Dynamics of Discovery and Exploitation: The Case of the Scotian Shelf Groundfish Fisheries

P. M. Allen

Chimie-Physique II, Université Libre de Bruxelles, Bruxelles, Belgium

and J. M. McGlade

Department of Fisheries and Oceans, Marine Fish Division, Bedford Institute of Oceanography, P.O. Box 1006, Dartmouth, N.S. B2Y 4A2

Allen, P. M., and J. M. McGlade. 1986. Dynamics of discovery and exploitation: the case of the Scotian Shelf groundfish fisheries. Can. J. Fish. Aquat. Sci. 43: 1187–1200.

The bases and shortcomings of the current models used in fisheries management are briefly examined. An alternative set of models in part based on the Volterra–Lotka equations are developed which incorporate recent advances in our understanding of the evolution of complex systems. Simulations based on a dynamic model of a Nova Scotia fishery reveal that human responses amplify rapid random fluctuations in recruitment and excite strong Volterra–Lotka type oscillations in a system that would normally repose in a stable stationary state. A dynamic, multispecies, multifleet spatial model calibrated to the Nova Scotian groundfish fisheries is presented and used to explore the concepts of "discovery" and "exploitation." Two types of fishermen are identified, "stochasts" and "cartesians," characterized respectively as hunters, or high risk takers, and followers, or low risk takers. Significant results include the importance of calibration in providing models of relevance to the real world; the "out of phase" relationship between abundance and the ease with which fishermen locate a highly sought species and its converse; the importance of information exchange in defining the attractivity of a particular fishing zone to different fleets and the ability of the model to take into account coded information, misinformation, spying and lying; and the fact that models based on global principles, such as "optimal efficiency" or "maximum profit," are clearly of dubious relevance to the real world.

Les auteurs font un bref examen des bases et des limitations des modèles actuellement utilisés en gestion des pêches. Ils présentent une autre série de modèles reposant en partie sur les équations de Volterra–Lotka qui tiennent compte des progrès récemment accomplis dans le domaine de l'évolution des systèmes complexes. Des simulations par modèle dynamique des pêches de la Nouvelle-Écosse montrent que les réponses humaines amplifient les fluctuations aléatoires rapides du recrutement et causent l'importantes oscillations de type Volterra–Lotka dans un système qui devrait normalement être dans un état stationnaire stable. Les auteurs présentent un modèle spatial dynamique à espèces et flottilles multiples étalonné en fonction des pêches du poisson de fond de la Nouvelle-Écosse et l'appliquent au concept de la « découverte » et de « l'exploitation ». On précise deux types de pêcheurs : les « stochastiques » et les « cartésiens » dont les caractéristiques respectives sont d'être des chasseurs, qui prennent des risques importants, et des adeptes, qui prennent peu de risques. On compte, parmi les résultats significatifs obtenus : 1) l'importance de l'étalonnage pour l'obtention de modèles pertinents aux conditions réelles, 2) le « décalage » de la relation entre l'abondance et la facilité avec laquelle les pêcheurs localisent les espèces très recherchées, ou l'inverse, 3) l'importance de l'échange d'information pour la définition de l'attrait d'une zone de pêche particulière pour les diverses flottilles et la capacité du modèle à tenir compte de l'information codée, de la mésinformation, de « l'espionnage » et des mensonges, et 4) le fait que les modèles basés sur des principes généraux, comme « l'efficacité optimale » ou le « profit maximal » apparaissent comme très nettement contestables quant à leur pertinence en conditions réelles.

Received October 8, 1985
Accepted February 10, 1986
(J8477)

Reçu le 8 octobre 1985
Accepté le 10 février 1986

Fishing is one of the few remaining examples in the world today of ancestral hunting activities in humans. A key element of hunting is that it contains both "discovery" and "exploitation," rather than simply the latter which characterizes agriculture.

As we shall try to make clear below, fishing represents a fascinating "case study" of the much more general and wider issues of adaptiveness, creativity, and learning. This is interesting not only for itself and the role that new methods can play in managing such a vital industry, but also because of the general principles it raises. Within a problem having fairly clear boundaries, all the great questions of our relationship to nature, the problem of managing a complex system, and of finding a balance between yield and risk, are posed, and hopefully from this type of work, a new understanding will emerge both in the particular and general cases.

Commercial fisheries are part of the complex marine ecosystem involving ocean climate, hydrography, biological oceanography, and fish ecology, and also the human system including the behaviour and knowledge of fishermen, the requirements of

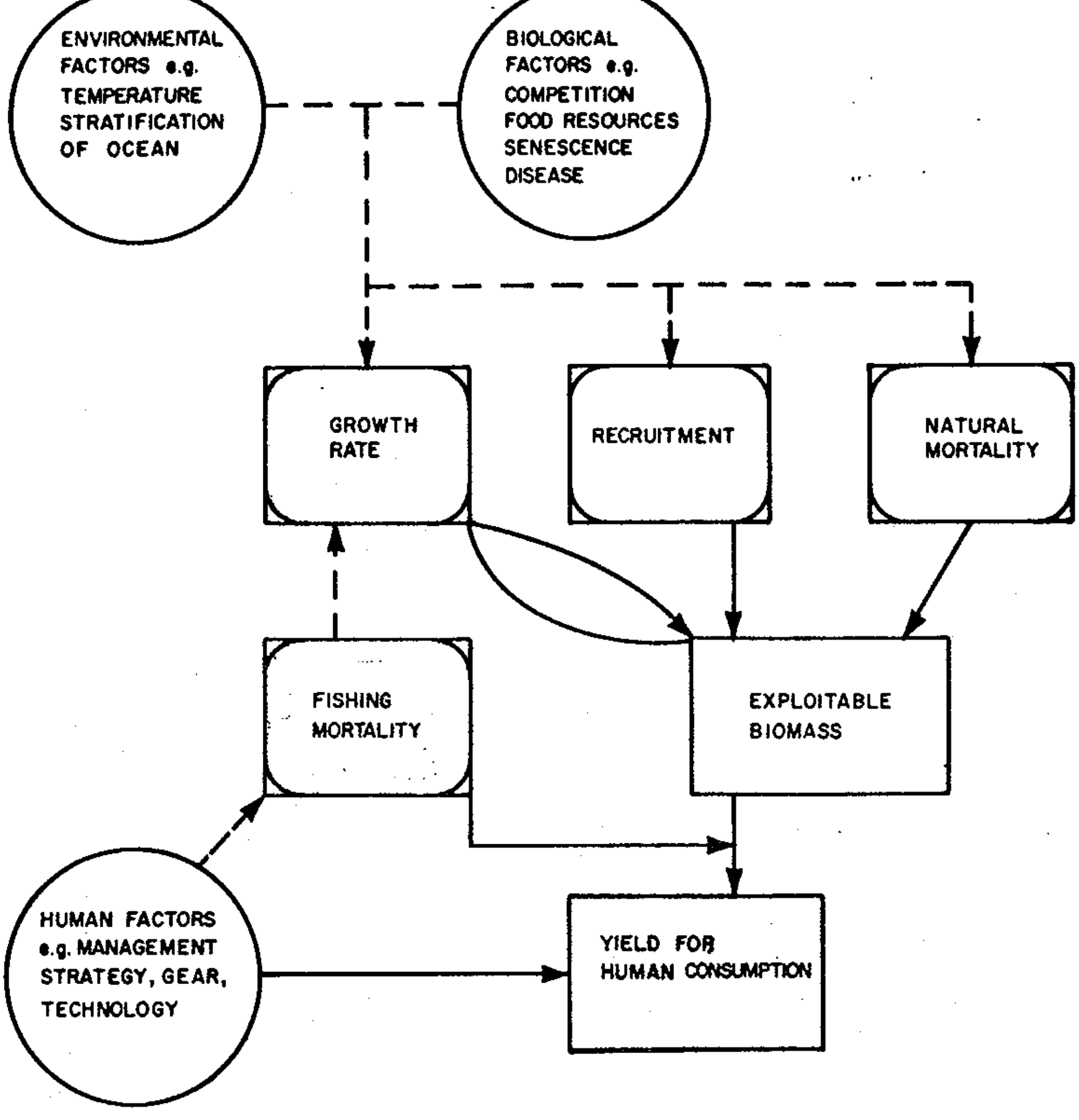


FIG. 1. Schematic diagram identifying areas of interest in fisheries.

the processing industry and markets for fish products, government policy, regulation, and political issues (Fig. 1) (McGlade and Allen 1985). Thus, fisheries science is not a discipline in itself, but rather the application of most of the basic sciences to the marine milieu and living resources of the seas. For example, the marine ecosystem, largely hidden from the human eye, is complex with respect to its species composition, as well as to the processes occurring within it. Thus, although we are really only interested in two of the apex predators, fish and man, we should be aware of the background against which their interaction is set, as shown in Fig. 1.

The interface of industry and fishermen with fisheries resources is multifaceted, and usually predicated by a knowledge of the resource distribution, demand, and availability (Kirby 1982; Pearse 1982). Fisheries will cause changes in the abundance of fish, such that the target species as well as those caught incidentally are likely to reflect trends in the market place as well as environmental and biological dynamics. If we add the consequences of technological changes, overcrowding in the littoral zones, and the impact of foreign fleets, it is evident that the "laissez-faire" attitude towards resource utilization that arose through the 1950's as a result of the persuasiveness of the scientific arguments is no longer a tenable stand for any level of government to take (Caddy 1983). To intervene in or monitor successfully such a complex system, and to formulate appropriate management schemes, it is important to identify the processes and causalities which serve to interrelate fish and their abundance, fishermen, fishery scientists, and managers, all of whom play an important role in the final yield of fish for human consumption. Yet it would be true to say that the multiplier effects such as employment in ancilliary activities, fishermen's employment, and their ability to move, plus the implications of the coexistence of inshore and offshore fleet components which should be integrated with information about the biological resource, are usually not dealt with explicitly in current management schemes.

