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A simulation model of artisanal fisheries of Senegal

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A simulation model was designed to correspond to a Senegalese artisanal fishery. Each fishing unit has a strategy, and at a given time chooses a tactic from a set of available tactics, according to a decision rule taking into account expected "revenues". The multispecies resource is modelled with simple stock production models, assuming quantities of biomass are inaccessible, depending on the resource component, season, and tactic. We compare the results of two simulations with the same number of fishing units, the same gears, and the same resource, but with different strategies. One set of strategies has smaller sets of tactics available than the other. Results indicate the importance of flexibility of the fishermen, which must be taken into account in management studies.

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Introduction

Artisanal fishing is of major social and economic interest in Senegal. A yearly catch of about 200 000 tonnes is made by about 4000 fishing units.

Exploitation patterns of several species show marked changes during the last 20 years, which, in some cases, cannot be explained within the classical population dynamics paradigm, which assumes that fishing mortality changes are due to changes in overall fishing activity. The number of fishing units remained quite stable and, with the exception of the purse seines, there was little technological innovation as a result of fisheries "development programmes".

Analysis of data collected by CRODT since 1974 (field investigation of more than 100 000 "one-day fishing trips" and daily fishing effort data) indicates that changes in exploitation pattern between species may have resulted from tactical choices of fishermen. These changes may sometimes be related to modifications in socio-economic or environmental conditions (Laloë and Samba, 1989). In other words, in a context of stable potential fishing effort, fishermen have changed the distribution of fishing mortality among exploitable stocks. This problem was identified by Garrod (1973). In this paper, we give a description of a multispecies–multigear system which may be subject to changes in the multispecies pattern of fishing mortality due to environmental effects on the resource and the fishery. In such a fishery, it is not valid to assume a long-term state of equilibrium that could *a fortiori* be seen as an "optimum", because fishermen have their own strategy, a consequence of which is variations in the fishing mortality applied to each exploitable stock. The ability of fishermen to adapt is probably necessary to success in this type of fishery and needs to be taken into account in fishery management (Laloë *et al.*, 1989).

We present the simulation model that was designed to correspond to a Senegalese artisanal fishery; that is, the model simulates activity and behaves analogously to the Senegalese artisanal fishery, and it reproduces the evolution of the fishery (Laloë and Samba, 1989). The model takes into account fleet dynamics characteristics, a need identified by Hilborn and Ledbetter (1979) and Hilborn (1985); it is also a useful tool for exploring the behaviour of fisheries as dynamic systems (Allen and McGlade, 1986; Hilborn and Walters, 1987; Charuau and Biseau, 1989).

The model

The activity of each fishing unit produces fishing mortality (which may be nil) on each exploitable component of the resource. That mortality depends on the tactic used, which is chosen from a set of available tactics. A "strategy" is a set of available tactics and the "decision rule" which leads to the adoption of one of them at a given time.

Description of fishing tactics

Two fishing trips are considered to have adopted the same tactic if they generate impacts on resource com-

Table 1. Definition of strategies related to available tactics.

Tactic	a	b	c	d	e	f	g	h	i	j	k	l	m	n	o	p	q	r	Number of units
Strategy																			
Gillnets	0	0	0	0	0	0	0	0	0	0	0	1	1	0	1	0	0	0	100
Hand lines (Kayar)	1	1	1	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	150
Hand lines (Saint-Louis)	1	1	1	1	1	1	0	0	0	0	0	1	1	0	1	0	0	0	1000
Hand lines (south)	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1	0	0	0	1800
Glacières	1	1	1	1	1	1	1	1	0	0	0	1	1	0	0	1	0	0	150
Glacières-seines	0	0	0	0	0	0	1	1	1	1	1	0	0	0	0	0	1	0	100
Seines	0	0	0	0	0	0	0	0	1	1	1	0	0	0	0	0	1	0	80
Seines (south)	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1	0	250
Industry	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	100

ponents which can be simply added (impact of tactic (j) during month (m) will be for example computed from the number of daily fishing trips using that tactic during that month; the fishing units which make those trips do not necessarily have the same strategy).

