30 • Fisheries : models of learning and uncertainty

PETER M. ALLEN
International Ecotechnology Research Centre, Cranfield Institute of Technology. Bedford, MK43 OAL, England

ABSTRACT

This paper focuses on the problems of the sustainable exploitation of marine ecosystems by man. In particular it presents new models of the evolutionary process which show how the dialogue between diversity creating mechanisms (sexual reproduction, ignorance and entropic processes in general) and the competitive constrainsts of the material world generates ecological structures. These represent a new domain of organization, beyond the mechanical, where the identities and behaviours of the populations are mutually interdependent, the system has many possible responses to perturbations and in which sustainability is related to the capacity to change, adapt and maintain diverse and varied strategies. For the practical implementation of these ideas a dynamic spatial fishery model has been developed which can be used as the basis for fisheries policy and management.

RÉSUMÉ

Cet article se penche sur les problèmes soulevés par une exploitation soutenue des écosystèmes marins par l'homme. Il présente en particulier de nouveaux modèles sur le processus évolutif qui montre comment le dialogue entre les mécanismes de création de la diversité (reproduction sexuelle, ignorance et processus concernant l'entropie de manière générale) et les contraintes compétitives du monde matériel génère des structures écologiques. Ceci représente, au-delà d'une approche mécaniste, un nouveau domaine d'organisation où les identités et les comportements des populations sont mutuellement dépendants; le système peut répondre de multiples façons à des perturbations et son caractère durable est relié à la faculté de changement, d'adaptation et de maintien de stratégies diverses et variées. Afin de mettre en pratique ces idées, un modèle dynamique spatial des pêcheries a été développé qui peut être utilisé comme base pour une politique de gestion des pêcheries.

INTRODUCTION

This is a contribution to a collection of papers which concern the exploitation of fish stocks off West Africa. However, the point of view and methodology discussed here will, hopefully, be of quite general utility. The problem of fishing off the West African coast, and sustaining the food or hard currency supplies of the on-shore populations is a geographically particular example of a the human condition in general. What we shall address here, therefore, are the generic issues that it raises: harvesting of species within an ecology, increased exploitation and sustainability, dynamic instability, the evolution of technology, of societies and of the exploited ecosystem.

The real issues concern the sustainable place of man in nature, and nature's response to our actions. This paper focuses on the need for us to accept, and deal with the real uncertainties of existence and to move our thinking beyond the narrow view which relies simply on the promotion of profit maximization of fleets through the action of competitive forces in a market which is as free as possible, and of a «technological fix» for any problems that may arise. We have to accept that it is the over-reliance on technology and simple economics today that threatens us. In order to see how this can possibly be, we need to reflect a little on the nature of both of these.

TECHNOLOGY AND ECOTECHNOLOGY

Technology is the application of science to «solve» a problem. Traditionally the scientific approach has been one in which complex situations resulting from some long evolutionary process are viewed with a willful «myopia». Through this self-imposed mental «magnifying glass» the system is seen as a series of separate problems or decision areas, requiring for example faster, stronger or cheaper technical solutions. If any part of the system being considered should still seem complex, then the power of the magnification is simply turned up until it reduces to a series of simple mechanisms. This is what is meant by reductionism, and despite the many authors who have tried to dethrone it, it is still very much with us.

An example of such reductionism is the management of fish stocks as single species, ignoring the obvious fact of their interaction with other populations, and with all the factors of their ecosystem. Another related example is when all the complexity of fishermen's behaviour, is looked upon as an «applied fishing effort» - F - an exogenous parameter which «management» is supposed to set or control. Such a simplistic approach would be laughable, were it not so serious.

Of course, such dramatic simplification is quite understandable in the initial phases of study of a complex problem, but this approach has now been with us for several decades, has become entrenched in both the thinking and in the «job descriptions» of fishery scientists, and also has become the system by which it is proposed that all fisheries should be managed.

In summary, the myopic vision of reductionism, which finds its classic expression in decentralised «profit optimizing» behaviour of a «free market», combines technological advance with short term economic calculations, losing entirely from view the system as a whole, and pushing the «costs» of any decision to «improve», outside the boundary of what has been given a price.

What we may call «environmental» problems are an immediate consequence of such an approach, and indeed of any narrow rationality. The basic reason is simple - there is no such thing as the environment. All there is are nested, dynamic, spatio-temporal structures resulting from a continuing evolutionary process. Decisions almost always have consequences which go beyond either the time frame or the situation boundary initially considered by the decision maker.

Separate fishing boats or fleets responding only to their own experience see that increasing their own efforts or technology gives them higher profits. But of course, when they all do it, the effects on fish stocks may be such that catches and profits fall, and very high technology is required just to scrape a living. The very latest trawling or gill netting technology may really be like a herd of goats in an arid landscape. Once you have crashed your system, then nothing can compete with them for survival, but of course their very presence may be the factor which stops the system from ever recovering.