Let us now turn to the recent advances that have been made in our understanding of the evolution of complex systems, as a result of the concepts underlying "dissipative structures." These have been discussed in detail elsewhere (Nicolis and Prigogine 1977; Prigogine and Allen 1982), and the main points which emerge are as follows.

(i) The evolution of such systems can be represented by an "evolutionary tree" of possible structures and organizations.

(ii) Any particular system will follow a trajectory through the tree which involves both the deterministic dynamics of "average" behaviours, and the effect of small chance phenomena at instabilities which can be amplified by the system and give rise to major changes. The tree itself can be profoundly modified by the presence of environmental disturbances, giving rise to fluctuating parameters.

(iii) The branches differ from each other qualitatively, having distinct traits and spanning different dimensions. In the case of a marine ecosystem, this could mean being populated by different species, in a set of alternative ecosystems.

In this paper, we consider a particular case study, that of fishery management and the groundfish fisheries off Nova Scotia, and discuss the existing types of model in use today.

Simple Fishing Models

The mathematical basis for the management of fish populations is rooted in the equations of population dynamics and mathematical ecology. There are two basic situations which are represented most often by the logistic equation, describing the growth of a single species in a limited environment, and the Volterra–Lotka equation describing the dynamics generated by a predator–prey interaction. All the rest are just concatenations of these, although additional refinements such as considerations of handling time and predator saturation can introduce important changes in the behaviour of the system (Jones and Walters 1976; Mangel 1982; Mangel and Beder 1985). Fishery management models in use today are only based on the logistic equation, although several complicating factors have been added such as population age structure and individual growth functions. We first examine these methods and their basis so that we may better appreciate their importance for the management of such systems.

Logistic Equation

This describes the growth of a single species in a limited environment. It can be made more complicated, taking into account the competition between different species which share the same resources, but its most simple and basic form is

$$(1) \quad \frac{dx}{dt} = bx\left(1 - \frac{x}{N}\right) - mx - Fx.$$

The first term on the right represents a density dependent "birth" term where the maximum niche size, N, sets a saturation level, mx corresponds to natural mortality, and the term Fx refers to the effect of fishing on the population. The fishing mortality, F, is related in standard theory to the catchability, q, of the fish and the fishing effort, E, exerted.

The term Fx is the yield, Y, of the system and provided that we assume equilibrium, it is easy to calculate yield as a function of F. The stationary solution of (1) is

$$x_s = N\left(1 - \frac{m + F}{b}\right)$$

and hence yield at equilibrium will be

$$(2) \quad Y = Fx_s = N\left(1 - \frac{m}{b}\right)F - \frac{N}{b}F^2.$$

This is a parabola, with a maximum value at $F = (b-m)/2$ the infamous F_{max}, "the maximum sustainable yield" which dominated the reflections of fishery managers prior to the last decade. Despite its extreme theoretical simplicity, attempts to guide fisheries to this maximum sustainable yield have proved extremely difficult. It seems that in a real system, levels of exploitation that are sustainable over a long period can only be found by trial and error, and in many fisheries this comes down to not having a management policy. Because of the rather mixed success of F_{max}, it was thought better to aim for a somewhat lower level of exploitation to reduce the risks of collapse in the system. In this way, $F_{0.1}$ was envisaged and defined as that level of fishing mortality giving rise to a slope on the yield-per-recruit/F curve of 1/10 that of the slope for a virgin fishery. In the simple logistic equation this turns out to be at $0.9F_{max}$, which is very close to a level of maximum exploitation, offering only a *narrow* safety margin.

We now consider the other pillar of mathematical ecology, which could have served as the basis for fishery management, but in fact did not.

Volterra–Lotka Equation

The important difference here is that the equations describe the interactions between species at two different levels in the system, a predator and its prey. The equations are

$$\frac{dx}{dt} = bx\left(1 - \frac{x}{N}\right) - sxy$$

$$\frac{dy}{dt} = sxy - my.$$

In the original work, N was assumed to be infinite, and the system gave rise to undamped cyclic oscillations of x and y around a neutrally stable stationary state, $x_s = m/s$: $y_s = b/s$. It was proposed as a basis to explain many of the oscillatory phenomena observed in natural populations, and it is interesting to note that Volterra's original work was performed in connection with the periodicities he had noticed in the populations of fish species in the Adriatic where he liked to go fishing. However, the neutrally stable (i.e. not stable) trajectories of this simple system with N infinite have been judged unsatisfactory as an explanatory model of observed behaviour, and many authors have insisted on the need to use a finite value of N. When this is done, the equations give rise to damped oscillations tending towards a stable stationary state, $x_s = m/s$ and $y_s = b(1 - m/Ns)/s$ (Fig. 2). Thus, they no longer offer an explanation of the oscillatory phenomena of natural populations. However, the addition of factors which take into account the effects given above, viz. handling time and predator saturation, can give rise to deterministic oscillatory solutions.

Historically, these equations did not form the basis of fisheries management. Instead the "logistic" approach was preferred. This reveals a basic reluctance of managers to treat "fishermen" as an active, responsive part of the whole system. The philosophy underlying the use of the logistic model is one in which the whole behaviour of the fishermen is subsumed and reduced to an "applied fishing mortality." Furthermore, by basing the calculation on an equilibrium hypothesis, this fishing mortality is supposed to remain constant at least for a time sufficient for the system to come to equilibrium. The whole question of the possible responses of the fishing industry to changing circumstances and profitabilities has been neglected, and it has been assumed that parameters such as b, m, and N can be represented simply by their average values, giving a deterministic relation between yield and fishing mortality. In addition, these models are nonspatial and refer to a population of a single species of fish.

It is not surprising that success in managing fisheries has been rather mixed.

Several developments have taken place in the past to construct better models on which to base management decisions. As early as 1957, Beverton and Holt developed the "Dynamic

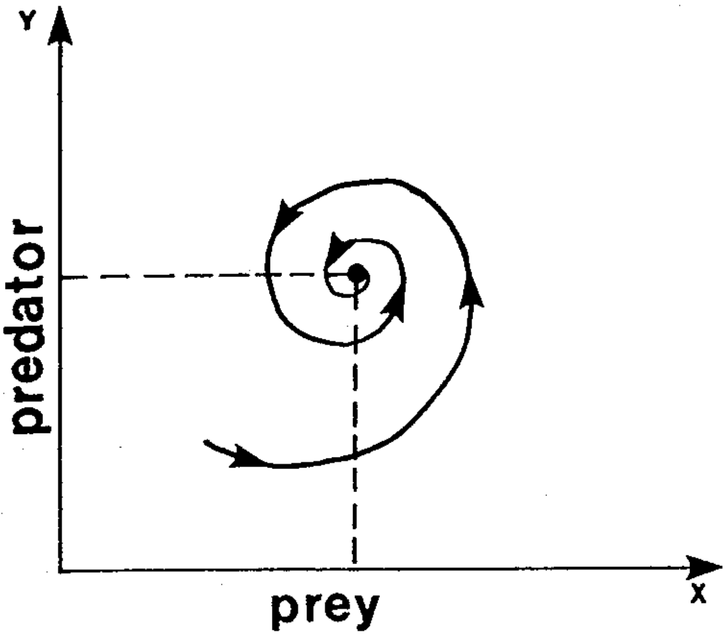


FIG. 2. Damped oscillations which characterize the approach to the stable, stationary state $x_s = m/s$ and $y_s = b(1 - m/Ns)/s$, which is the solution of the Volterra–Lotka equations with a limited carrying capacity for prey X and predator Y.

Pool Model," which was ostensibly a truly dynamic approach. Unfortunately, it came to fisheries scientists who were used to dealing with equilibrium, and thus some of the fundamental concepts became lost in static thinking. An important example is the yield per recruit (Y/R) calculation, which implicitly assumes that either constant fishing mortality or constant age structure holds. Considerable effort has been devoted to determining the "best" management strategies on the bases of the relationship between F and Y/R. The usual procedure is to compute the level of F that corresponds to some specified value of Y/R. As it may take 10 yr for a cohort to pass through a fishery, the calculation is invalid unless each age group suffers the same level of fishing mortality. The alternative of calculating an "instantaneous" Y/R based on the actual age pyramid is little better because it depends on the age structure remaining fixed throughout the life of each cohort. Beverton and Holt's objectives of moving towards a dynamic framework have therefore been frustrated, with equilibrium calculations prevailing in their stead.