In our example we distinguish 18 fishing tactics, each of them corresponding to a combination of gear, target species, and geographical location. The first six tactics (a–f) correspond to hand lines. As an example, tactic (a) is fishing with hand lines on rocky bottoms along the northern coast of Senegal; the target species are mostly members of the serranidae family ("tiofs"), even if catches are possible on some other components of the resource. Tactics (g) and (h) correspond to hand lines with ice on board ("glacières") along the northern or southern coasts of Senegal. Tactics (i), (j), and (k) correspond to different uses of purse seines, and tactics (l) and (m) to different uses of gillnets. Tactic (n) means "agriculture" and tactics (o), (p), and (q) correspond to "no fishing". These latter tactics are introduced because fishing units may sometimes choose to do something other than fishing. The last tactic, r, "industry", is introduced to take into account catches made by industrial fisheries. Daily cost of fishing (Cj) or "non-fishing revenue" (NFR$_j$. to take into account opportunity costs) are given with each fishing or non-fishing tactic; they are used to estimate "net revenues" from the use of each tactic.

Description of fishing units by strategies

Two fishing units have the same strategy if, at a given time, they have the same probability of choosing each of the possible tactics (two fishing units with the same strategy do not necessarily use the same tactic at a given time).

Table 1 describes nine strategies with sets of available tactics. As an example, it can be seen that hand liners from Kayar may practise agriculture while hand liners from Saint-Louis cannot, but the latter have a wider choice of fishing tactics. The last column of Table 1 shows the number of fishing units with the corresponding strategy (as an example 1000 fishing units have the "hand lines from Saint-Louis" strategy). Some fishing units may use more than one gear, such as gillnets or hand lines, with or without ice (strategy "glacière").

Description of the resource

A component of the resource is a set of one or more populations. The state of that set is specified by one quantity ("biomass"), with a simple stock production model used to describe its dynamics. We used stock production models because of their low parameter requirements and the nature of our available information (in another context, a simulation model with analytical description of stocks dynamics was built by Charuau and Biseau (1989)).

Table 2 describes 11 resource components, or target groups, of one or more species. These descriptions were made using qualitative and quantitative information on artisanal and industrial fisheries in Senegal and Mauritania.

The principle of the simulation

Each month, fishing activity is distributed among the different tactics. The number of trips using tactic j during a month m ($f_{j,m}$) may be computed from the proportions $p_{kj,m}$ of units of k^{th} strategy using tactic j during month m, the number of units of each strategy and the number of workable days in a month.

Knowing $f_{j,m}$ values and the state $B_{i,m-1}$ of each resource component at the beginning of month m, we model B_i and estimate its mean biomass values ($Bm_{i,m}$) during that month from:

$$dB_{it}/dt = H_i \times B_{it} \times (B_{it} - Bv_i) - \\ - \sum_{j=1}^{18} q_{ij} \times f_{j,m} \times (B_{it} - \alpha_{ij,m} \times Bv_i)$$

where the H_i's are functions ($H_i = -4 \times MSY_i/Bv_i^2$) of the unfished biomass and potential yields (Table 2). This equation differs from the Graham–Schaefer model by assuming the existence of an inaccessible quantity of

Table 2. Characteristics of the 11 resource components.

Stock	Observed yields (t)	Natural mortality	Virgin biomass (t)	Potential yield (t)	Price/kg (F.CFA)
Tiofs	4 000	0.3	33 333	5 000	400
Pageots	9 000	0.5	40 000	10 000	220
Chinchards	50 000	0.5	200 000	50 000	100
Dentés	2 500	0.4	20 000	4 000	200
Tassergal	7 000	0.3	66 666	10 000	220
Sardinelles	70 000	1.0	150 000	75 000	70
Sole	1 000	0.5	5 000	1 250	400
Gillnet fishes	3 000	0.4	20 000	4 000	150
South demersals	50 000	0.4	300 000	60 000	250
South pelagics	140 000	0.8	375 000	150 000	50
Out south Senegal	14 000	0.4	100 000	20 000	100

Table 3. Catchability coefficients (10^6) for the 18 tactics with the 11 components of the resource.

	Stock										
Tactic	1	2	3	4	5	6	7	8	9	10	11
a	3	1	1	0	1	0	0	0	0	0	0
b	1	3	1	0	1	0	0	0	0	0	0
c	1	1	1	2	0	0	0	0	0	0	0
d	1	1	1	0	3	0	0	0	0	0	0
e	0	0	0	0	0	0	0	0	0.5	0	0
f	0	0	0	0	0	0	0	0	0	0	4
g	5	1	1	1	1	0	0	0	0	0	0
h	0	0	0	0	0	0	0	0	1	0	0
i	0	0	0	0	40	0	0	0	0	0	0
j	0	0	30	0	0	25	0	0	0	0	0
k	0	0	0	0	0	0	0	0	0	10	0
l	0	0	0	0	0	0	1	5	0	0	0
m	0	0	0	0	0	0	30	1	0	0	0
n	0	0	0	0	0	0	0	0	0	0	0
o	0	0	0	0	0	0	0	0	0	0	0
p	0	0	0	0	0	0	0	0	0	0	0
q	0	0	0	0	0	0	0	0	0	0	0
r	5	20	20	10	6	30	0	0	5	3	15

Table 4. Monthly proportion (α) of the unfished biomass of the tiof resource component inaccessible to tactics (those values only concern tactics which permit catches of tiof).

