theta_1) = \sum_k \frac{\| c_k - \widehat{c_k} \|^2}{\| c_k - \bar{c}_k \|^2}. \tag{2}$$

Where c_k, $\widehat{c_k}$ and $\bar{c}_k$ are observed, fitted and mean values of the time series of catch per action for resource component k. $\|\|^2$ notation means the sum of squared differences between observed and fitted values from time step t_0 to t_d (e.g. $\| c_k - \widehat{c_k} \|^2 = \sum_{t=t_0}^{t_d} (c_{kt} - \widehat{c_{kt}})^2$). Estimates of θ_1 are the values $\widehat{\theta_1}$, *functions of the data*, that provide a minimum value of $C(\theta_1)$.

The quality of the results depends on many conditions. We shall consider here the quality of the experimental design provided by fishing units with reference to (i) parameter estimation and (ii) indication quality.

[3] "Fishing activity" f_t is considered as a known given value (as the x variable in linear regression $Y = a \times x + b + \varepsilon$).

6.1 Parameter estimation

As the estimation of parameters is made conditional on the estimates of the f_t time series, the quality of the latter is crucial. When several fishing fleets are present, with several fishing methods having different impacts on the resource, a classification of fishing actions is needed according to these impacts. Classes of this typology are usually called "métier" or "tactic" (see for example Laurec et al. 1991; Pech et al. 2001; Ulrich et al. 2001). The f_t values are functions of the numbers of actions in each tactic. This leads us to consider stratified sampling designs where each stratum is a population of fishing actions with similar impacts on the resource. Estimates of f_t values will then be functions of strata sizes at time t. If each fishing unit always adopts the same tactic, the strata are homogeneous, their sizes are stable and the tactic may be used as a criterion for classification of fishing units. Therefore, to confuse classifications of fishing units and fishing actions provides some comfort and makes no problem[4], even if these units are of a different kind.

This confusion causes problems if some fishing units choose between several types of fishing actions, for example fishing units of a "Single multitarget fishery" (Gulland and Garcia 1984) or of an "integrated fishery" (Garrod 1973). Such fishing units may have several available gears and they also may use one given gear in several ways. If the gear is used to allocate a fishing action to a sampling stratum, the choice of gear is also the choice of a stratum whose size becomes variable. Then the possible choice between different uses of a given gear leads to intra-strata heterogeneity. These strata size variability and heterogeneity are due to the fishermen's decisions. It therefore becomes necessary to distinguish between fishing units and fishing actions. A class (fleet or strategy) of fishing units may gather fishing units having the same set of available tactics for a decision rule which at any given time leads them to adopt each of these tactics with the same probability (Pech et al. 2001).

If some fishing units choose between several types of fishing actions, strata size variability makes it more difficult to estimate the f_t values: we need a much more detailed sampling effort in order to achieve a given quality of estimation. Intra-strata heterogeneity leads to a second problem since catches reflect a mix of results in variable proportions decided by the fishermen, which makes the relation between abundances and CPUE more questionable.

Therefore it is important to consider activity and results of "single tactic" fishing units. This may explain to some extent why most models of dynamics of exploited populations do not make any distinction between types of fishing units and types of fishing actions.

This does not mean that it is not possible to estimate parameters of a population dynamic model when fishing units have such strategies. It simply means that to achieve some given precision, there is a greater need for observation and data computation. A solution exists by selecting "single tactic" fishing units from which we may estimate CPUE with acceptable confidence. "Standardised efforts" of the "multi tactic" fishing units may then be estimated from their total catches divided by the estimated CPUE.

If all fishing units are "multi tactic"; then we may use results from scientific surveys. From comparison of commercial catches with the results of scientific surveys, we may have acceptable estimates of the f_t time series.

But this will in turn make problems in the field of indication...

6.2 Indication quality

The confusion between fishing units and fishing action classifications also leads to a simplification that provides some "comfort" in the indication's field. Here again, depending on fishing practices, those confusion and comfort may be somewhat misleading.