Such methods have also been attacked in a series of papers by May and Beddington (Beddington 1979; Beddington and May 1977; May et al. 1979). They examined the effects of fluctuations in the value of parameters such as b, m, and N of the logistic equation. They showed that as exploitation increased the system moved towards instability and risked collapse. In a similar vein, work by Doubleday (1976), Nisbet and Gurney (1982), and Sissenwine (1984) showed the importance of fluctuations in natural systems. The idea that fluctuations around the average values of parameters could have an important impact on the sustainable catch had *not* been taken into account by managers aiming at high economic returns from "maximum sustainable exploitation rates." These were important results and have led to a further reduction in the confidence of management in the methods available to them, but have not resulted in any significant replacement by valid alternatives. Thus, it is pertinent to use the work of Hortsthemke and Lefever (1984) to show the effects of fluctuating parameters on

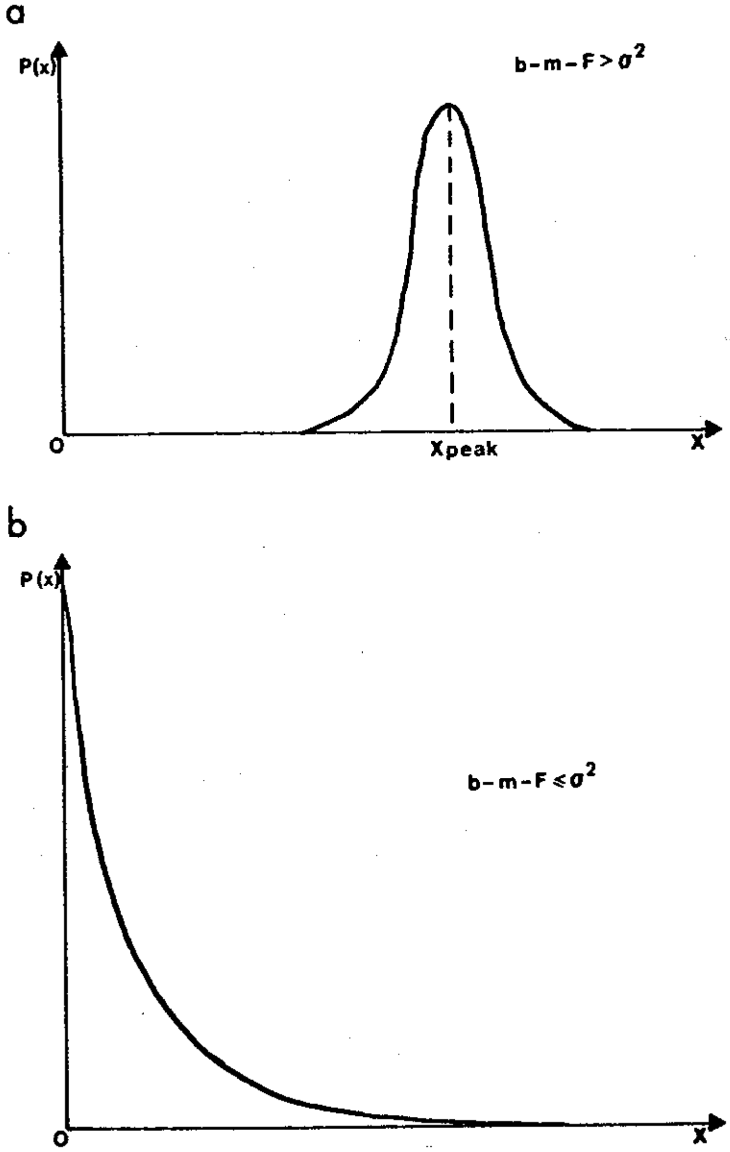


FIG. 3. Probability distribution curves of fish abundance (x), under a constant fishing mortality rate (F), where (a) $(\overline{b - m - F}) > \sigma^2$ and the $x_{peak} = N\left(1 - \dfrac{m + F + \sigma^2}{b}\right)$ and (b) $(\overline{b - m - F}) \leq \sigma^2$.

the logistic fishing model described earlier. As we shall see, it must fundamentally modify the very basis on which fishery models currently repose — the logistic description.

Logistic Fishing Model with Fluctuations

In the manner of Horsthemke and Lefever, we write the logistic equation taking into account the fact that in reality, at the very least, the birth rate b of a fish population such as haddock (*Melanogrammus aeglefinus*) fluctuates strongly around its average value:

$$(3) \quad dx = \left((\overline{b - m - F})x - \frac{b}{N}x^2\right)dt + \sigma^2 x dW_t.$$

The first terms gives the usual determinstic evolution, but the second term is a Wiener process which allows for the effects of fluctuations in b to be taken into account. The solution of this equation can be written

$$(4) \quad P_s(x) = \Omega e^{\frac{-bx}{N\sigma^2}} x^{2\left[\frac{(\overline{b - m - F})}{\sigma^2} - 1\right]}$$

showing that the stationary probability distribution of x has a m which is critically dependent on the sign of the term $\overline{(b - m - F)}/\sigma^2] - 1$. Thus, if $\overline{(b - m - F)}$ is greater than we have a distribution of the type shown in Fig. (3a). This responds to the previous deterministic situation, except that x_{peak}, the most probable value, is at

$$x_{peak} = N\left(1 - \frac{m + F + \sigma^2}{b}\right)$$

hich means it is displaced towards zero by the variance of the ise σ^2 in b. Although the fluctuations are both up and down, ound the same average as before, the net effect is a decrease the observed value of x. If fishing effort is increased so that $\overline{- m - F)} < \sigma^2$, then the distribution $P_s(x)$ has $x = 0$ as the ost probable value and an exponential type of tail of probaility for finite values of x (Fig. 3b). In this situation there are ost often no fish, but sometimes there are "bursts" of population which are fished rapidly out of existence. When fishing F_{max}, it only requires $\overline{(b - m)}/2 < \sigma^2$ for the transition to ccur from a distribution of the first type to that of the second. he parameters and fluctuations for most groundfish (cod, haddock, pollock, etc.) certainly seem to fulfill this condition. ven when we fish at the "safer" limit of $F_{0.1}$, it turns out to rov[illegible] he same transition if $0.9(b - m)/2 < \sigma^2$ (McGlade nd Allen 1985).

The basic description of a fishery thus requires modification ecause as F is changed and a collapse in x begins, then evenually fishing effort will also collapse as other activities, zones, r species become more attractive targets for fishermen. This witch may allow the rebuilding of the fish stocks, x, and later return of fishing effort. What we really need to know is how ast fishing effort drops with decling returns on effort. How fast an fish stocks rebuild themselves? How fast does information bout the size of a stock lead to an increase in fishing effort, an ncrease in information, and a repeat of the cycle? What we ave just described is the basic logic underlying the Volterra–Lotka equation. Fundamentally we are arguing that fishery models should be based on *these concepts* rather than on the logistic equation, because, instead of viewing fishermen as purely passive elements, the Volterra–Lotka equation explicitly brings them and their reactions into the system to be modelled. To do this, and to show why in fact such a change was not [illegible]mediately obvious, we turn to our case study, the groundfish fisheries of Nova Scotia.

Fishing for Groundfish off Nova Scotia

The main species of groundfish caught in this area are cod (*Gadus morhua*), haddock, and pollock (*Pollachius virens*). Each of these represents a "fishery," with management conducted according to spatial zones designed to coincide to a large extent with fish stocks. The data we consider are from NAFO (North Atlantic Fisheries Organization) Division 4X, over the period 1965–81.

In the previous sections we suggested that fisheries management must move away from simply considering fish populations and turn to models which include the behaviour of fishermen as an intrinsic part of their structure.

For example, a drop in yield may reflect the effects of several possible phenomena such as a decline in fish abundance, a decrease in fishing effort for reasons concerning profitability external to the fishery, or a reduction in the fisherman's knowledge about the location of fish aggregates. A Volterra–Lotka equation would only fit the first of these explanations, since it supposes cycles of fish abundance and effort, based on an endogenous logic, where external attractions are not supposed to influence the actors. Fishing effort and catch per unit effort are supposed to be mutually related and to give rise to cycles with lag between catch per unit effort and effort. To the really important question — are cyclic catastrophes in fisheries caused by natural events in the ecosystem outside of our control, or are they man-made — a pure Volterra–Lotka equation would suppose the latter. The real answer may be considerably more subtle.

Cod and pollock in the Division 4X show no Volterra–Lotka logic at all (Fig. 4a, 4b). Effort expended to catch fish is simply not related to the return on that effort. In contrast, haddock does exhibit something resembling a "cycle" (Fig. 4c). Can we explain these results and fit them into a coherent scheme? An answer appears as soon as one considers the question of fish price. The price paid to fishermen reflects the demand that exists among consumers for the different species of fish. In Nova Scotia the relative price for haddock, cod, and pollock is often approximately 3:2:1. This is the fundamental reason why the "causality" or "logic" of the Volterra–Lotka equations only exists for haddock. It is a "hunted species," while cod and pollock are often taken when it is difficult to obtain haddock, as by-catches or when inventories of these species fall to low levels. This is one reason why the understanding and control of a fishery cannot be based on single species equations or single spatial zones. Fishermen switch in and out of fisheries depending on the abundances available in others. As suggested by others (e.g. Mangel and Clark 1983), the relative profitability of fishing different species in different zones will be what drives fishing effort and generates the catch figures.