Tactic	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Glacières (g)	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Others (a–d)	0.1	0.1	0.1	0.1	0.1	0.2	0.4	0.4	0.4	0.2	0.1	0.1
Industry (r)	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1

biomass ($\alpha_{ij,m} \times Bv_i$) that can be expressed as a proportion $\alpha_{ij,m}$ of the unfished biomass. We used this equation because it allows for "local over-exploitation" which may be important within the short range of the canoe fishery (Fréon, 1986), and because the catch-effort equilibrium curves are analogous to Pella and Tomlinson curves with exponents lower than 2 if α is greater than 0. This would not be the case if inaccessible biomass was a proportion of "current" biomass. This model is described in more detail by Laloë (1988).

In a given month m, we assume that quantity $\alpha_{ij,m} \times Bv_i$ depends on the resource component i, the tactic j, and the season. Each q_{ij} value is the "catchability" of the available biomass of the i^th^ resource component with tactic j (Table 3).

Values of $\alpha_{ij,m}$ were chosen in order to reproduce observed catches per trips and their seasonalities. As an example, inaccessible proportions of the "tiof" unfished biomass are given in Table 4. Lower accessibility (higher α values) for the "tiof" from June to October is assumed to affect only hand liners that have a shorter operating range than "glacières" or industrial vessels.

Table 5. Definition of strategies related to available tactics (second simulation).

Tactic	a	b	c	d	e	f	g	h	i	j	k	l	m	n	o	p	q	r	Number of units
Strategy																			
Gillnets	0	0	0	0	0	0	0	0	0	0	0	1	1	0	1	0	0	0	100
Hand lines (Kayar)	1	1	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	150
Hand lines (Saint-Louis)	1	1	0	1	1	1	0	0	0	0	0	0	0	0	1	0	0	0	1000
Hand lines (south)	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1	0	0	0	1800
Glacières	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	0	0	150
Glacières-seines	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	0	100
Seines	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1	0	80
Seines (south)	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1	0	250
Industry	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	100

At a "high frequency level" (from one month to another) changes in effort distribution may come from changes in $p_{kj,m}$ values. Values of p_{kj} at month m+1 are computed from p_{kj} at month m and "net revenues" ($\mathcal{R}_{j,m+1}$) expected from available information by fishermen for each tactic j. Those expected revenues are computed from observed "net revenues" during months m and m−11 (one year earlier):

$$\mathcal{R}_{j,m+1} = (R_{j,m} + R_{j,m-11})/2$$

with

$$R_{j,m} = \sum_{i=1}^{11} P_i \times q_{ij} \times (Bm_{i,m} - \alpha_{ij,m} \times Bv_i) - C_j$$

for fishing tactics and $R_{j,m} = NFR_j$ for non-fishing tactics. Results from former years are used to take into account the fishermen's knowledge of global annual periodicity of stock availability.

$p_{kj,m}$ values may then be computed from:

$$p_{kj,m+1} = p_{kj,m} + \lambda \times (\mathcal{R}_{j,m+1} - \bar{\bar{\mathcal{R}}}_{k,m+1})/\bar{\bar{\mathcal{R}}}_{k,m+1}$$

where $\bar{\bar{\mathcal{R}}}_{k,m+1}$ is the mean of expected revenue calculated with the set of tactics available to units having strategy k. If necessary, some transformations are made in order to ensure that $0 \leq p_{kj,m} \leq 1$ and $\Sigma_j\, p_{kj,m} = 1$. The parameter λ is a flexibility parameter whose value must be chosen in relation to the time-step used (a month in our example). We took a value $\lambda = 1.5$ from very simple considerations: if there are only two available tactics, one of which gives an expected revenue twice that of the other, the increase in the proportion of units which will choose the "best" tactic will be 0.5.

At lower frequency levels, changes in effort may come from changes in number of units, strategy definitions, or in parameter values (e.g. prices, costs, availabilities, etc.).

