Modeling Adaptive Fishery Activities Facing Fluctuating Environments: An AI Approach

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ABSTRACT. Fishery exploitation systems are driven by environmental fluctuations, the communities' adaptability, and the dynamics of interaction between these two. Better understanding and monitoring of fishery systems therefore requires an integrated representation scheme. An object-oriented model is presented for that purpose. Each component of the fishery system is considered a sub-object of a "fishery-system" generic object. In the hierarchy, environments, markets, fish stocks, fish industries, and equipment, as well as fishing, trading, and consuming communities are identified. The different components can exchange information, fishes, currencies, or human actors. A sub-model of the human actors' decision process formalizes the interactions between the different components of the represented system. An application of this sub-model to a Senegalese (West Africa) small-scale fishery is presented. Ten years of fishery activity with observed communities' appearances and collapses, simple biological resource and fish prices dynamics have been successfully simulated. This scale model of the fishery system provides a simulation tool whereby hypotheses can be tested and the consequences of a perturbation (e.g., resource or market fluctuation, management decision) evaluated on the whole system dynamics.

Small-scale fisheries are now recognized as an important economic resource. In Senegal (West Africa), fisheries catch more than 200,000 tons of fish per year and provide 75% of the total production (Chaboud and Charles-Dominique 1991).

For most natural resource exploitation systems, global observed dynamics are a consequence of three factors: external forces, inner adaptations, and interactions between the two (Charles 1991, Starfield et al. 1993). In the case of fishery systems, external forces are mainly represented by renewable biological resource dynamics, fish market fluctuations (Holling 1978), and successive management plans (Boude 1991, Laloë et al. 1991, Walters 1986). The internal dynamics are mainly driven by the exploiting communities' adaptability to external constraints and changes (Laloë and Samba 1991). The numerous links existing between these complex components of the fishery system lead to a global complex interaction network. Indeed, when a new management decision, a change in the biological resource, or a species price fluctuation occurs, biology, economy, and sociology often interact and produce a multicomponent response that is very difficult to forecast. In the knowledge representation field, research on fishery dynamics (Allen and McGlade 1986, Cury and Roy 1991, Rykiel 1989) point more and more to the difficulty of managing these fisheries only by means of disciplinary models (e.g., stock assessments, socioeconomic models) and the need to represent the complex interaction dynamics. It then appears necessary to look for new modeling tools that could help understand and monitor such systems.

Because they may provide solutions to these constraints, systemic theory and AI-derived technologies are both considered promising research fields for this purpose (Coulson et al. 1987, Quensière 1993, Rykiel 1989). The work described here is concerned with such exploratory modeling and simulation of global fishery dynamics. A scale model of the Senegalese fishery system is presented whose final objective is to simulate, at a global level, the possible consequences of various types of perturbation affecting the system. In this work, special attention has been paid to the management of environmental fluctuations by the exploiting communities. We first describe the global representation framework of the Senegalese fishery system. The included sub-model of the human actors' decision process is then detailed, with an example of simulations it can provide.

The Conceptual Model

The system dynamics simulation problem has two main constraints. The first one is that all the biological, economical, sociological components of the fishery system must be represented in the same scheme because of their close dynamic dependency. To capture this resulting complexity, the second, in some ways contradictory, constraint is to allow a progressive, step-by-step representation of the whole system. This second constraint implies a previous decomposition of the system into component parts. Due to the close interrelations between all the components, that decomposition process has to be carefully organized to permit a coherent end compilation of the different modeling steps.

The systemic approach (De Rosnay 1975, Le Moigne 1990, Von Bertalanffy 1968, Walliser 1977) intends to supply methodological frameworks to account for complexity in system representation. In the modeling field, this approach is based on initial global designs of the investigated system and subsequent, possibly Cartesian, analytical focuses (Destouches 1977). For this purpose, it also suggests preferential cuts for the decomposition problem (Le Gallou 1992). The systemic approach thus facilitates global perception and representation of complex systems. These features have been deemed important for a clean progression in the modeling process.

Using this approach, an initial conceptual model of the fishery system was first built to provide a canvas for the computer model. From the *structural* point of view, the fishery system is viewed, in this model, as a set of interconnected networks. Each network is defined by one kind of matter flow. From previous studies of the Senegalese fishery system (Durand et al. 1991, Laloë and Samba 1990, Weber 1980, 1982), four networks have been retained where, respectively, fishes, currencies, human actors, and information circulate. Each type of "fluid" is involved in a proper network and can be interconnected with another one, the fluid being there converted or exchanged (e.g., fishes converted into currencies). A fifth network represents the privileged interactions that some objects may have between each other (for instance, the interaction network can be used to describe how a fisherman will filter all the traders' needs to only consider the traders with whom he usually deals). The design of these networks gives the ability to take into account, in one unique formal scheme, all the pertinent components that may act in the fishery system's dynamic as well as their environment. (Environment is meant here in its largest sense; that is, for a given component, or any other related component in one or another network.)

From the *functional* point of view, the system dynamics is viewed as sets of changes coming from each component's environment (i.e., modification of any other component related to the one concerned) and the corresponding component response. The sum of every component's responses to the disturbances it has to manage will then produce the evolution of the whole system.