From the equation $E(Y_t) = g_{\theta_1}(y_{t-}, f_t, z_t)$, with estimated values of θ_1, we may now estimate at a given time t_0 the dynamics of the resource conditional upon the future f_t $(t > t_0)$ values. We also may estimate the value of any function of the state of the resource and f_t values (e.g. catches, revenues...). Therefore, the more f_t values can be "precisely decided", the more precise and clear will be the answers to questions about the dynamics of the resource and the results of the exploitation.

But if some fishing units choose between several types of fishing actions it is not possible to compute a unique f_t from a given set of fishing actions operated by a given set of fishing units, and there is no single decision maker who can fix the value of f_t...

In this case, if the number of fishing actions of a given set of fishing units (i.e. a set of nominal efforts) is the variable whose value can be fixed by an identified decision maker (the person or the institution who is supposed to use the indications provided by application of the scientific model), the impact of this decided activity is not a constant but a random variable whose range depends on the "alternative sets" of tactics available to the units of the various strategies (see for example McFadden 1973; Holland and Sutinen 1999).

This does not mean that no management is possible, but that the f_t values depend on both nominal efforts and the decision of the individual fishing units. The latter must also be taken into account in the model.

Several models exist, focusing on various aspects of fleet dynamics (e.g. Smith 1969; Allen and Macglade 1986; Laurec et al. 1991; Laloë and Samba 1991; Charles 2001).

[4] In this case, the catchability ratio of actions operated by two given fishing unit is assumed to be constant. With this assumption, standardised effort values may be obtained through procedures leading to estimate the fishing power of each fishing unit as a main effect in a linear model describing log values of catches per unit of nominal effort. There may be space-time effects, but interactions between these effects and fishing units effects are assumed to be nil. In gaussian general linear models, $(Y = X\beta + \varepsilon)$, with independent $N(0, \sigma^2)$ residuals, least squares estimates of β and the estimated sum of squared residuals provide together a sufficient statistic. The Robson's (1966) model for effort standardisation is such a linear model without interactions between fishing units and space-time effects. If this assumption is realistic, the model provides a "complete" use of the data. If not, fishing power estimates are more or less realistic, depending on the non-orthogonality of the experimental design provided by the fishing units and standardised effort estimates may be biased.

Laloë and Samba (1991) consider the connection between activity seen, at a given time t, as numbers N_{st} of active fishing units (per strategies, hereafter identified with subscript "s") and as numbers f_{jt} of fishing trips (per tactic, hereafter identified with subscript "j").

The expectation of f_{jt} may be written:

$$E(f_{jt}) = \sum_{s=1}^{S} p_{sjt} \times N_{st} \quad (3)$$

where p_{sjt} is the probability that a fishing unit of strategy s chooses the fishing tactic j at time t. These p_{sjt} values are parameters of multinomial distributions, represented throughout "conditional logit models of qualitative choice behaviour" (McFadden 1973) taking into account expected revenues from available tactics.

This leads us to consider a model of joint dynamics of exploitation and resource whose parameters concern the resource (as θ_1 in Eq. (1)) and many other ones (θ_2) such as prices, costs, and parameters accounting for the decision rules of the fishing units (see Pech et al. 2001). This model connects the population dynamics model (Eq. (1)) with a second one providing the expectation of the f_t values, which are not considered as fixed variables. This model describes the joint distribution of Y_t and f_t process with parameters $\{\theta_1, \theta_2\}$.

This changes several things in the fields of estimation and of indication

6.3 Parameter estimation

We are now interested in the analysis of the likelihood

$$\mathcal{L}(Y_t, f_t; \{\theta_1, \theta_2\})$$

which we will call hereafter the "*joint dynamics model*". We estimate values of $\{\theta_1, \theta_2\}$ with a least squares criterion taking into account the squared differences between observed and fitted sizes of sampling strata and, in each stratum, between observed and fitted catch per action for each component of the resource:

$$C(\theta_1, \theta_2) = \sum_{e,k} \frac{\| c_{ek} - \widehat{c_{ek}} \|^2}{\| c_{ek} - \bar{c_{ek}} \|^2} + \sum_{e} \frac{\| f_e - \widehat{f_e} \|^2}{\| f_e - \bar{f_e} \|^2} \quad (4)$$