We made a 13-year simulation with the following initialization: all biomass initial values ($B_{i,o}$) were half of the unfished values and, for each strategy, all $p_{kj,o}$ values were assumed to be equals. At certain times during the 13-year period we changed some parameter values in order to introduce observed or assumed changes in general fishermen and resource environment. These changes are discussed below.

Until the beginning of the sixth year, catchabilities of tactics (f), (g), (i), and (j) are nil; use of these tactics occurred at that time. At the beginning of the seventh year, catchability of tactic (d) decreases from 3×10^{-6} to 2×10^{-6}; this corresponds to the collaboration between hand liners and seiners (i) which search for "tassergal" (bluefish) along the northern coast of Senegal.

At the beginning of the ninth year, catchability of industrials (r) on "chinchard" (horse mackerel) is multiplied by 2 in order to reproduce the corresponding increase in effort of industrial fishery on that particular target group.

At the beginning of the tenth year, the price of "dentés" increases from 200 to 400 F.CFA/kg. The prohibitive cost (60 000 F.CFA) of tactic (m) (gillnets searching for sole) decreases to the "normal" cost of 4000 F.CFA. This could simulate an authorization of the use of that prohibited tactic in the town of Kayar. Availability of tassergal for all concerned artisanal tactics decreases to take into account an empirically observed relation with upwelling intensity in Senegal and Mauritania. Values of α lower than 0.6 were arbitrarily increased to this value.

Results

Throughout the simulation, we tried to reproduce the observations we had made (catches per trip, number of trips, and their time paths). We did not use any quantitative fitting methods, but instead looked for a resemblance to the observed situations.

The simulation gave quite acceptable results in the sense that we could find what we were looking for, with little tuning of parameters. Some aspects could have been improved, especially regarding the number of

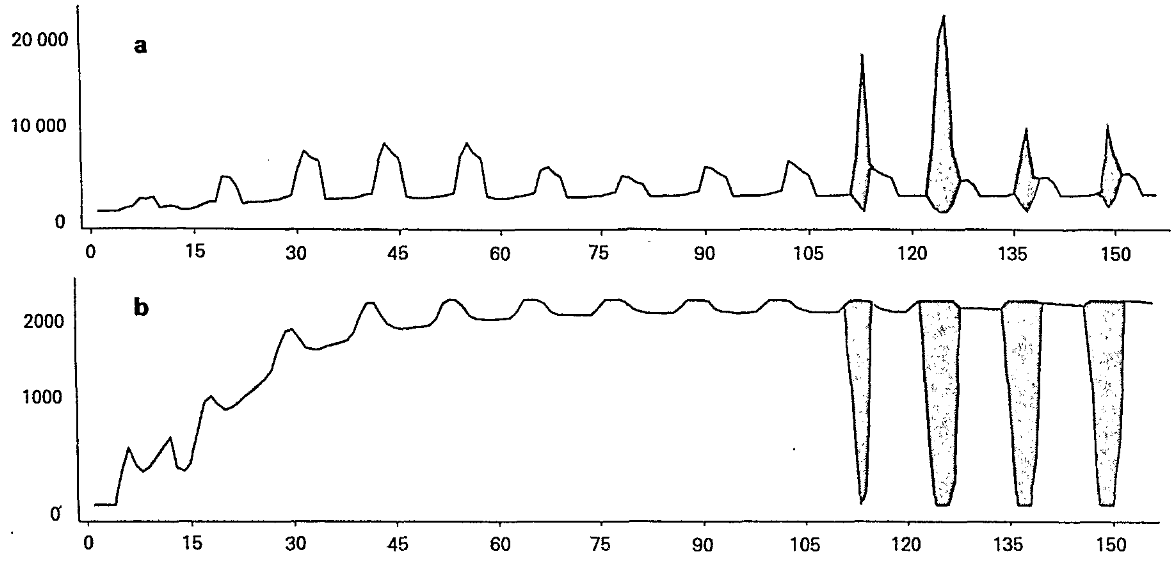

Figure 1. Monthly number of daily trips with tactic (m) (gillnets targeting sole, shaded) and (1) (gillnets targeting other fishes). a: first simulation; b: second simulation.

trips, which appear to have been higher than we know from the real situation. The problem may perhaps be in the excessive versatility of this kind of simulation model: in order to obtain a more satisfying result, the user of the model may choose between many solutions, and it is difficult to say which of them is the best one (if any). Such a model must therefore be used with caution and with the help of biologists, economists, environmentalists, and sociologists with a good knowledge of the fishery being simulated.