This approach clearly puts forward object-oriented (Masini et al. 1990), distributed AI (Bond and Gasser 1988) and multi-agent systems (Ferber 1989) design for the computer model. Indeed, under these formalisms, generic flows (e.g., information, action) can be used to interconnect components of any kind. Moreover, the possibility to first define simplified networks enables a step-by-step progression in the modeling process. Finally, in multi-agents' systems, populations are viewed as sums of individualized agents, entirely described with unique characteristics, behaviors, and interrelations. The global population dynamics will therefore be an emergent evolution from the multiple agents' behavior and interactions. These types of simulations appear well suited for general understanding of sociologically based systems (Drogoul and Ferber 1994, Gasser 1993). Multi-agent simulations have also already provided valuable results in multicomponent fishery system modeling (e.g., Bousquet and Cambier 1991, Bousquet et al. 1992).

In the model presented here, agents are "cognitive" (or "social"). This terminology, in contrast to "reactive" (or "biological") agents, includes that idea that the behavior of the agents is not only a set of simple stimulus-response reactions, but that a reasoning process may take place between these two. The cognitive agent is a priori able to control its own behavior and take its experience into account (memory).

The SMECI shell from ILog (ILog 1992) was used for the implementation. In this Le-Lisp expert system designer, structural representation is object-oriented; functional specification supports "message" and "demons" features as well as everyday-language rules, tasks, hypothesis testing, and forward-chaining inference.

Structure Design

In the computer model, each of the generic components (harbors, fishermen, fish traders, species, etc.) that has been reviewed in the different networks is defined as a category (i.e., class) with specific characteristics and behaviors. All categories are bound in a hierarchy where each sub-category "is-a-kind-of" the upper category. In the specific case of the Senegalese small-scale fishery system, the corresponding hierarchy has been elaborated and is presented in Figure 1.

Three major categories have been defined: communities, environments, and stocks. Knowledge is individualized as a "stock" sub-category rather than diffused in the actual characteristics of the objects. In this sense, knowledge is a set of available information about the features, effects, and constraints of a given behavior. For instance, knowledge about a given fishing tactic is characterized by the fish species that can be harvested when someone uses it, the equipment needed to perform it, the gross profit it can provide, information on the number of people practicing it, etc. Any object related to one or another knowledge category object will be provided with the information needed to adopt (or reject) the corresponding behavior. A global knowledge category allows generic treatment and each specific knowledge or potential behavior can be specifically documented in sub-categories. Knowledge is thus available as a stock in the same conditions as any other "material" stock.

Each category is defined by several slots and constitutes a template with which agents (i.e., instances) can be individualized with different slot values (Fig. 2). These slots may take their values from either quantitative or qualitative variables or variable lists, other referenced objects in other categories, or Le-Lisp methods. More generally, a slot can accept any Le-Lisp entity or list of entities (Lisp = LISt Processing). As in the classical object-oriented representation, all objects in a sub-category inherit the slots of the upper category. Moreover, the interaction network (i.e., privileged relations