Where f_e, $\widehat{f_e}$ and $\bar{f_e}$ are observed, fitted and mean values of time series of size of stratum e (a stratum e may gather several tactics). c_{ek}, $\widehat{c_{ek}}$ and $\bar{c_{ek}}$ are observed, fitted and mean values of time series of catch per action for component k in stratum e. Estimates of (θ_1, θ_2) are the values $(\widehat{\theta_1}, \widehat{\theta_2})$, functions of the data, that provide a minimum value of $C(\theta_1, \theta_2)$.

6.4 Indication

Once the set of estimates of the parameter values is available, it may be used for further indication purposes. Among the functions of the parameter estimates, the estimated values of the data are of particular interest for model "validation" (for example with graphical comparison of observed and fitted time series). With the conditional dynamic model, this set of estimated values is the catch or cpue's time series $\widehat{c_k}$. With the joint dynamics model "cpue" $\widehat{c_{ek}}$ are considered for each stratum and are completed with strata size time series $\widehat{f_e}$. These time series end at some given time t_d (e.g. the end of available data); it is possible to continue the application of the model with changes to the values of some parameters at some given times ($t > t_d$). Conditional on these changes and the model formula, the results will again be functions of the data, through parameter estimates.

With the conditional dynamic model, these changes may concern f_t values. A typical question that may be answered deals with the impact of such changes on the resource and on functions of the resource, for example, revenues of fishing with given values of fish prices and fishing cost. With the joint dynamics model, the f_t values are no longer considered as direct control variables. For example, the latter may be the size of the various fishing fleets or the alternative set of choices for some strategies (e.g. if the use of some tactics is banned...). Here, new f_t values are not directly introduced, but result from an interaction between several types of decisions.

The impact of some changes may be very different when considered in the conditional dynamic or in the joint dynamics model. Let us consider a change in the price of one or several of the harvested species. With the conditional dynamic model, this does not lead to some change of the f_t values. Use of this model will "only" permit us to estimate the impact of this price's change on fishing revenues. With the joint dynamic model, this price is a parameter of the function describing proportions p_{sjt} in Eq. (3). Therefore, this change of price has an impact on the f_t values and, further, an impact on the resource. These impacts may be estimated as functions of the (θ_1, θ_2) estimates. They are functions of the general indicator. They are indicators if someone involved is interested in such results.

7 Illustration with a "fitted to catch-effort data set" model of the Senegalese artisanal fisheries

A joint dynamics model with a general fit for a catch-effort data set from the Senegalese artisanal fishery is available[5] (Pech et al. 2001). In this example, time series data are available, per fortnight from 1974 to 1992. Effort data are the numbers of daily fishing trips for seven strata defined by "landing port - fishing gear" combinations. For each stratum, fishing results consist of a time series of catch per trip for each catchable component of the resource (13 components are identified). There are 36 such catch per trip time series. Each stratum includes at least one tactic (for example the stratum "handlines at Kayar" gathers six different tactics). There are 23 different tactics defined, 17 of them are artisanal fishing actions and one

[5] The results presented here are obtained with the data set and the fitting procedure described by Pech et al. (2001) with two main changes: least squares concern untransformed CPUE data (no log transformation) and catchabilities are seasonal (instead of inaccessibility parameters).

"industrial" tactic is introduced to account for catches made by the industrial fishing fleets. Five artisanal fishing strategies are identified, each of them with a given alternative set of choice (list of available tactics). For each of those five strategies, one available "non fishing tactic" is defined with an opportunity cost as parameter. A sixth strategy is "industrial"; it gathers a hundred virtual fishing units, which have only the industrial tactic available. This tactic is given a catchability parameter for each component of the resource. It is therefore possible to modify the impact of industrial fishing by changing the number of fishing units or by changing one or several catchability parameters. A "diagram of Pech" (Pech et al. 2001, Fig. 2) may be used to summarize all these characteristics in a convenient way.