Our present way of making and managing changes guarantees that we shall eventually crash the larger system, and therefore it is imperative that we should find a new approach to our exploitation of both the natural environment, and of ourselves.

Ecotechnology is that new approach. It looks at problems within their wider context, and considers both the effects of change within the narrow system, and also of the response that this will provoke from its surroundings. This new ecotechnological approach requires that we first understand how a system has become what it is, and what maintains or threatens its present condition. Then, with this knowledge, we attempt to estimate the complex response of the system as a whole to different possible actions or policies. From this an image of the longer term, system wide consequences of our possible actions can be obtained, providing a basis for wiser decision making. The proper basis for ecotechnology is therefore a better understanding of evolution. What is it? Where does it come from? And how could we anticipate, guide, encourage or avoid it? Are humans inside or outside its realm ?

EVOLUTIONARY DRIVE

Evolution is about qualitative, structural change. If we are to understand it, then this is its key aspect. It concerns not merely the changing numbers of the initial variables, but the fact that new structures, and states of organization can emerge. Not only does this happen, but in fact it is always in the process of happening. This is because evolution leads to systems which possess the ability to evolve, and the capacity to adapt and change in response to the uncertainties of the real world. This ability resides ultimately in the internal diversity and variability of populations.

Today, we understand that the present was not inevitable, but has been created by its history, a history that is marked by creativity and the emergence of new forms and functionalities. In this light, human survival (or extinction) is related to an ability to cope with uncertainty and change. Instead of trying to manage «equilibria» which are a product of our own particular mythology, we must try to manage unstable, and unpredictable resources.

The basis of scientific understanding has traditionally been the mechanical model (Prigogine and Stengers, 1987; Allen, 1988)). In this view, the behaviour of a system can be understood, and anticipated, by classifying and identifying its components and the causal links, or mechanisms, that act between them. In physical systems, the fundamental laws of nature govern these mechanisms, and determine what must happen.

In isolated or closed systems these restrictions place such limits on the behaviour of the system that we can in fact predict the properties of the final state, thermodynamic equilibrium, quite generally for almost any system, however complex. This was such a triumph for classical science, that it was believed (erroneously) that analogous ideas must apply in the domains of biology, ecology, the human sciences, and particularly of course, economics (Arrow and Debreu, 1954; Debreu, 1959)

But such ideas were misguided. In fact systems encountered in ecology and economics are always evolving and are not at equilibrium. Biological, ecological or human systems are discussed in terms of the typical behaviour of typical elements, or stereotypes, that make up the classification scheme that we have decided to apply. Underneath any such model, however, there will always be the greater particularity and diversity of reality.

In the classical scientific view, the future of a system is predicted by the simple expedient of considering the behaviour of the equations which govern its motion. But while it is easy to write down the equations of mechanics for imaginary point particles, when considering a complex system, it is necessary to make certain approximations in order to arrive at mechanical equations which are supposed to govern its motion. In order to take this step, the assumption that must be made is that the elements making up the variables (individuals within a population, firms in a sector etc.) are all identically that of the average type. In which case, the model reduces to a "machine" which represents the system in terms of a set of differential (perhaps non-linear) equations which govern its variables. And this is the Newtonian vision of the world as a vast and complex clockwork mechanism.

In this view, predictions are made by simply running the model forward in time, and statements about the future, under given conditions, can be made by studying the types of solution that are possible for the equations in the long term. Scientific explanation of this kind is based on the internal functioning of the system. The equilibrium solution of the differential equations are viewed as expressing some maximum or minimum of some potential function, just as in physics, the dissipative forces of friction and viscosity work to lead any mechanical system to a thermodynamic equilibrium expressing maximum entropy.

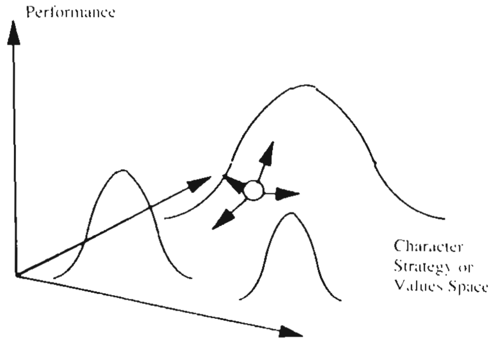
But this is completely false for complex systems.

Even in physical systems, if they are open to flows of energy and matter, there is no longer a unique final state expressing some "optimal" principle. The external experimental conditions no longer suffice to determine a unique future, as such systems can structure in a variety of ways depending on the internal details of their constituent components - details which cannot be controlled from the outside of the system. In other words, there is a single, predictable outcome to experiments on isolated systems - thermodynamic equilibrium, but not for open systems where matter and/or energy can flow through the system (Nicolis and Prigogine, 1977). This changes profoundly both our notion of "explanation", and of scientific understanding. When non-linear mechanisms are present, the system may continue to change indefinitely - either executing a cyclic path of some kind, or possibly even a chaotic movement around a "strange attractor". More importantly, its evolution may involve structural changes of spatial and hierarchical organization, in which qualitatively different characteristics emerge. New problems, satisfactions and issues can be "turned on" spontaneously by the system.