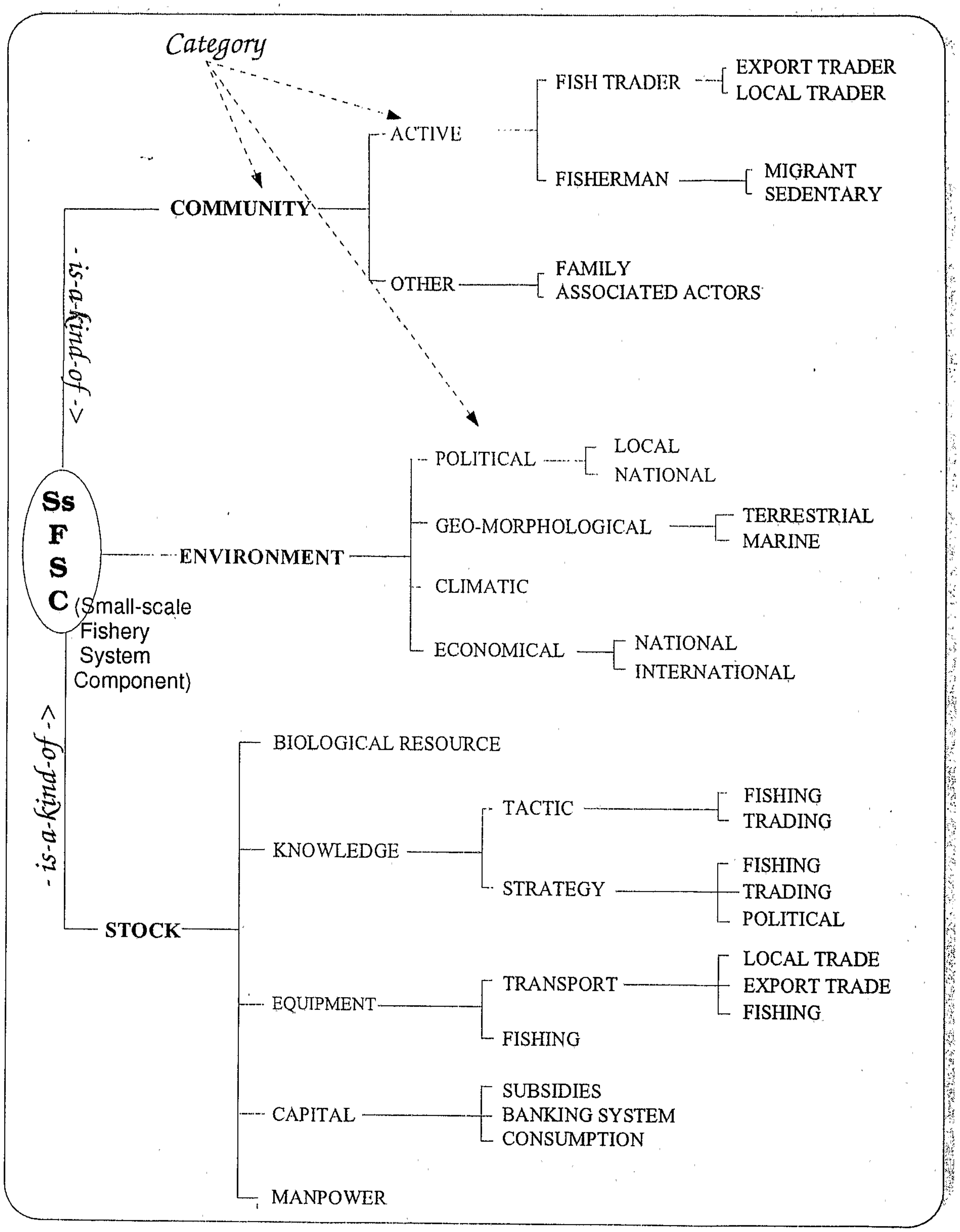


Figure 1. *A general framework for the model: the category (i.e., class) hierarchy of the small-scale fishery system.*

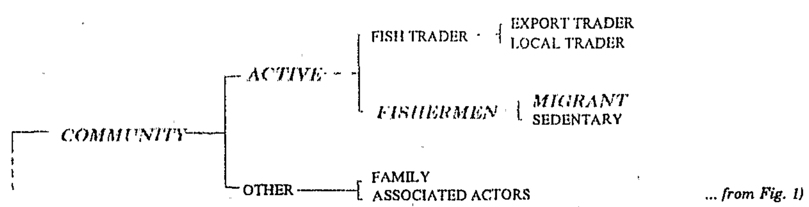
between actors) is implemented in the structure of the model: each instance may be bound more closely to other ones and "detect" any modifications of these latter ones.

The aim of the model is to simulate in time step the matter transfers (communities, fishes, currencies, information) between the different components of the previously described category tree (i.e., the new abstracted fishery system). The agents' ability to do this depends on the environment context in which they stand, the resources (e.g., equipment, knowledge) they own, the result of the choices they made at the preceding time step, and finally the information they can (or cannot) get from other objects. Then, provided with a "projected behavior," these agents take what they need (what they can) from the different stocks available (e.g., equipment, fishes, money). They can then act in the next time step and adapt to their environment.

This unique design applies to every component of the fishery system, but this framework also enables a generic representation of the fishery system component interactions. In this work, a sub-model of the decision process has been retained to formalize and organize the various matter transfers between the agents in the category tree. An example of a simulation dealing with human actors' transfers between different fishing communities will constitute the support for the description of this sub-model.

Fishery Activity Simulation

A great part of the fishery system's dynamics is driven by the human communities' ability to react to their fluctuating environment. Indeed, fishermen have developed multipurpose knowledge and multispecies fishing ability. They can thus switch quickly from one fishing tactic (i.e., fishing gears, fishing and landing sites, target species, etc.) to another depending on traders' new requests, sudden drops in species fishing yields, new selling prices or subsidies (Chaboud



A *COMMUNITY* of *ACTIVE MIGRANT FISHERMEN* is defined as a:

COMMUNITY:	species owned	object list (category BIOLOGICAL RESOURCE)
	fish quantities owned	integer list
	money owned	integer
	size	integer
	home site	object (category TERRESTRIAL) ... *etc.*
, ACTIVE:	working site	object (category TERRESTRIAL)
	available material	object list (category STOCK)
	lowest fish selling price	method (procedure)
	available tactics	object list (category TACTIC)
	available tactic habits	float list
	available tactic values	float list
	current tactic	object (category TACTIC) ... *etc.*
of FISHERMEN:	available landing sites	object list (category TERRESTRIAL)
	curent landing site	object (category TERRESTRIAL) ... *etc.*
, MIGRANT:	family-fishermen distance	method (procedure) ... *etc.*
CATEGORY NAME	CHARACTERS /SLOTS	LISP SYMBOL

Figure 2.
An example of the objects' slots and heritage.

and Charles-Dominique 1991, Laloë and Samba 1990, Wilson et al. 1991).