From the estimates of the parameters of the model, Pech et al. (2001) provide some examples of the impact of various changes dealing with the prices of exported species, the carrying capacity of octopus, and the mortalities generated on some species by the industrial fishery. We shall here present, for illustration, one example in order to highlight some aspects discussed above. From the fitted model, we may consider the estimated state of one given component of the resource, for example the so-called "groupers" component that gathers the serranidae species. The dynamics of this component are assumed to be determined by the equation:

$$\frac{\mathrm{d}B_t}{\mathrm{d}t} = rB_t\left(1 - \frac{B_t}{K}\right) - \sum_{j=1}^{J} q_{jt}\widehat{f_{jt}}(B_t - \alpha_j K).$$

Where the estimated value of K is 22587 tons and r is assumed equal to 0.4 (due to identification difficulties, some parameter values are fixed from available knowledge). With such values, the estimated MSY is 2259 tons. q_{jt} is the catchability of tactic j on groupers at time t (seasonality and inter years variability may be present and are accounted for by parameters of the model) α_j represents the proportion of the virgin biomass inaccessible to the tactic j. $\widehat{f_{jt}}$ are the numbers of fishing trips as estimated by the model.

After the end of the available data period (1992), estimated values of artisanal and industrial fishing mortalities are equal to 0.155 and 0.171. The total fishing mortality estimate is therefore equal to 0.326, which may be considered as an excessive value if we refer to the value of 0.2 ($r/2$), which would correspond to F_{MSY}. Suppose that for some reason (e.g. artisanal fishing activity must be maintained for social considerations, or it appears that a control of this activity is not really feasible), the decision maker considers reduction of the industrial mortality in order to reach the objective of a total fishing mortality equal to 0.2. If we consider the conditional dynamic model, the answer is quite simple: the industrial fishing mortality should be 0.045, i.e. a quarter of the current value. This can be obtained by a decrease in the number of vessels mainly targeting groupers. Technically, the consequence of such a decision can be examined by reducing the catchability of the virtual industrial vessels from 7.578 10^{-6} (the estimated catchability of industrial vessel on groupers) to $(0.045/0.171) \times 7.578\ 10^{-6}$, i.e. 1.99 10^{-6}.

We introduced this new value in the joint dynamic model at the beginning of 1993 and looked at results five years later

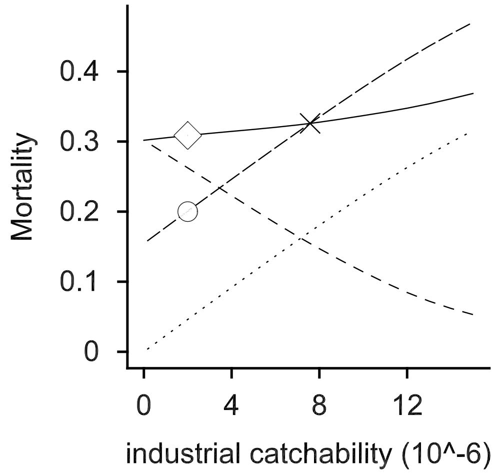

Fig. 1. Groupers fishing mortality levels in 1998 as a function of industrial catchability fixed in 1993 for this stock: industrial (···), artisanal (– – –), total (——). The line (— —) presents the total mortality assuming constant artisanal mortality (conditional model). The × indicates the total mortality level in 1992. The ○ indicates the objective in 1998 assuming no artisanal mortality change. The ◇ indicates the total mortality level in 1998 with the joint dynamic model.

(1998). The main result is a total fishing mortality much higher than 0.2 (0.308) with a very different distribution among artisanal and industrial fisheries (0.262 and 0.046). This result may appear natural if we consider that the reduction of industrial mortality leads to an increase of biomass, which further leads to a greater interest in the species for artisanal fishing units. As a consequence, there is a transfer of mortality between the two fisheries...

This phenomenon appears clear in Figure 1 presenting artisanal, industrial and total mortalities (in 1998) as a function of the industrial catchability fixed in 1993.