We also found some unexpected results, which are perhaps the most interesting. As an example, the hand line c.p.u.e. with the "dentés" target group showed a seasonal pattern which gave higher values when its accessibility was at a low level! This effect results because the seasonal patterns in accessibility of other target groups are more contrasted.

We made a second simulation of another fishery, using the same resource components, the same types of gear and the same number of fishing units. The difference was in strategies; there were fewer choices between tactics (Table 5). Tactics which do not appear in this

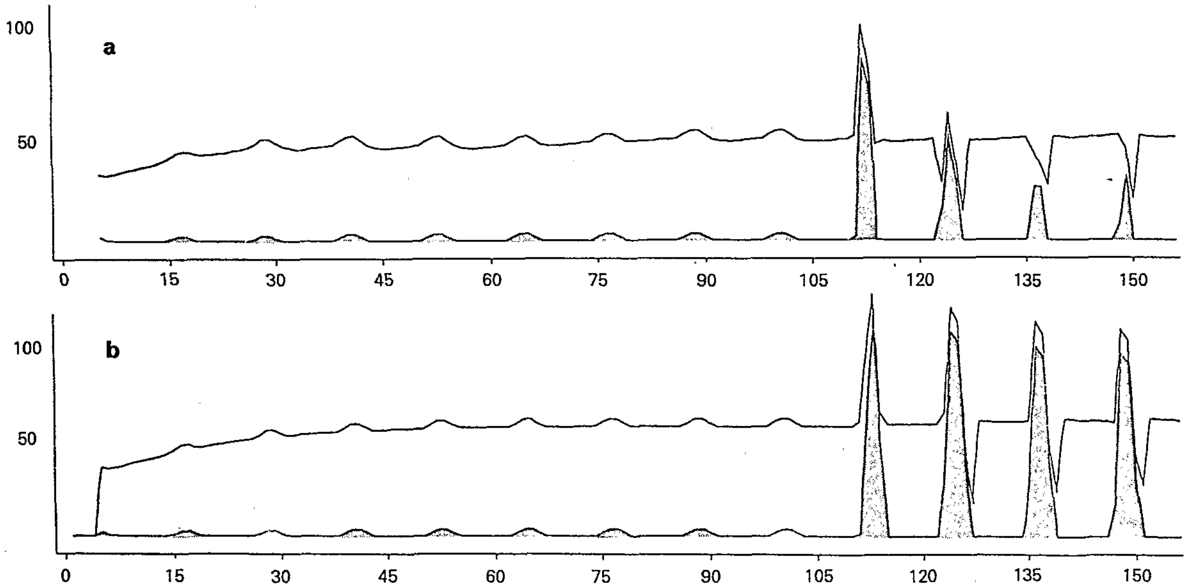

Figure 2. Monthly c.p.u.e. (kg) for sole (shaded) and other fishes from aggregated tactics (l) and (m). a: first simulation; b: second simulation.

second simulation are some of those which were not introduced through "Fisheries development programmes", or promoted by scientific studies.

Results indicate that this second fishery does not work as well as the first one; number of days at sea is lower, as well as total yield and aggregated revenues.

We show in Figure 1 the monthly number of trips with tactics (l) and (m) (gillnets targeting gillnet fishes or sole). In Figure 2 we show the evolution of the c.p.u.e. (kg) in the sole and gillnet fishes from these two aggregated tactics. One can see different possible impacts caused by the authorization of tactic m.

In the first simulation, effort becomes considerable (up to 20000 trips per month) during the tenth and eleventh years, which leads to an over-exploitation phenomenon and low c.p.u.e. During the last two years, we observe a strong decrease in effort on sole.

In the second simulation, use of tactic (m) is much lower, because only 100 fishing units (see Table 5) can use this tactic. The consequence is an under-exploitation rate which is stable during the last four years of the simulation. This example highlights the consequence in terms of "autoregulation capacity" of flexibility.

Conclusion

While our model must be improved in order to reliably describe the behaviour of a flexible multispecies, multigear fishery, the results demonstrate that stock assessment and *a fortiori* management are not adequate if we neglect the flexibility of fishermen.

In our study, we had a considerable amount of data that provided evidence of flexibility and gave good information on spatial-temporal catches and efforts. We tried to offer a descriptive framework which takes into account characteristics of fleet dynamics and interactions between components of the fishery system. We hope to have been at least partly successful, but we also found a need for more satisfactory descriptions and classifications. As an example, definition of our "flexibility parameter" λ is perhaps too simplistic and its value too arbitrarily fixed. Research effort must be maintained to improve the description of that part of the system in order to enhance the global framework which is necessary to a better use and understanding of the available information.

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