Ten years of collected data on fishery activity with observed community appearances and collapses were used as a support for simulating the fishermen's decision-making processes. The simulated fishing community practices gillnet fishing and mainly catches sole species. This community works at the Kayar landing site in the middle-north of Senegal (Fig. 3). The gillnet fishing season lasts two or three months around May. The fishermen involved are migrant people from Saint-Louis, north of Senegal. The model was used to simulate the evolution of the number of boats practicing gillnet fishing, which is called the gillnet fishing effort tactic (Fig. 4).

The gillnet fishery dynamics shows a strong seasonal trend when it occurs at the end of the 1980s and, from one year to the other, the effort intensity presents large fluctuations. The time series clearly appears disturbed, and several responses can be observed depending on the nature and context of the perturbation. At the beginning of the series, the gillnet fishing effort sometimes increases but is not sustained the following years. For example, in the year 1981, it appeared that fish traders' demand for sole increased and led to the observed increase in the gillnet fishing effort (information gathered from on-site fishermen interviews). Nevertheless, this "environmental alteration" did not give sufficient advantage to keep fishermen going with this tactic the following years. In summer of 1985, a concomitant increase in species prices and fishing yields is followed by a sudden increase in the gillnet effort. The following years, the effort is maintained during the fishing season, leading to the divergence of the previous communities' distribution between the different fishing tactics available, reinforcement of the fish traders' requests in this harbor, and conflicts (in 1985 and 1988) between migrant fishermen practicing

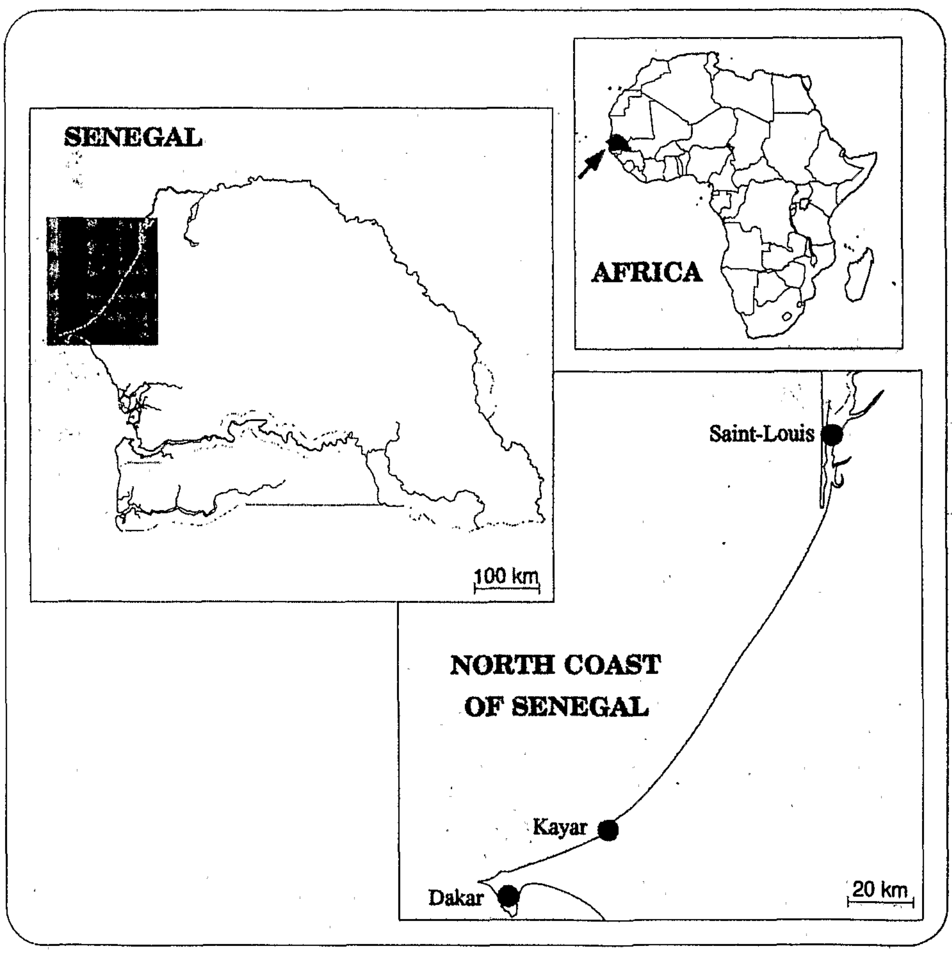


Figure 3.
General localization of the investigated landing sites.

gillnet fishing and the sedentary ones practicing line fishing.

We were interested in representing, with the model, the changes that occurred from 1985 to 1990. The aim of the simulation was to reproduce how fishermen, faced with new information about their environment, decide whether they change their regular tactic (e.g., gillnet fishing or line fishing) and how their decisions affect the structure and functioning of the fishery system. From the computer point of view, the modeling problem of the fishing communities' decision processes lies in defining what links are to be made between agents in the category tree and what agents are to be linked to reproduce the tactic transfers observed between the different fishermen's communities.

The decision scheme that has been used is expressed by the sequence "detection-evaluation (+information)-decision-action." In the special case of the communities involved in the simulation, this sequence is described in Figure 5 and can be detailed as follows.