From such a result, we consider that the decision has no effect on the initial objective. This indicates that other solutions should be considered if the objective of reducing this fishing mortality remains an absolute priority. We shall not discuss this here. But many other things have changed, for example the price of the catch distribution of groupers between artisanal and industrial components of the fishery (Fig. 2). This latter result is very informative from several viewpoints...

8 Discussion

8.1 A set of indicators or a set for indication?

From a data set collected from a design built to answer some given questions, we try to produce a list of functions of these data. As far as possible, each element of this list should be an indicator. But any function of this list may also be an indicator, i.e. a function of data that contributes to answer a question that someone involved in the system may address. So a pertinent action for a set of indicators is to gather all the information present in the data set, so that a sufficient statistic can be considered as a set for indication... With the usual catch-effort data sets this quality appears as a statistician's holy grail.

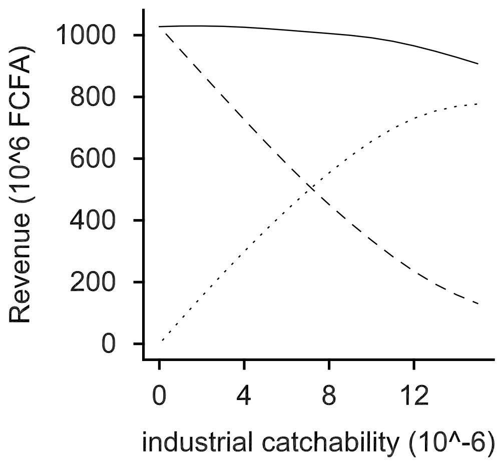

Fig. 2. Price of groupers catches as a function of industrial fixed catchability on groupers: industrial (···), artisanal (– – –), total (——).

In the simplest case of the Schaefer model, when assuming an observation error process (Hilborn and Walters 1992) where observed catches are realisations of random normal independent variables with equal variance, least squares estimates of r, K and q and the residual mean squares s^2 may be viewed as best (as minimally sufficient as possible) available statistics. Instead of the list $\hat{r}$, $\hat{K}$, $\hat{q}$ and s^2,we may prefer to provide an invertible function of this list whose elements are more meaningful indicators, e.g. estimates of MSY, F_{MSY}, f_{MSY} and s^2. The latter may also be the list $\{\frac{\hat{r}\hat{K}}{4},\ \frac{\hat{r}}{2},\ \frac{\hat{r}}{2\hat{q}},\ s^2\}$ from which we may exactly compute the former $\{\hat{r},\ \hat{K},\ \hat{q},\ s^2\}$. So they both contain the same information which may be related to the fact that a minimal sufficient statistic may be expressed in different possible ways, but that the minimal sufficient partition of the sample space is unique (see Arnold 1988).

To provide a list of meaningful indicators is of evident interest, but this must not mean that this list may be considered as "complete", and, particularly, that it defines exactly the objective of any decision. If we provide estimates of MSY and f_{MSY}, this does not mean that MSY is the management objective. Indeed, from those values we may compute an estimate of MEY (Maximum Economic Yield, provided we may know from elsewhere the cost of one unit of fishing effort and prices of fish). We also may compute estimates of the level of more cautious effort, lower than f_{MSY}, at which the expectation of catches would be, say 90%, of MSY.

Therefore, the set of indicators from a data set could be seen as a list of potentially interesting indicators, together providing as far as possible a minimal sufficient statistic, useful to estimate any further indicator. This set of indicators is, and may be primarily, a set for indication. A main characteristic is that we do not suggest that the indicator set includes all possible indicators, which would mean that we know the needs of information of all possible users; the objective is "only" to provide from a data set an information base from which any further information needed could be fulfilled. Such an indicator set may be viewed as an element of an "indicator dialogue box" (O'Connor personal communication) which may be used through dialogue between stakeholders and scientists.

8.2 Which model for a given data set?

We have presented above two different possible models for estimation purposes for the case of catch-effort data. Which of them is the best is all but evident.

If an institution exists which can fix the level of the impact of fishery activity, as is defined in the representation of the resource, a conditional dynamic model may appear sufficient to answer management questions. This is what happens when each fishing unit always operates fishing actions that have the same impact on the resource. In addition, estimation of the impact of activity makes no major difficulty in this case.