Simple Dynamic Model

As a first step towards unravelling this complexity, we have considered the haddock fishery in Division 4X and developed a simple program on a microcomputer to explore its dynamics. The equations take into account three age groups for fish, $X1 = 1 + 2$ yr olds, $X2 = 3 + 4$ yr olds, $X3 = 5+$ yr olds. We have used real numbers (in millions), weight at age, and the catch per boat required to keep it in the fishery. The following equations are used to model the haddock in Division 4X and the number of boat units actively fishing for haddock in this zone:

$$(5)\quad \begin{aligned} dX1/dt &= bX3\,(1 - TX/N) - mX1 - S1X1Y - X1/T1 \\ dX2/dt &= X1/T1 - mX2 - S2X2Y - X2/T2 \\ dX3/dt &= X2/T2 - mX3 - S3X3Y \\ dY/dt &= RY(1 - C/(P(W1X1S1 + W2X2S2 + W3X3S3)) \\ dP/dt &= \mathrm{RR}\cdot P\,(1 - \mathrm{CA}\cdot P/\mathrm{MA}) \end{aligned}$$

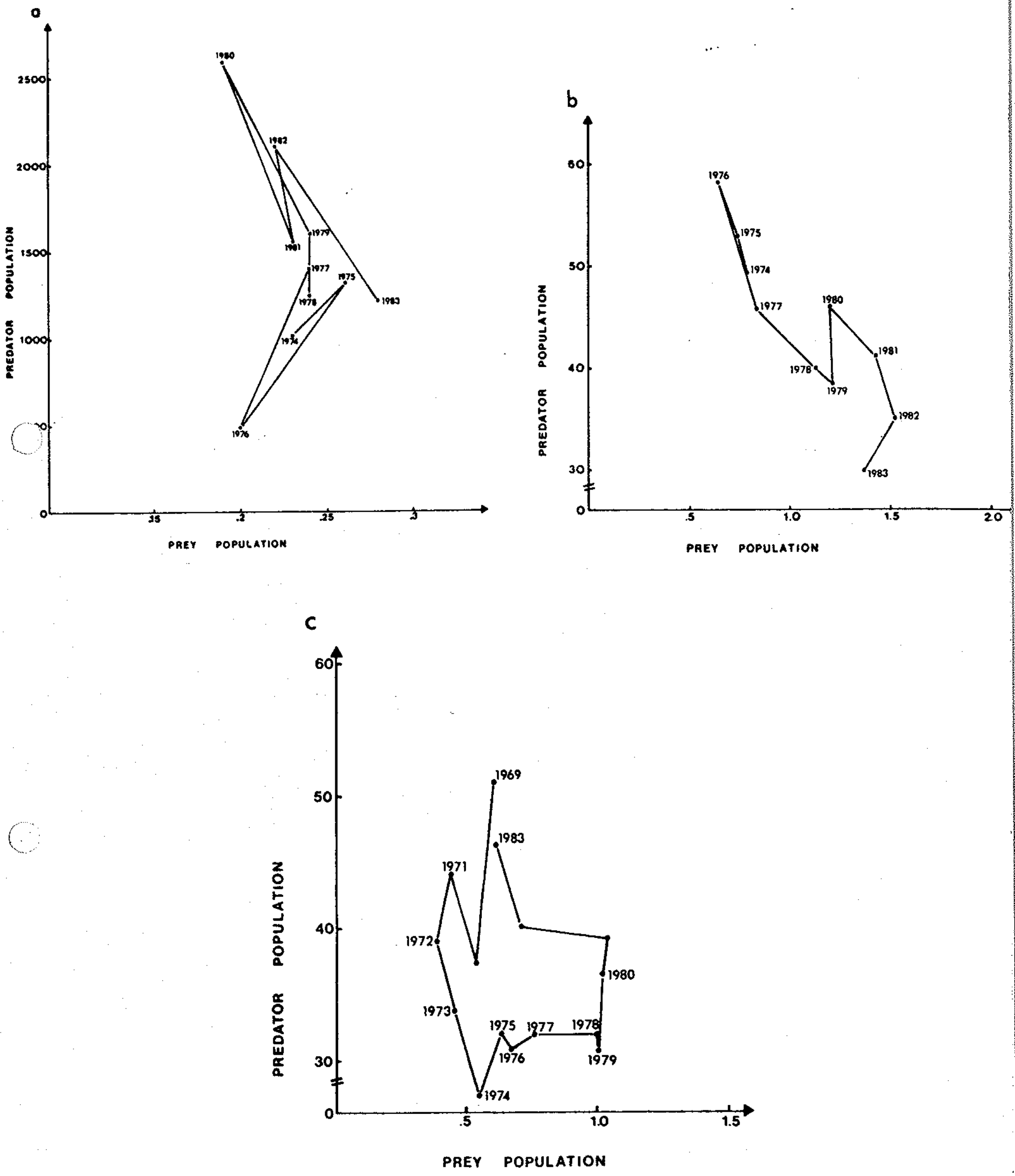
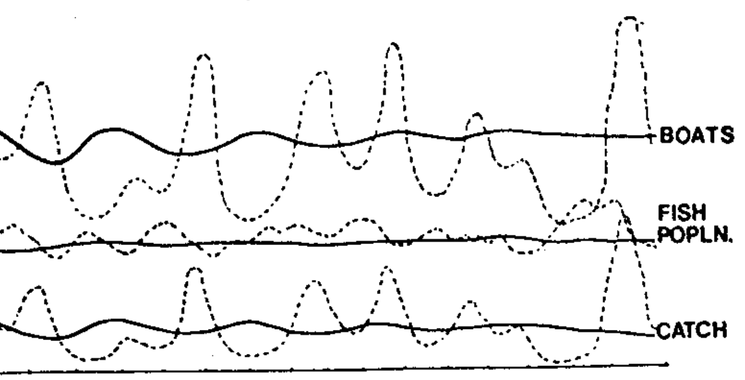


FIG. 4. Predator population (fishing effort) versus prey population (catch per unit effort) in NAFO Division 4X for (a) cod, (b) pollock, and (c) haddock.



;. 5. Simulation results for the haddock fishery in NAFO Division ζ, supposing that the parameters of the equations can be represented their mean values: *a*, deterministic approach to equilibrium; *b*, the erage values of all the parameters are the same as for *a*, but now each year the value of *b* is chosen to be good (1.45*b*), average 75*b*), or bad (0.05*b*) according to a random number. The system longer goes to equilibrium, but instead executes fairly large, irreg-ır oscillations which resemble reality.

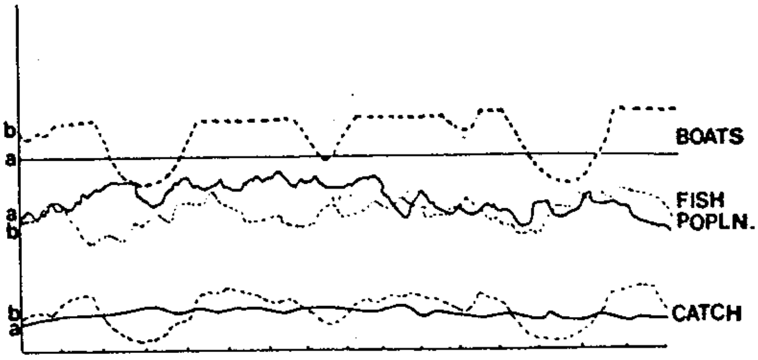


FIG. 6. Simulation results for the NAFO Division 4X haddock fishery showing the effects of limiting effort: *a*, with $y = 100$, we observe that at a slightly reduced yield, the system evolves for 80 yr without a major upset; *b*, with $y = 200$, we observe that in the long run one pays for the higher yield through more frequent crises. Policy exploration should be about attempting to find an acceptable balance between risk and yield.

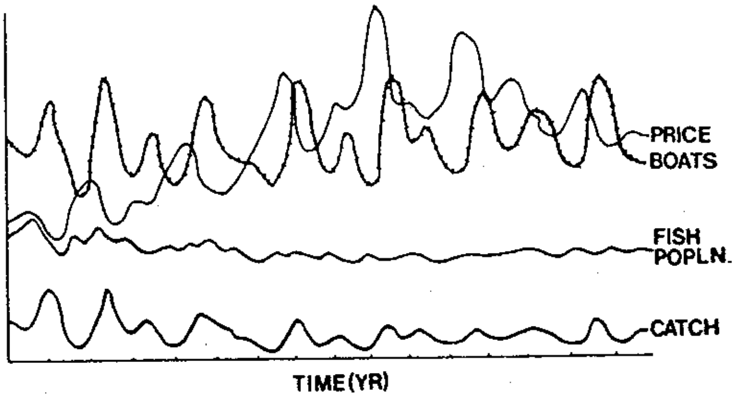


FIG. 7. Simulation results for the Division 4X haddock fishery in which the price of fish has been allowed to vary depending on supply and demand. Although this changes the evolution, it increases the number of crises. The effect of different rates of response and market elasticities can be examined using the model, and policy options can be explored taking into account the response of the market.

here b = birth rate, TX = total numbers of fish, m = natural ortality, $T1$ and $T2$ = time span of groups 1 and 2, $S1$, $S2$, ıd $S3$ = rate of capture between boats and fish at age, Y = ımber of boat units, R = rate of response of effort to profit-ɔility, $W1$, $W2$, and $W3$ = weight-at-age for $X1$, $X2$, and $X3$, = revenue each boat wishes to make to maintain its effort, R = rate of response of price to catch per unit time, P = rice, CA = catch per unit time, and MA = market per unit me at unit price. These equations have a stationary state, and ıe saturation factor $(1 - TX/N)$ ensures that it is stable. igure 5 (*a*) shows a typical deterministic simulation in which ıe values of $X1$, $X2$, $X3$, and Y and catch evolve in a damped scillatory motion towards their stationary values. But it ıkes at least 70–80 yr to get near to equilibrium, and so the aditional fisheries management assumption that equilibrium lways holds seems somewhat optimistic.

The model becomes more interesting when we add to the irth rate (*b*) a realistic amount of fluctuation around its verage value. We use a random number each year to decide vhether a year is good, medium, or bad (where good, bg = .45*b*; medium, bm = 0.75*b*; and bad, bb = 0.05*b*), around ıe same average *b*. The result is dramatic (Fig. 5 (*b*)). The ystem amplifies the random fluctuations in *b* and sets itself ıto relatively violent and regular oscillations at approximately ıe Volterra–Lotka frequency.