Detection

The available information about the different fishing behaviors is gathered in the various instances of the "tactic" knowledge category. Each fishing tactic is defined by five main slots: the fishing gear needed to perform it, the species it can catch, the landing site where the fish catches are to be sold, the number of fishermen currently practicing this tactic, and the economic opportunity of its practice. This last feature is a time-dependent variable that corresponds to the amount of money that can be obtained when all the harvested products are sold. When they are modified, the fishing yields and the species prices are automatically transmitted to the "tactic" agent by, respectively, the "resource" agents and the "site" agents. When it receives one or both items of this information, the "tactic" agent automatically determines its value.

A given community is defined by a privileged tactic that it practices ("current tactic" slot in Fig. 2) and a set of tactics it masters and may

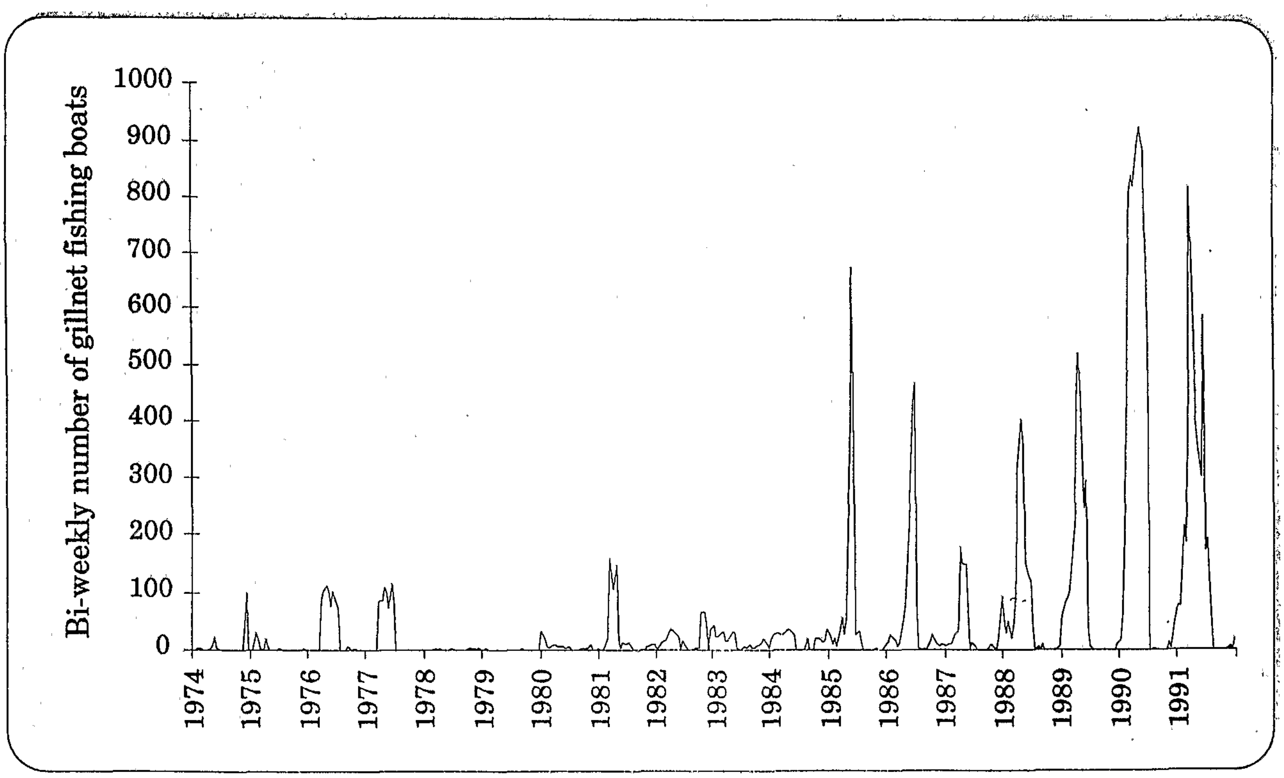


Figure 4. *Observed bi-weekly number of gillnet fishing trips at Kayar landing-site from 1974 to 1991.*