If this institution does not exist, e.g. because fishing units (or at least some of them) may choose between various types of action with different impacts on the resource, a representation of individual fishing unit decisions is needed to answer questions about the level of impact. Therefore a joint dynamics model is useful. But here we must distinguish problems of estimation of past and future impacts. Once fishing is done, its impact can no longer be changed and if we estimate it (e.g. from scientific surveys or from results of some of the fishing units in the data set), a conditional dynamic model remains useful. But, unless we may manage each fishing unit activity as if it was a scientific vessel, it is not possible to decide "exactly" the impact of future activity. It is "simply" possible, for one decision, to try to represent its "impact on the impact" on the resource. This leads to the need for a joint dynamics model.

From the same data set, the indicator set $\widehat{\theta_1},\ \widehat{\theta_2}$ from a joint dynamics model is an extension of the indicator set $\widehat{\theta_1}$ of the associated conditional dynamic model. Therefore the set of questions that may be answered is greater in the first case. But there may be some illusion: there may be no unique solution $\widehat{\theta_1},\ \widehat{\theta_2}$ for $\theta_1,\ \theta_2$ estimation (this may even be true for the conditional dynamic model "alone"). Some elements (or function of the elements) must be fixed (i.e. constraints must be imposed). $\widehat{\theta_1},\ \widehat{\theta_2}$ is a set of random variables which may be correlated. Therefore any estimate of one element may depend on the constraints and on assumptions from which they are derived. These constraints may be not explicit. For example, when considering a conditional dynamic model we impose an arbitrary constraint on θ_2 and this may have a great impact on the estimates[6] of θ_1. Therefore knowledge is needed on individual parameters (or functions of parameters) and on sub-models in which they appear. *This implies that separate and combined "mono-disciplinary" research in both the fields of social and natural sciences remains essential.*

As previously said, it is never quite possible to pretend that an indicator set may be a minimal sufficient statistic[7]. We only

[6] For example, from a given simulated catch-effort data set, production model characteristics of two stocks harvested by a given fishery depend highly on assumptions made for the number of available tactics (Laloë et al. 1998).

[7] With the assumptions done for equilibrium methods (Gulland 1961; Fox 1975), Schaefer's model may be fitted with a simple linear regression of CPUE on equilibrium efforts. From statistical linear model theory, estimates of the parameters and residual mean squares provide a minimal sufficient statistic. "Unfortunately", these assumptions are not considered as realistic...

try to approach this quality and we may be more or less successful, depending on the considered model of which the data set is assumed to be a realisation. *This means that research effort is needed in the field of statistics, to progress in this way, to "find" what this goal has not achieved, and to assess the consequences of such a situation in terms of the quality of the set for indication*. The more simple this model is, the greater will be the quality of the statistical results. This means that we cannot provide any definitive criterion for qualitative comparison between the various models that could justify rejecting one of them.

8.3 Links with the ecosystem approach for fisheries

The development of the "ecosystem approach to fisheries" appears now as a widely accepted concern (see for example Garcia et al. 2003). Such an approach must include a multi-component resource. This may be justified from at least two viewpoints.

First, whatever the exploitation may be, there are interactions between components of an ecosystem that may be important and that should be taken into account in the representation of the dynamics of the resource. In this case, conditional dynamic models must be used with a representation of fishing activity deduced from the chosen definition of the resource (e.g. one catch or one mortality coefficient for each of the components of the resource).

Second, if the available fishing tactics differ by the distribution of their impact on the various components of the exploited resource and if in addition the tactic choice made by the fishing units are at least partially based on these differences, the multi-component aspect of the resource must be considered if we want to account for the (impact of the) decisions of the fishing units. Therefore conditional dynamic models may be sufficient in order to represent past dynamics, but joint dynamic models are needed for the representation of future dynamics. This may be all the more important as flexibility of fishing units may be a source of viability for themselves (they may have one viable solution at each given time) and for the resource (if depleted components are no longer interesting targets).