It must be emphasized that the fluctuations which we have roposed for the haddock fishery are considered by fishery xperts to be conservative, compared with reality. Turning off he fluctuations would give rise to a stationary state after some 70 or 80 yr, but in answer to the question, are cyclic crises in isheries of natural or man-made origin, we suggest a new ınswer: *both*. Human responses amplify rapid random fluctu-ıtions and excite Volterra–Lotka type oscillations, but without he natural "noise" there would be nothing to amplify, and the ishery would be stable. This effect has in fact been observed n other fisheries such as for the north Californian dungeness rab (*Cancer magister*) (Botsford et al. 1983).

Our simple model has revealed a remarkable mathematical phenomenon: a system which normally would repose in a stable, stationary state can be set into a strong, characteristic oscillation with a particular frequency by the action of relatively rapid, random noise in the environment. This confirms a result presented at a workshop held in Texas, when Stucki and Horsthemke (1982) showed that a simple Volterra–Lotka system could be set in oscillation by environmental white noise. In their case, however, the stationary state was not truly stable, only of neutral stability. Our results confirm theirs, and go further by showing that stability in the deterministic system is no guarantee when environmental white noise is added. This line of research is being developed by Horsthemke and Lefever (1984), and we believe it to be of great interest for the understanding of natural and man-made systems.

Despite the simplicity of our model of equations (5), it offers management a useful tool with which to study the effects of certain policy decisions. Simulations presented in the Fig. 6 and 7 show the possible effects of different measures. For example, if fishing effort is limited to some upper level, there is a transition in the type of probability distribution underlying the fish population dynamics (Fig. 6 (*a* and *b*)). By putting a low upper limit on Y, we find a stable finite yield which never goes into crisis, despite various chance events in the fish dynamics. As this upper limit is raised, increasing short-term yield, successive crises occur at more and more frequent intervals until Y is "free" and cyclic disasters occur, with infrequent bursts of fish population rapidly fished out by an exaggerated effort.

This self-perpetuating, vicious circle represents just one possible regime in which the ecosystem could operate. Haddock, being high priced, are hunted ferociously, and therefore are rare, and high priced. Other species merely serve as financial stop-gaps when haddock are unobtainable. Other regimes with different species mixes, prices, and catches can also be explored by our model.

Dynamic, Multispecies, Multifleet Spatial Model

We now examine the fundamental ideas of "discovery" and "exploitation" which are at issue in the hunting of fish. We have constructed a dynamic multispecies model and applied it to the Nova Scotian groundfish fisheries. The model takes into account fishermen's decisions to switch species and fishing grounds according to their perceived relative opportunities. The equations (Appendix) describe the dynamics of fish populations in the different zones of the system as they spawn and multiply, and are then taken out of the system by fishing; the model can deal with up to four species of fish. The second set of equations describes the movement of fishermen, responding to information they have about catches being made by fleets fishing in the area. The model can describe the movements and behaviour of up to eight fleets and can trace the movement of fish and fishermen across some 40 spatial zones. Each boat is attracted to fish in a particular zone according to the relative attractivity of that zone as seen by the boat in question. Thus, the expected return that can be obtained from the reported catch and species mix in a zone is weighed against the cost of transferring to another zone, and the distance of that zone from the home port.

In constructing this "attractivity," we use the concept of "boundedly rational" decision making on the part of individuals. We suppose that the probability of an individual being attracted to a zone i, among all the others, is given by

$$P(i) = \frac{A_i}{\sum_i A_i}$$

where A_i is the attractivity of zone i. Since probability must vary from 0 to 1, A_i must always be defined as positive. A convenient form is

$$A_i = e^{IU_i}$$

where I is the quality of information and homogeneity of the population and U_i is a "utility function" and constitutes the "expected net rate of return" in zone i, taking into account the revenue from expected catch and the costs involved in obtaining that catch. These costs will take into account the distance d_{ij} from i to j and the fuel costs as well as the distance of zone i to port. In this representation the value of the parameter I determines the homogeneity of response between the different choices. If I is small, each choice will be made with equal probability, regardless of the real attraction of zones contained in the U_i. If I is large, even the smallest differences in real returns between the zones will lead to a single choice being made with 100% probability. Thus, I is related to "information exchanges" in the system.

When there are many individuals making choices, the fractioning of the population will reflect their relative attractivities. The population choosing i, y_i, from the total population y will be

$$y_i = y\frac{A_i}{\sum_i A_i}$$

with $A_i = e^{IU_i}$ as above.

With a population y perceiving and responding to the utilities U_i, the parameter I now reflects two factors: the "clarity" of information received and the homogeneity of the receiving population.

In our example, boats move between the different spatial zones of the system and the attractivity of any particular locality depends on where the boat concerned is situated. The fraction of boats of fleet L, situated at j, that is attracted by zone i is

$$y_i^L \cdot \frac{A_{ij}^L}{\sum_i A_{ij}^L}$$

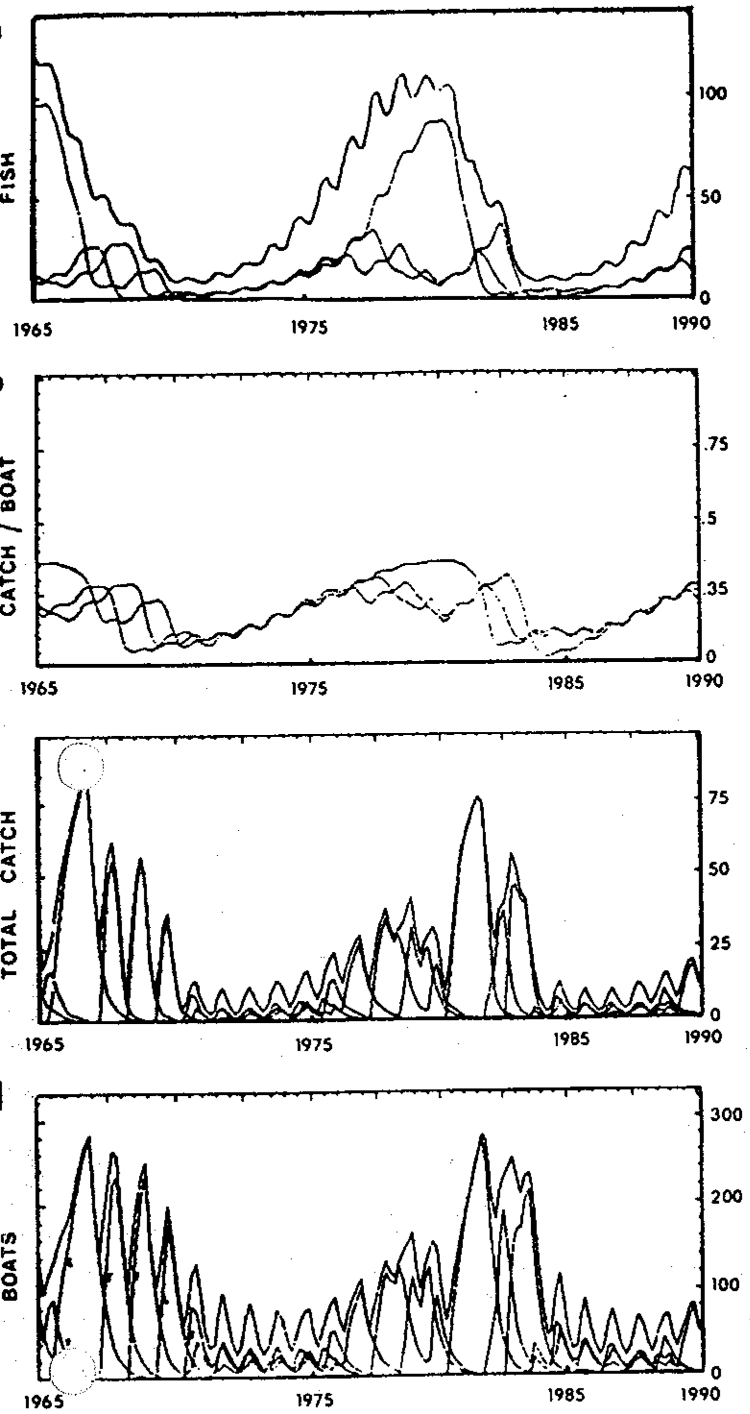
and the total number attracted to i from all the possible j's is

$$y^L p_i = \sum_j y_j^L \cdot \frac{A_{ij}^L}{\sum_i A_{ij}^L} = (\text{potential } y_i^L).$$

The movement of boats around the system is therefore generated by the difference at a given time between $y^L p_i$ and y_i^L, the number of boats *actually* in i. If $y^L p_i$ is greater than y_i^L, boats will move into i from other zones. If $y^L p_i$ is less, they leave. They move at a *finite* rate depending on the rapidity with which they are willing and able to react. As they travel to different zones to fish, the relative attractivities of the zones are modified. Once this is detected, further response on the part of the fishing boats results in new patterns of fishing effort, with continuous dynamic movement of boats and fish resembling, when calibrated, that of the real system.