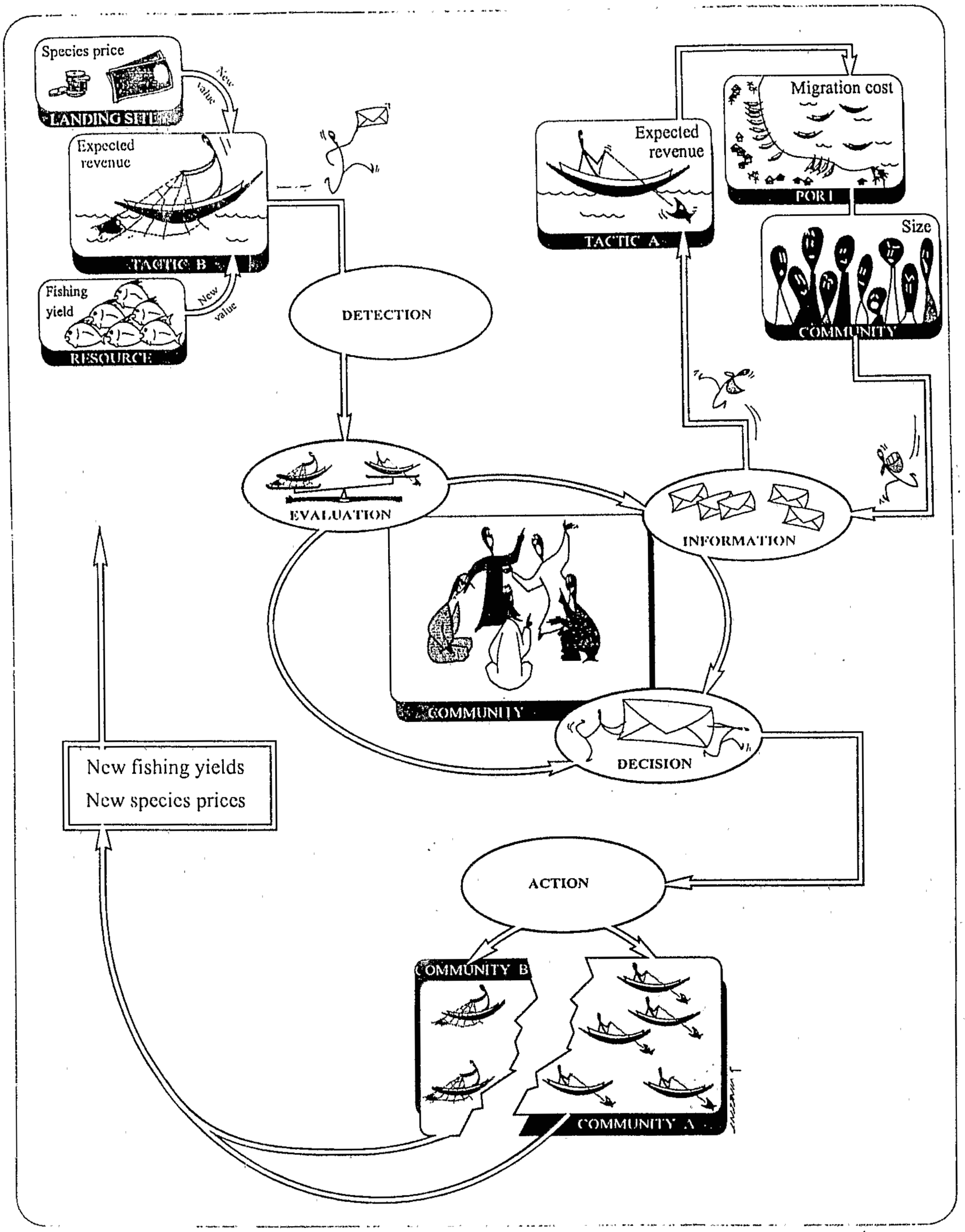


Figure 5. *Schematic representation of a community agent's decision process (shaded boxes are categories, ellipses are processes).*

The interaction network woven by a given community allows it to be informed of any modification of the environment of interest (detection). That community then calculates the "value" of this new information (evaluation). For this purpose it may, if required, fetch more information from other objects (information). Once the new information has been evaluated, the community compares the opportunity of the new action with the opportunity of its present state. It can then decide whether to change its behavior or not (decision). Once a decision is made, the action can then be engaged (action); it may lead to division of the community and, consequently, to modification of other objects (e.g., modifying catch yields and fish prices, depending on greater or lower captures), thus providing new perturbations (see details in text).

use ("available tactics" slot in Fig. 2). The localization of the community is known from the site that characterizes the tactic the community presently uses. Each community may get any information from the tactics it masters. When any slot of a tactic is modified, a message is sent to all the communities that master the tactic (see Fig. 5).

Evaluation

Once a community is informed of a change in the system, it has to determine what behavior to adopt regarding this perturbation. The determination of the community evaluation criteria (in this case, the way by which communities determine that practicing a given tactic is better than practicing another one) is one crucial step in this modeling scheme. To determine these factors, previous literature has been investigated, as well as numerical analysis of formerly collected quantitative data, expert scientists, and on-site interviews (Le Fur and Gaye 1994). These studies pointed out three major factors to represent when modeling the fishermen's choices: the gross profit value of the tactics, the risk involved, and the experience gained in practicing them. The ensuing model of the evaluation process is as follows:

- The community first compares the value (species yields times species prices) of the new tactic to the values of the other tactics it masters. If the best value does not correspond to the currently practiced tactic, fishermen react to this new information. The greater the difference in value between the current tactic and the "new" one is, the greater the number of fishermen wishing to leave the community will be. This evaluation leads to the production of a percentage of fishermen unsatisfied with their current tactic.
- The second evaluation criterion accounts for the observed fact that the number of fishermen practicing a given tactic constitutes a risk indicator for that tactic: the greater the number of fishermen practicing a tactic, the lesser the risk to be mistaken when embracing this tactic (and vice versa). "Community" agents thus go and get information from other "tactic" agents to know how many fishermen practice it. Note here that the size of a given tactic does not intervene as a motivation factor for the fishermen since, although they are not directly informed of this information, they intentionally search for it in order to make their decision (information step in Fig. 5)
- The two first criteria are bound to fishermen communities' environments (tactics, other communities). The third one is an inner evaluation that accounts for the habit that each community has to practice one tactic or another. For this purpose, at each preceding time step, a habit slot is updated for each of the communities' available tactics, depending on their current tactic at this time step. Then, the greater the difference between the "new" tactic habit and the current tactic habit is, the greater the number of fishermen leaving the current tactic for the new one will be.