So, behind the words "Ecosystem approach of fisheries" we may consider a fisheries system from several viewpoints that are far from being merged (Garcia et al. 2003). None of them may be the best, even with some given set of available data. Their qualities are highly context dependant and also depend on the questions we try to answer. Use of conditional models remains necessary, but this must not be done at the exclusion of any other alternative. If so, this could exactly lead to the same criticisms as those made against "classical mono species" studies.

Acknowledgements. I thank Janet Riley for her very helpful comments.

References

Allen P.M., Mac Glade J.M., 1986, Dynamics of discovery and exploitation: the case of scotian shelf groundfish fishery. Can. J. Fish. Aquat. Sci. 43, 1187-1200.

Anonymous, 2002, New concepts and Indicators in Fisheries and Aquaculture. des Clers S., Nauen C.R. (Eds). A.C.P.-EU Fisheries Rep. N° 13,

Arnold S.F., 1988, Sufficient statistics. In: Kotz S., Johnson N.L. (Eds). Encyclopedia of statistical sciences, Wiley Interscience, New York, 72-80.

Béné C., Doyen L., Gabay D., 2001, A viability analysis for a bio-economic model. Ecol. Econ. 36, 385-396

Bougnoux D., 1993, Sciences de l'information et de la communication. Textes essentiels, Larousse.

Beverton R.J.H., Holt S.J., 1957, On the dynamics of exploited fish populations. Ministry of agriculture. Fisheries and food. Fishery Investigations. Series II XIX.

Charles A., 2001, Sustainable fishery systems. Blackwell Science.

Cury P., Cayré P., 2001, Hunting became a secondary activity 2000 years ago: marine fishing did the same in 2021. Fish Fish. 2, 162-169.

Fisher R., 1925, Theory of statistical estimation. Proc. Cambridge Phil. Soc. 22, 700-725.

Fox W.W., 1975, Fitting the generalized stock production model by least squares and equilibrium approximation. Fish. Bull. U.S. 73, 23-37.

Garcia S.M., Staples D.J., 2000, Sustainability reference systems and indicators for responsible marine capture fisheries: a review of concepts and elements for a set of guidelines. Mar. Freshwater Res. 51, 385-426.

Garcia S.M., 2000, The precautionary approach to fisheries: Progress review and main issues (1995-2000). In: Nordquist M.H., Moore J.N. (Eds.), Current fisheries issues and the Food and Agriculture Organization of the United Nations, pp. 479-560. The Hague, The Netherlands, Kluwer Law International and Martinus Nijhoff Publishers.

Garcia S.M., Zerbi A., Aliaume C., Do T. Chi, Lasserre G., 2003, The ecosystem approach to fisheries. FAO Fish. Tech. Pap. T 443, 81.

Garrod D.J., 1973, Management of multiple resources. J. Fish. Res. Board Can. 30, 1977-1985.

Gulland J., Fishing and the stocks of fish at Iceland. Fish. Invest. Minist. Agric. Food. U.K. Ser. 2, 23, 52.

Gulland J., Garcia S., 1984, Observed patterns in multispecies fisheries. In: R.M. May (Ed.), Exploitation of marine communities. Dahlem Konferenzen; Springer Verlag, 155-190.

Hilborn R., Walters C.J., 1992, Quantitative Fisheries Stocks Assessment, Choice, Dynamics and Uncertainty. Chapman and Hall, London.

Hilborn R., 1994, Foreword. In: Pauly D. On the sex of fish and the gender of scientists. A collection of essays in fisheries science. Chapman and Hall.

Holland D.S., Sutinen J.G., 1999, An empirical model of fleet dynamics in New England trawl fisheries. Can. J. Fish. Aquat. Sci. 56, 253-264.

Laloë F., Samba A., 1991, A simulation model of artisanal fisheries of Senegal. ICES Mar. Sci. Symp. 193, 281-286.

Laloë F., Pech N., Sabatier R., Samba A., 1998, Model identification for flexible multifleet-multispecies fisheries. A simulation study. Fish. Res. 37, 193-202

Laloë F., 1999, Le statut de la modélisation dans une démarche interdisciplinaire. Nature Sci. Soc. 7, 5-13.