One of the many possible areas of interest opened up by such a model is the examination of different spatial strategies, and what we have called "the dynamics of discovery and exploitation." For hunted species, the yield will depend on "locating" aggregations of prey and then mobilizing and directing fishing effort to this location. This objective can be achieved in different ways: either an "unstructured" population of "generalist" fishermen who do both functions, or various structured possibilities involving "risk taking" skippers who are specialized in "discovery" and others who only go to locations where present information tells them the "highest returns" can be found. This structured organization requires information exchange between the different types of fisherman. To handle this in our model, we have considered that the "expected return" from fishing in a zone i that influences the U_i^L of attractivity will be "channelled" between fleets or types according to an "information exchange" matrix. Thus, the "expected catch" in a zone for a particular fleet or type is generated by total information received from other vessels of the same and other fleets. The concept of "information exchange," of lying or speaking in codes to one's own fleet is expressed in the term

$$\text{Expected catch} = \sum_{L'} \epsilon^{LL'} \left[\sum_k \left[\frac{p^k w^k \cdot sx^k y^{L'}}{(1+s)^\tau \left(\sum_k x^i\right)}\right] \cdot \frac{1}{(1+0.3y^{L'})}\right]$$



IG. 8. Simulation of the haddock (*Melanogrammus aeglefinus*) fish-
ry in Division 4X: (a) fish population; (b) catch/boat; (c) total catch;
l) boat units.

here L' = index of fleet type, k = indicates the species of sh, w^k = the average weight, p^k = price per kilogram of the pecies k, and τ = time for boat to handle 1 unit of x (where = 1000 t). The epsilons describe the reception of catch nformation. The term at the end $(1/(1 + 0.3y^{L'})$ makes the erm sensitive to catch per boat instead of just catch as the umber of boats increases.

Thus, vessels play a dual role when fishing: they "exploit" ne zone they happen to be in, and they sample local conditions nd transmit the information to chosen associates.

This model is still under development, but we shall present ome of the preliminary studies we have made, and which give se already to some interesting points. In Fig. 8a–8d we show ne results generated by a simple version involving only one eet and one fish species, with three fishing grounds situated

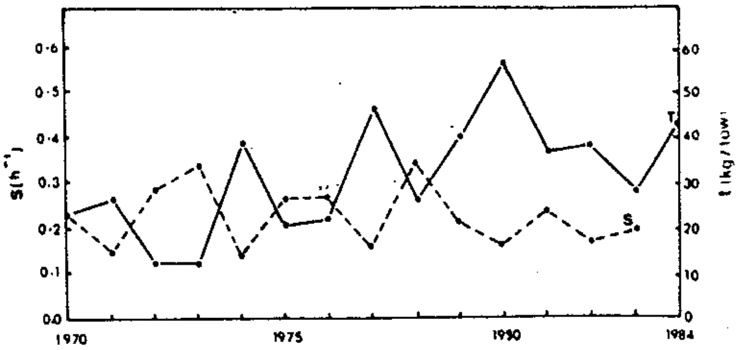


FIG. 9. Ease with which fishermen locate fish (S) (catch rate/abundance) and fish abundance (t) over time for haddock in Division 4X, where abundance is derived from research vessel survey estimates.

100 km from the home port. The simulation starts with the approximate figures for haddock in NAFO Division 4X in 1965 and runs forward to 1990. It corresponds fairly well to observation for the period 1965–84, and this must unfortunately lend some credibility to the continued evolution until 1990. Leaving aside this practical question of "prediction," what the simulation also shows is the importance of "fishermen's knowledge" in generating the catch figures observed. The catch and effort figures for the three zones *aggregated* cannot be easily interpreted, since at various moments fishing effort can be misdirected to zones where fish are less abundant. This shows that in an inhomogeneous system such as the real world, aggregation of data over inhomogeneities can lead to changes in the apparent "catchability" of fish as boats home in on high abundances. In this example, a hunted species of fish gives rise to a situation where fish abundance (x indicated by t per tow) and the ease with which fishermen locate the fish (S) (catch rate/abundance) change over time out of phase (Fig. 9). This is because as fish density increases aggregates generally form, but they must first be discovered by fishermen before effort can be channeled to their exploitation, and boats will fish in the "right places." Thus, initially, t increases and S drops. Once discovery has occurred, effort is directed to the dense aggregates and fish abundance drops, while S increases. This turns out to be the case for haddock in Division 4X where independent estimates of fish abundance can be made from research vessel data. It also applies in our model of the haddock fishery in Division 4X. But is is not found for cod or pollock in Division 4X. There is no "out of phase relationship" between abundance and the apparent value of S. This supports the validity of our fundamental hypothesis that only haddock is really hunted in Division 4X. Cod and pollock are only taken as a stop-gap when haddock is rare, and so finding these species is not the main limiting factor on their catch. In this way the model helps to unravel some of the misleading information contained in the commercial catch data, which a nonspatial approach would fail to reveal. It is partly these misconceptions concerning the "apparent" abundance of fish derived intuitively from catch data that allows a "managed" fishery to continue to suffer cyclic crises despite the best efforts of managers.

Another significant result that the model generates concerns the "discovery" and "exploitation" mechanisms and the questions of information exchange, rationality, and randomness. Other important considerations are superimposed on the basic spatial movements towards the aggregates of high priced fish at the nearest locations. For example, skippers whose behaviour is only weakly influenced by this information, who either

TABLE 1. Number of boats in stochastic fleet (Bs) and in cartesian fleet (Bc) under different conditions of I, the quality of information and homogeneity of the populations (I_s and I_c), and with varying information matrices (a = information within the stochast fleet; b = information from cartesian fleet to stochast fleet; c = information from stochast fleet to cartesian fleet, d = information within the cartesian fleet). Price of fish species F_2 is three times F_1.

	Information matrix $\begin{pmatrix} a & b \\ c & d \end{pmatrix}$											
	$\begin{pmatrix} 1 & 0.5 \\ 0.5 & 1 \end{pmatrix}$		$\begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}$		$\begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}$		$\begin{pmatrix} 1 & 0 \\ 1 & 1 \end{pmatrix}$		$\begin{pmatrix} 1 & 1 \\ 0 & 1 \end{pmatrix}$		$\begin{pmatrix} 1 & 0.1 \\ 0.1 & 1 \end{pmatrix}$	
I_s	0.2		0.2		0.5		0.2		0.2		0.2	
I_c	2.0		2.0		2.0		2.0		2.0		2.0	
Time (yr)	Bs	Bc	Bs	Bc	Bs	Bc	Bs	Bc	Bs	Bc	Bs	Bc
1	62	50	61	50	62	50	61	50	62	50	61	50
2	83	68	85	67	83	67	85	69	83	67	84	67
3	114	93	119	83	89	72	114	95	116	79	116	92
4	149	122	160	92	97	55	150	126	137	82	150	118
5	189	156	225	85	139	34	191	161	228	74	192	150
6	238	196	290	69	183	22	237	200	296	59	241	185
7	270	229	371	50	186	16	269	236	382	45	275	209
8	283	251	424	34	185	13	281	256	432	31	294	222
9	258	236	448	23	192	12	253	239	457	21	276	218
10	217	210	438	18	263	12	209	210	445	17	242	185

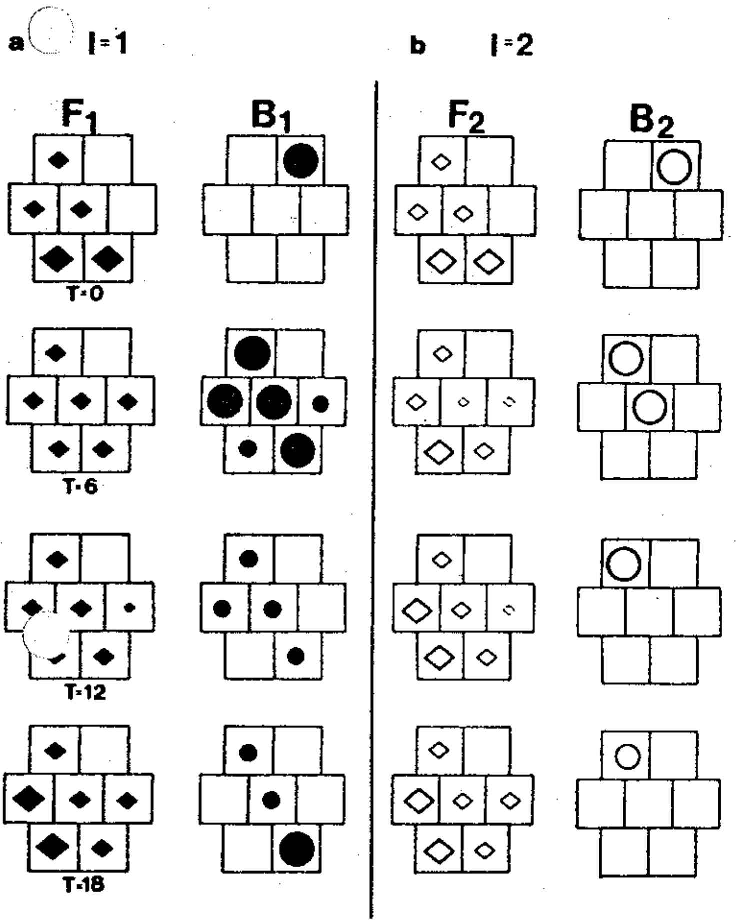


FIG. 10. Simulation results from a 15-yr run of one species of fish (F) and one fleet type (B) with ($T/1.2$ = yr): (a) I = 1, and F_1, B_1; (b) I = 2 and F_2, B_2.

search "randomly" or according to some personal scheme of knowledge, will be characterized in our model by a small I. We will call them *stochasts*. At the other extreme we have skippers who, for various reasons, are unwilling to take any risk and will go to the zone promising the best *known* return, no matter how low, as long as it is certain. We shall call them *cartesians*. They will be characterized by a larger value of I.

To demonstrate the effects of I, we compare two simulations performed under identical conditions, except that in one case we set I = 1 and in the other I = 2. When I = 1 (Fig. 10a) the fleet discovers the various zones of high return and travels to successive areas, fishing out high paying aggregates. There is a period when stocks must recuperate, but basically the fishery continues, with "search" and "discovery" occurring over the whole area, leading to a typical series of good and bad years as observed in reality.