Decision

At the end of this three-step evaluation, the "value" of a tactic is therefore a different quantity for the tactic (absolute value) and for the communities (inner value). The "inner" value's difference between the two compared tactics leads to a percentage of fishermen in the community wishing to leave their current tactic and practice the new one. The remaining part of the community keeps in its current state.

Action

When some fishermen decide to change their current tactic, they look for an existing community that could dispose of the same slot instances as their current one (i.e., same set of available tactics, same ethnic group, same habits for each of the tactics) except for the current tactic slot that must correspond to the "new" tactic chosen. If this community is found, the given percentage is transferred from one community to the other. If not, these fishermen "create" a new community agent, which is a clone of the original, unless the "current tactic" slot changes to the new tactic preferred. This new community will then evolve on its own with other tactic habits and other choices.

At a given time step, a community agent may detect many different perturbations. To take this overlap into account, a waiting mechanism is implemented where, for each detection, new incoming decisions are stacked in a special object slot. A final decision is then elaborated that takes into account every stacked sub-decision. In this way, no action can be completed by any agent until it has detected all available modifications of its environment. Thus the fishermen's transfers from one tactic to the other (and consequently from one site to the other) can be represented through time, depending on the resources and market fluctuations.

For each of these determinants, simulations have been carried out. One of the latest is presented in Figure 6. The estimated series corresponds to a step-by-step prediction of the gillnet fishing effort. This variable is obtained at each time step by gathering the size of each community whose current tactic value corresponds to the Kayar gillnet fishing tactic. At each time step, the observed fish prices and fishing yields are introduced in the model. This is done by modifying the corresponding slots in, respectively, the landing sites and the resources' category agents (see top of Fig. 5). Taking each of these new values as a perturbation, this information is then propagated through the agents in the category tree, and fishermen transfers occur between communities (and tactics).

In the simulation presented in Figure 6, a 15-day step has been retained to account for the fishermen's response delay to the perturbations. In the lower part of Fig. 6, the typical shape of the residuals' series clearly indicates a lag be-