Larkin P.A., 1977, An epitaph for the concept of maximum sustained yield. Trans. Am. Fish Soc. 106. 1-11.

Laurec A., Biseau A., Charruau A., 1991, Modelling technical interaction. ICES Mar. Sci. Symp 193, 225-234

Legay J.-M., 1997, L'expérience et le modèle. Un discours sur la méthode. Sciences en questions, Inra éditions.

Mace P.M., 2001, A new role for MSY in single species and ecosystem approaches to fisheries stock assessment and management. Fish Fish. 2, 2-32.

McFadden D., 1973, Conditional logit analysis of qualitative choice behavior. In Zarembka P. (Ed). Frontiers in econometrics, pp. 105-142. Academic Press, New-York.

O'Connor M., 1999, Dialogue and debate in a post normal practice of science: a reflexion. Futures 31, 671-687.

Pech N., Samba A., Drapeau L., Sabatier R., Laloë F., 2001, Fitting a model of flexible multifleet-multispecies fisheries to Senegalese artisanal fishery data. Aquat. Living Resour. 14, 81-98

Pella J.J., Tomlinson P.K., 1969, A generalized stock production model. Bull Int. Am. Trop. Tuna Comm. 13, 419-496.

Pitcher T.J., Pauly D., 1998, Rebuilding ecosystems, not sustainability, as the proper goal of fishery management. In Reinventing fisheries management. Pitcher T.J., Hart P.J.B., Pauly D. (Eds).

Pitcher T.J., Preikshot D., 2001, RAPFISH: a rapid apraisal technique to evaluate the sustainability status of fisheries. Fish. Res. 49, 255-270.

Ravier C., Fromentin J.-M., 2001, Long term fluctuations in the eastern Atlantic and Mediterranean bluefin tuna populations. ICES J. Mar. Sci. 58, 1299-1317.

Riley J., 2001, Indicator quality for assessment of impact of multidisciplinary systems. Agric. Ecosyst. Environ. 87, 121-128.

Robson D.S., 1966, Estimation of the relative power of individual ships. ICNAF Res. Bull. 3, 5-15.

Rochet M.-J., Trenkel V., 2003, Which Community indicators can measure the impact of fishing? A review and proposals. Can. J. Fish. Aquat. Sci. 60, 86-99.

Röling N., 1994, Platforms for decision-making about ecosystems. In Fresco L.O., Stroosnijder L., Bouma J., van Keulen H., (scient. eds). The future of the land. Mobilising and integrating knowledge for land use options. Wiley, New York, pp. 385–393

Roqueplo P., 1997, Entre savoir et décision, l'expertise scientifique. Sciences en questions, Inra éditions.

Schaefer M.B., 1954, Some aspects of the dynamics of populations important to the management of the commercial marine fisheries. Bull. Int. Atl. Tuna Comm. 1, 25-56.

Serchuk F.M., Rivard D., Casey J., Mayo R., 1997, Report of the ad hoc working group of the NAFO Scientific Council on the precautionary approach. NAFO SCS Document 97/26, 14.

Smith V.L., 1969, On models of commercial fishing. J. Polit. Econ. 77, 181-198.

Trenkel V., Rochet, M.-J., 2003, Performance of indicators derived from abundance estimates for detecting the impact of fishing on a fish community. Can. J. Fish. Aquat. Sci. 60, 67-85.

Ulrich C., Gascuel D., Dunn M.R., Le Gallic B., Dintheer C., 2001, Estimation of technical interactions due to the competition for resource in a mixed-species fishery, and the typology of fleets and métiers in the English Channel, Aquat. Living Resour. 14, 267-281.

Walters C.J., Christensen V., Pauly D., 1997, Structuring dynamic models of exploited ecosystems from trophic mass-balance assessments. Rev. Fish Biol. Fish. 7, 139-172.

Wagner P., 2002, Qu'est-ce que la théorie des modèles ? In Enquête sur le concept de modèle (dir. P. Nouvel). Science, histoire et société. PUF pp. 7-28.