Figure 10b shows the long-term evolution of the fishery if I = 2. Over time this is disasterous, although in the short term it simply directs boats rather clearly to the "best" zone for fishing. The information about which is the best zone is generated only by boats which are fishing, and there is a kind of "locking" onto one particular location with a shut down of "random" sampling. In the long run this leads to the fishery simply exploiting a single location instead of the whole area, with a small catch and small fishing fleet. In contrast, I = 1 results in the maintenance of fishing activities over the whole area of the system and a much higher catch and larger fishing industry. Thus, less "information" allows a more "fuzzy" or "random" response on the part of boats, meaning that they continue to explore the less visited parts of the system. In a way they take more risks, but the result is that the system survives instead of virtually shutting down. If boats refuse to take risks and go only to where they know for sure that there are some fish, the end result is disaster. Discovery must involve risk. But to abandon discovery is in reality to make disaster certain.

In the next series of simulations we again explore the effect of having the two types of fishermen, stochasts and cartesians, and test their relative and combined effectiveness for different conditions of information exchange: the results are shown in Fig. 11a–11f and summarized in Table 1. Figure 11a shows 10 yr of evolution for a situation in which catch information is passed between stochasts (I = 0.2) and cartesians (I = 2.0) at 0.5 the rate it is within each type. Over the initial period, the stochasts are more successful than the cartesians, keeping ahead by discovering aggregates quicker than the others. In the later period when fish stocks have declined, the two strategies do almost equally well.

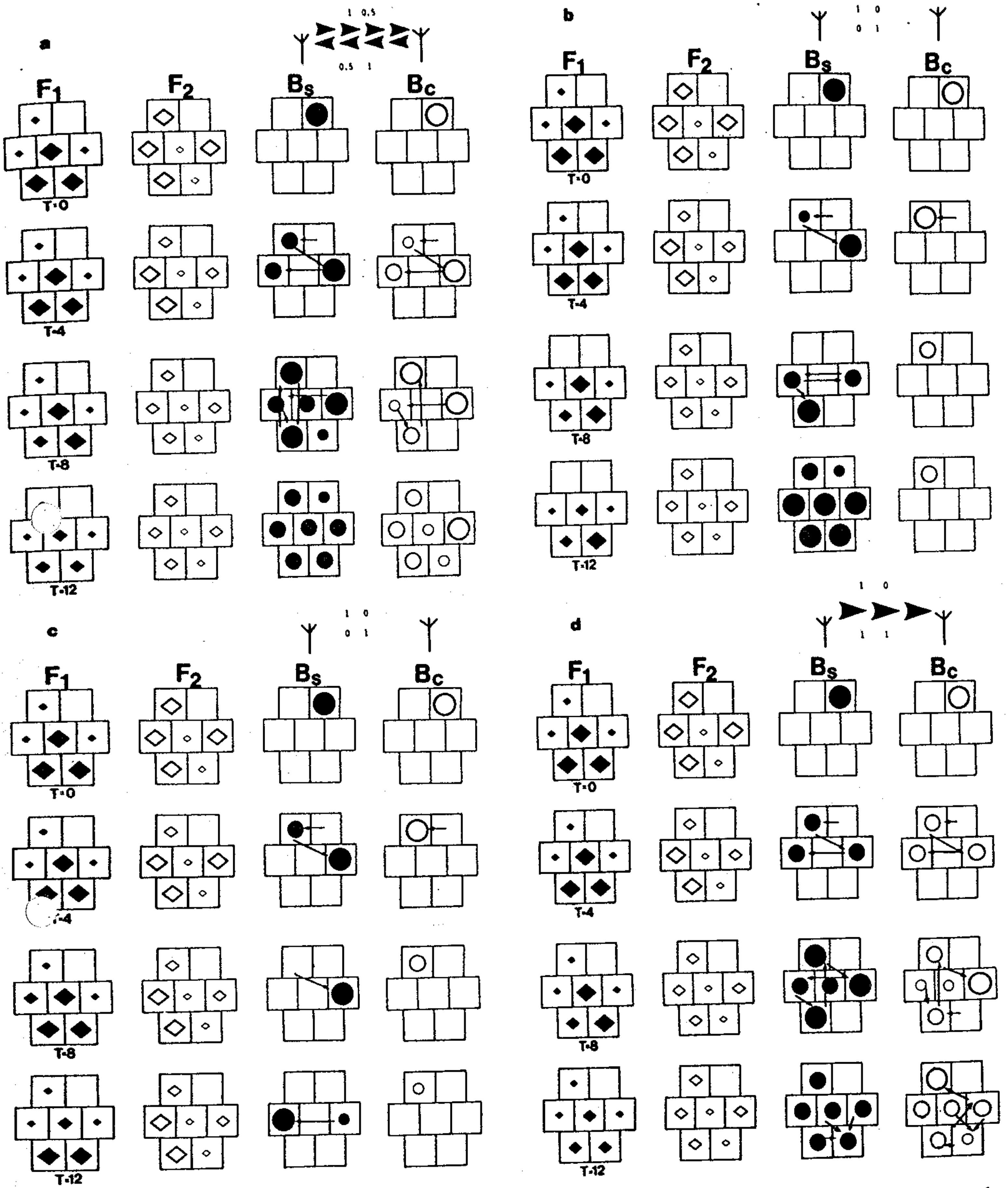


FIG. 11. Simulation results over 10 yr ($T/1.2$ = yr) with two fish species, F_1 and F_2, and two fleet types, Bs (stochast fleet) and Bc (cartesian fleet). F_2 is three times the price of F_1. The size of the symbols is relative and particular to each run; thus, they are used simply to indicate very small (approximately less than 10), medium, and large quantities. The numbers in the information matrix $\begin{pmatrix} a & b \\ c & d \end{pmatrix}$ refer to exchange of information and are keyed as follows: a = information flow within the stochast fleet, b = information flow from cartesian fleet to stochast fleet, c = information flow from stochast fleet to cartesian fleet, d = information flow within the cartesian fleet. (a) $I_s = 0.2$, $I_c = 2$, and partial information exchange (0.5) between fleets; (b) $I_s = 0.2$, $I_c = 2$, and no exchange between fleets; (c) $I_s = 0.5$, $I_c = 2$, and no exchange between fleets; (d) $I_s = 0.2$, $I_c = 2$, and no information flow from cartesians to stochasts; (e) $I_s = 0.2$, $I_c = 2$, and no information flow from stochasts to cartesians; (f) $I_s = 0.2$, $I_c = 2$, and small level (0.1) of information flow from stochasts to cartesians. (*Fig. 11 concluded next page*)

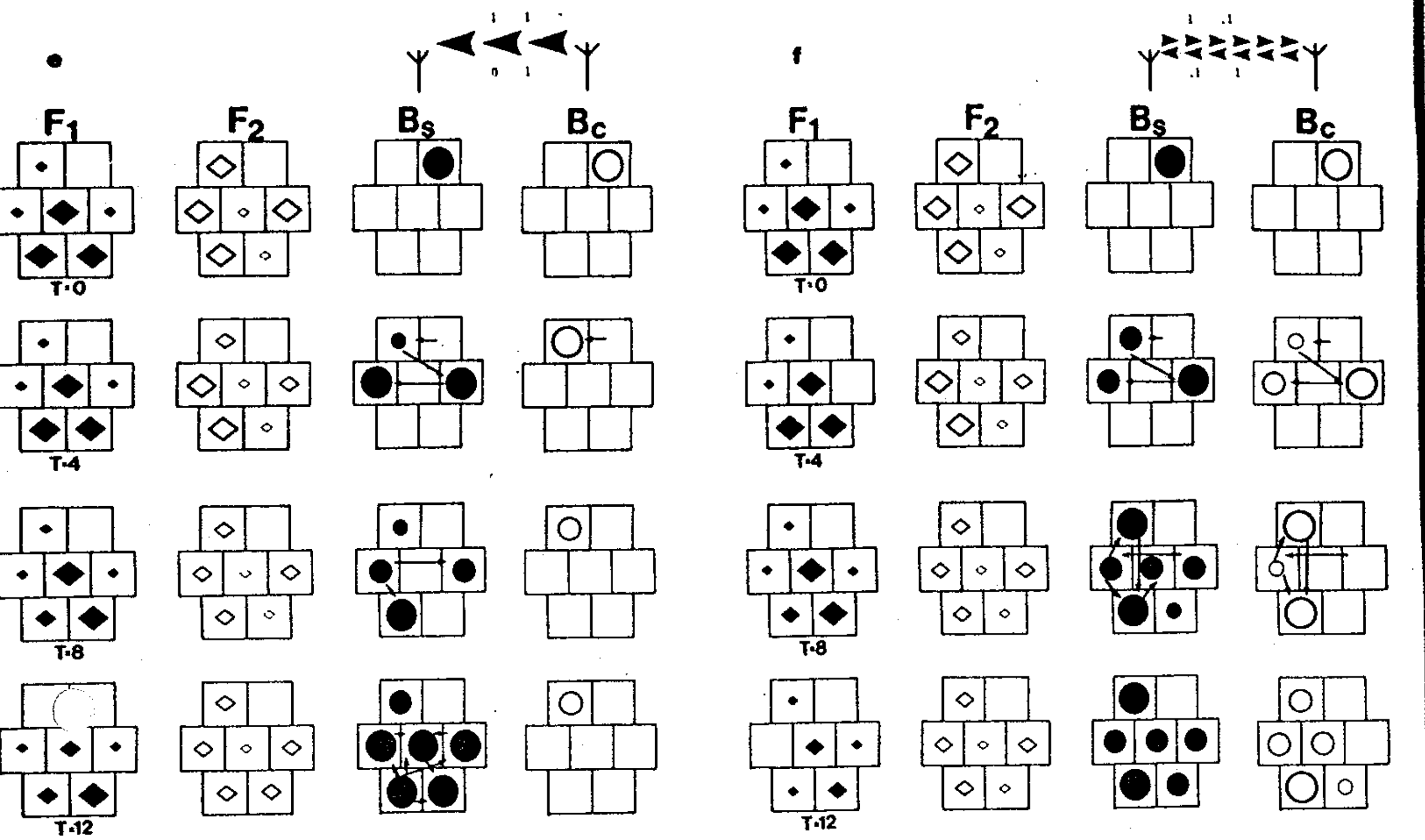


FIG. 11. (*Concluded*)

The second case shows how the stochasts act as the "eyes" f the fishing fleets. If, however, the information they have not transmitted to the others, then the system as a whole oes not exploit the resource very efficiently. The cartesians, arved of information about fresh discoveries, simply wither way, fishing out the one zone that they have discovered Fig. 11b). The only surviving strategy is that of the stochasts, ut this is not necessarily effective at concentrating effort rongly in the zones where large aggregates have been located. similar phenomenon is found when stochasts have a higher alue of *l*, and remain much more bunched (Fig. 11c).