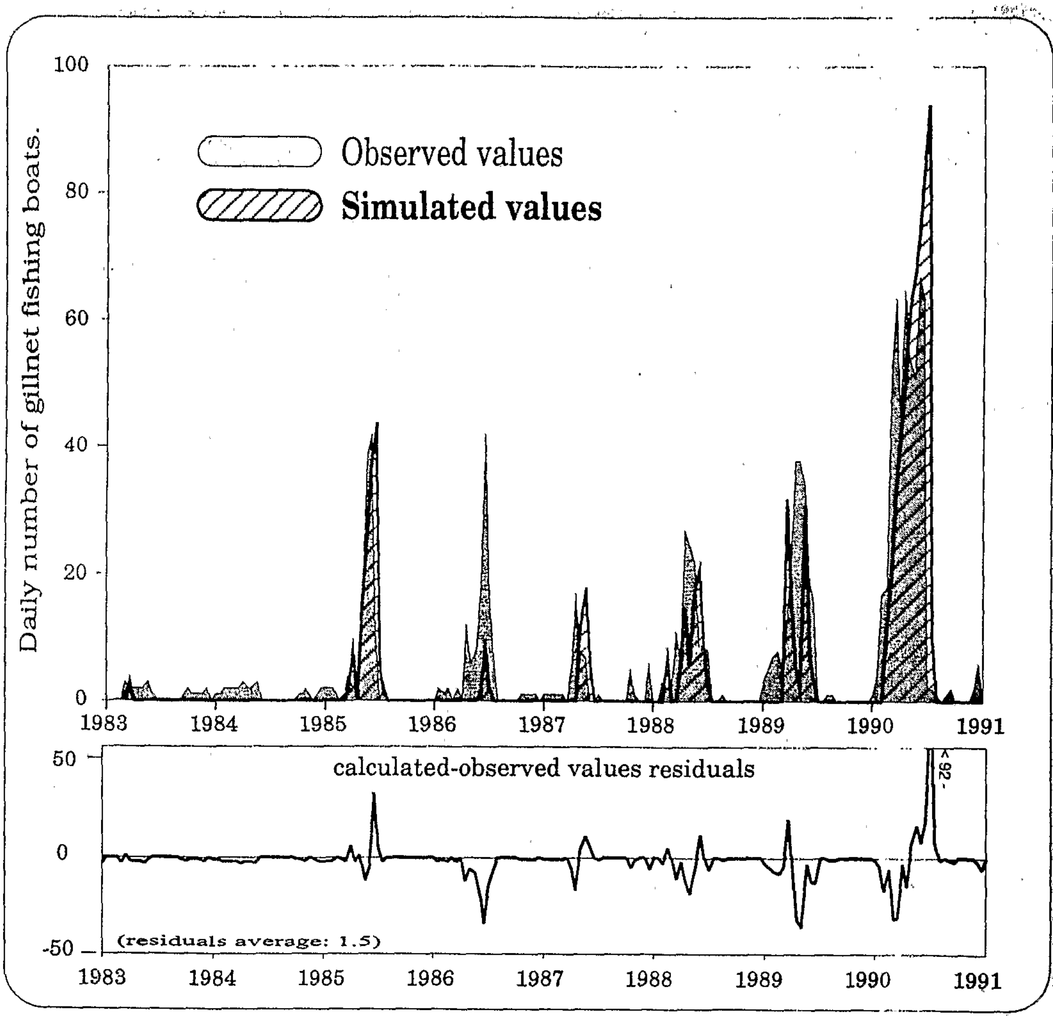


Figure 6.
Simulation of the gillnet fishing effort at Kayar from 1983 to 1991.

tween the observed and simulated series. These differences between observed and simulated values indicate that some dynamic determinants are still lacking in the model. Though this lag is not represented, the residuals' average is very low, divergence and progressive stabilization of the gillnet fishery are simulated, and the observed overall inter-annual fluctuations can be reproduced.

Discussion

Though oversimplified and improvable, the sub-model of the decision processes seems to give sufficiently accurate results to support the central role of the actors' decision making in research concerned with interactions between natural systems and human societies/exploitation systems. During the development of the model, it would have been easier to represent all the functional relations between the system's objects by means of structured rule bases. Indeed, tracing and debugging is more comfortable; the rules' sequential chaining facilitates the monitoring of the simulation, and rule writing is a more natural way to transcript human experts' knowledge. However, several drawbacks have led us to rule out this implementation and to choose multi-agent features to represent the generic and specific behaviors of each object in the system.

From systemic theory, the decomposition principles (Le Gallou 1992) imply the simplest interface possible between the modules born of a system decomposition. Following the initial decomposition, the end compilation of rule-based modules would have led to great connecting and reorganizing difficulties. On the other hand, in the described model, each agent carries its behavior with it and can (partly) elaborate its interaction network on its own (procedural attachment). The objects get, in this way, a kind of autonomy. The association of different modules is then a simpler compilation of objects, and connection is thus simplified.

The second need of the model is to provide a kind of autonomy to the whole modeled system. In other words, the model has to function by itself and not by means of sequential external instructions of an operator (the rule bases). This functionality is necessary, in a multi-agent context, to enable, when necessary, any "creativity" in the system's dynamics. For instance, all along the simulation, new communities are created each time with a new, specific, past fishing experience. The evolution of the communities' distribution then changes in an irreversible way as time passes. This feature can provide new properties to the global system without any operator intervention, which is probably the way the "real" system works. From our point of view, that feature makes the difference between reality-to-model transcription and reality simulation. It entirely justifies the multi-agent representations in the modeling field herein investigated.

As formerly presented, this fishermen's decision-making model is integrated in a wider model where other actors and environmental components are represented. This generic representation framework enables the extension of the decision process scheme to any object of the system . For instance, it is presently being implemented for a sub-model of the fish traders' decision processes (Where and what fishes shall I buy? How much and where shall I sell them?). Moreover, extended developments of this scheme can be considered. For instance, one may implement fish stocks feeding in marine environment objects in order to migrate to other fishing sites objects, management authority getting information from known strategies in order to respond to a modification of fish exportation balance, etc.

At the upper level, we tried to stress the need for a coherent and global representation of the fishery system despite the constraints this implies. Indeed, for the community agents, environment is considered a source of perturbations whereas, at a population level, the global dynamics these agents produce can modify what was considered as the environment. For instance, biological resource dynamics or national fish prices will be modified by a gillnet effort increase. In this work, it seems that the simulation of local behavior led to an overall satisfactory representation of the fishery dynamics on a global seasonal or inter-annual scale (the upper interacting scale). By producing these global dynamics, the fishery activities model can connect easily to more classical biological production or socioeconomic models. The global model is then able to reflect as well the Environment → communities' action (at the local functional scale) as the communities → Environment's (at the global functional scale).

The association of a "top-down" method (the systemic approach) and a "bottom-up" formalism (the multi-agents') therefore proved to be efficient in achieving our objectives. Finally, this pair of methodologies not only provides descriptive (multi-agents' formalism) and synthesis (systemic approach) tools but constitute, when they are used together, a powerful research tool with which interaction problems may be better perceived.

Acknowledgments

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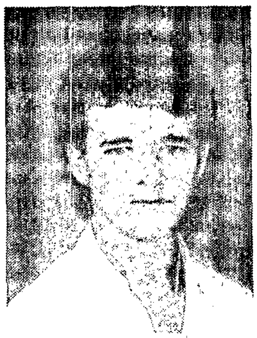

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