These conclusions are reinforced by Fig. 11d and 11e, which ow what happens when either the cartesians or the stochasts heat by not transmitting information about their catches. here is an interesting asymmetry. If the cartesian fails to form the stochast, then it has very little effect, while if the ituation is reversed, the cartesians perish, leaving the field free stochasts. Therefore, a natural reaction for cartesians will e to *try* to obtain information, while the others will simply ttempt not to give it. This has resulted in the evolution of listening in" on radios, of coded messages, of "lying," misinformation," etc.

Figure 11f, incorporates another source of structural comlexity: an explanation of the baroque of the real world. Here, e suppose a very weak mutual exchange of information. This very effective globally. The stochasts locate aggregates nd direct very concentrated fleets of cartesians to the relеant locations. The possibility of such efficiency means that a atural evolution would be to have in each competing fleet subdivision of "researchers" and "producers" so that they ooperate within a fleet, but not with competing fleets. The mmense richness and apparent obtuseness of much of human behaviour can be better understood in terms of such a model. In large fishing fleets, this type of complicity is indeed present, since the managers persuade their best captains to go off in search of new fishing grounds by promising them in return a trip to a highly profitable area as a reward.

In the Nova Scotian situation there are two types of fishermen: those who are "average" and those who are called "highliners." The latter are adventurers who take risks, discovering new concentrations of fish and always leaving areas in search of further discoveries before they are completely fished out. There is a population of "risk takers" and a population of "imitators." Risk takers happen to earn significantly more money than the others by their strategy, and this enables them to take risks. This is another example of a self-perpetuating situation, where a successful highliner ensures his continued ability to operate as a highliner, by being able to afford better equipment, and withstand small periods of "bad luck." An "imitator" must have both determination and good luck if he is ever to make the transition. This is an evolutionary mixed strategy, where it is the complementarity of two behaviours that ensures reasonable exploitation of a resource.

General Discussion

In the preceding sections we have tried to show that new concepts emerging from dissipative structures and nonlinear systems give rise to models which can be usefully applied to the understanding and management of fisheries. We feel that these ideas are of great generality and should enable some wider conclusions to be drawn.

A number of important points have been raised. First, when faced with the problem of understanding a complex system, it s vital to identify the "actors" in that system and to include explicitly their responses and actions in the model. The "subjective" views of each actor must be taken into account rather than supposing that some global principle, such as "optimal" efficiency or an equilibrium state, can be invoked. Such assumptions are clearly dubious in the real world where we are most often faced with dynamical systems composed of individuals, each of whom is trying to attain his ends and who s doing so on the basis of information which is constantly being gained and lost as the system changes.

The second point concerns fluctuations. They are not simply a "nuisance," a perturbation of average results, but instead are the motor of evolutionary change and explain the very "nature" of many systems. In the case of our fishery example the feedback responses of the human system are such that they amplify the nearly random fluctuations of the environment, and generate large, fairly regular cycles of boom and bust, despite the fact that the deterministic system has a stable equilibrium solution.

The third issue is that of the importance of calibration of these types of models. In our case study it has been possible to use realistic figures and parameters, so that the phenomena discussed and predicted are of relevance to the real world. It is harder for industries and practitioners to ignore a model that deals with real numbers, since then the intuitions and prejudices of decision makers require justification. The real use of such models must be as a "learning tool" rather than as a *predictive* instrument. They enable us to understand the part of the evolution of a system which may be due to the mechanisms contained in the model, and suggest when additions are necessary to understand the behaviour of the evolving and creative world in which we live. They also allow decision makers to explore the possible implications of proposed actions before putting them into effect, and can be used to better "imagine" the future, and to suggest other ways of doing things. Our ideas are therefore very close to those of Holling (1978) in this respect, viewing "management" as an on-going process, where we continue to adapt our ideas and models to the evolving situation.

The final point we raise is probably the most important. It concerns the question of "discovery," of evolutionary survival, and of information exchange. There is a fascinating parallel between the picture we have derived concerning fishing behaviour and that revealed by recent research into foraging behaviour in the animal kingdom, particularly in work on ant societies (Deneubourg et al. 1983). The vital issue is that "discovery" like "invention" and "creation" can be achieved through "nonrational" behaviour, although subsequent exploitation may depend on "rational" reactions. The multifacetted process of "discovery" and "exploitation" concerns all of us at many levels. Either as individuals or in our various roles in families, firms, institutions, communities, and even nations, we must try to decide how to divide our time and effort between the performance of tasks characteristic of our present role, with known values and pay-offs, or the continued search for, and openness to, the possibilities of new roles and new pay-offs in the future.

As individuals we can either deliberately allow ourselves to explore new paths and connections, or instead, we can organize most of the components of our lives so that we minimize such diversions which, at any given moment, have no obvious purpose. There are again two extremes: "stochasts" and "cartesians." The former take intellectual, emotional, or financial risks by adventuring into the unknown, be it with ideas, aesthetics, personal relationships, or entrepreneurial activities. Their discoveries are what nourishes society in the long run, and assures its survival by allowing to to evolve, and to find new sources of sustenance. The latter devote themselves to fulfilling as efficiently and completely as possible the role they feel has been assigned to them. Their behaviour constitutes the "backbone" of society, and offers a very necessary definition of "normality." The successful, long-term functioning and survival of an individual, a society, a firm, or a nation requires both types of behaviour, just as our example dealing with "fishing" showed.

These wider aspects of human behaviour, illustrated and brought to light by our model of fishing, with its complementary tasks of "discovery" and "exploitation," will be the object of further study. The whole question of "innovation" and of management can be examined in terms of these new ideas. Old views of policy and planning as a "rationalization," and classification, streamlining, and separation of different functions must be reexamined. We need to design systems which are capable of being creative, not imposing too much rationality or too much information on them. Neither should we restrict movements or thoughts to only the known or recognized channels characterized at present by an obvious usefulness. Discovery requires freedom, while the efficient functioning of society requires cooperativity and organization. Perhaps with models such as ours, we can begin to understand and explore a new "rationality" which encompasses both harmoniously.

As Confucious said, "Give me a fish and I eat today, but teach me *how* to fish and I shall never be hungry." If we can discover *how* to fish, then we shall indeed have taken a large step forward.

Acknowledgments

This work was supported by the Department of Fisheries and Oceans under contract 09SC.FP101-4-0580 and by the Global Learning Division of the United Nations University, Tokyo. We thank scientists from the Marine Fish Division, Bedford Institute of Oceanography, and from Chimie-Physique II at the University of Brussels for many helpful discussions. We also thank G. Engelen for help with the computer program, C. Walters for helpful comments, and R. Mohn for a 13-hour conversation en route to Montreal.

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Appendix: Equations of the Multispecies, Multifleet Spatial Model

The differential equation governing the change in population of the fish k, at point i, is

$$\frac{dx_i^k}{dt} = b^k x_i^k (1 - x_i^k/N_i) - \sum_L \frac{s x_i^k y_i^L}{\left(1 + s\tau \sum_k x_i^k\right)}$$

The equation governing the change in numbers of vessels of fleet L at point i is

$$\frac{dy_i^L}{dt} = \xi\left(\sum_j \frac{y_j^L A_{ij}^L}{\sum_{i'} A_{i'j}^L} - y_i^L\right) + r y_i^L \left(1 - C_i \Big/ \sum_k \frac{s x_i^k}{\left(1 + s\tau \sum_k x_i^k\right)}\right)$$

where x_i^k = fish population of type k at i, y_i^L = boat numbers of fleet L at point i, b^k = rate of natural increase of species k, N_i = natural carrying capacity of the point i, s = rate of interaction between fish and boats, τ = time for a boat to handle 1 unit (1000 t) of x, ξ = mobility of the boats, r = rate of response of effort to profitability, C_i = cost of fishing at i, A_{ij}^L = attractivity of i, to L, viewed from j, $A_{ij}^L = \exp(IU_{ij}^L)$, U_{ij}^L = utility function (as described in text) or "expected net rate of return" in zone i viewed from j by a boat in fleet L, taking into account the revenue from expected catch, the costs involved in obtaining that catch $\theta(d_{ij} + d_{ip})$, and the information flow matrix ϵ^{LL} between fleet types L' and L, I = quality of information and homogeneity of the population, θ = fuel cost per unit distance, d_{ij} = distance from i to j, and d_{ip} = distance from i to port.