This capacity for structural change is not contained in the dynamical equations. They are capable of functioning but not of evolving. Evolutionary change must result from what has been "removed" in the reduction to the deterministic description that is the non-average. The system is therefore driven by two kinds of terms: deterministic average mechanisms operating between typical components, and non-average local behaviour that in non-linear systems can be amplified and lead to qualitative structural changes in the average mechanisms (fig.1).

Fig. 1

For a single population there exists a kind of «adaptive landscape» of possible advantage, in some character or strategy space.



In some recent papers (Allen and Mc Glade, 1987;1989)) mathematical simulations have been made of this new evolutionary dialogue between "average" processes and "non-average" detail. This has led to the new concept of evolutionary drive. Evolution was shown to select for populations with the ability to learn, rather than for populations with optimal behaviour, a result similar to the «Red Queen Hypothesis» (Van Valen, 1973). This corresponds to the selection of "diversity creating" mechanisms in the behaviour of populations, initially involving genetics, and later cognitive processes. These experiments show that this mixture of exploratory diffusion of individuals in some behaviour space, and their differential successes, makes the difference between what is «organic» and what is merely «mechanical». There is a process of simultaneous «stretching» and «squeezing» of populations in the space of possible behaviours that is the core of our new understanding (fig. 2). This view, of course, bears a striking ressemblance to the ideas of Yin and Yang, and of «dialectics», but in our case we not only have a vision of such a process, we also have mathematical equations which can represent it.

In further computer experiments, it was found that if some characteristic or strategy could exist which would result in self-reinforcement, then once it emerged it could trap the population and block evolution at least for some time (fig. 3). An example of this from biology is the Peacock s tail', where a gene produces the beautiful tail in the male, and makes such a tail attractive to the female. In sexual reproduction, anything which enhances the probability of mating produces a positive feedback on its own population dynamics, and fixes itself. However, it is at the expense of functionality with respect to the external environment. Peacock's tails are not an aid to finding its food better, or escaping predators, but only a characteristic marker of a positive feedback trap.

In human systems, such positive feedback systems abound. Much of culture may well be behaviour which is fixed in this way. In most situations imitative strategies cannot be eliminated by the evolutionary process, and so fashions, styles and indeed cultures rise and decline without necessarily expressing any clear functional advantages. Indeed, "culture" could be viewed not so much as being «the best» way of doing things somewhere, but perhaps as resulting from ignorance of other ways of doing things. Human activities in general, from fishery science to patagonian folk dance, exhibit these properties of autocatalytic, self organization, where ritual and shared ideology emerge and serve as the identity and focus of a social group, irrespective of the precise merits or truth of the ideology itself. So much of human attention is focussed on playing a role in groups where values are generated internally, and the physical world outside is largely irrelevant.

The work above has been further extended to show how "adaptive landscapes" are really generated by the mutual interaction of populations. In the space of «possibilities» closely similar populations are most in competition

Fig. 2

Evolution corresponds to the simultaneous «stretching» and «squeezing» of populations that we show here.

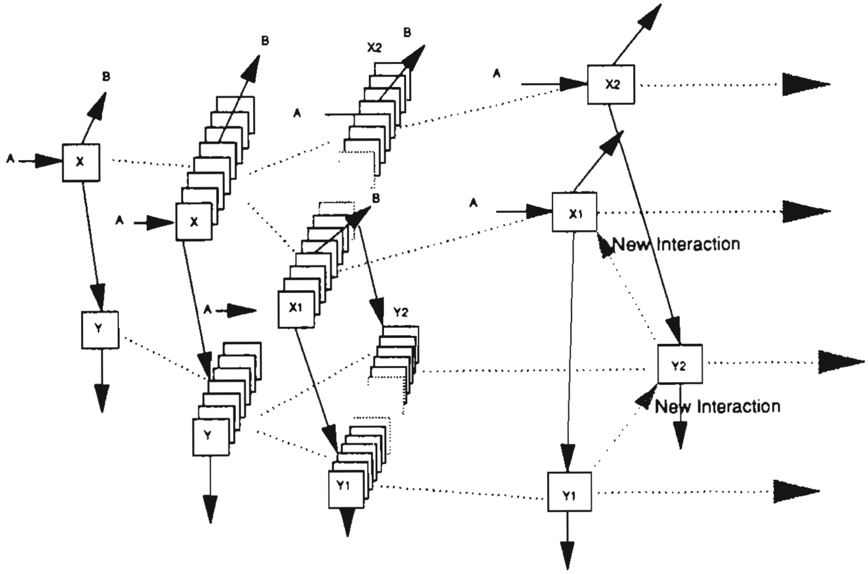
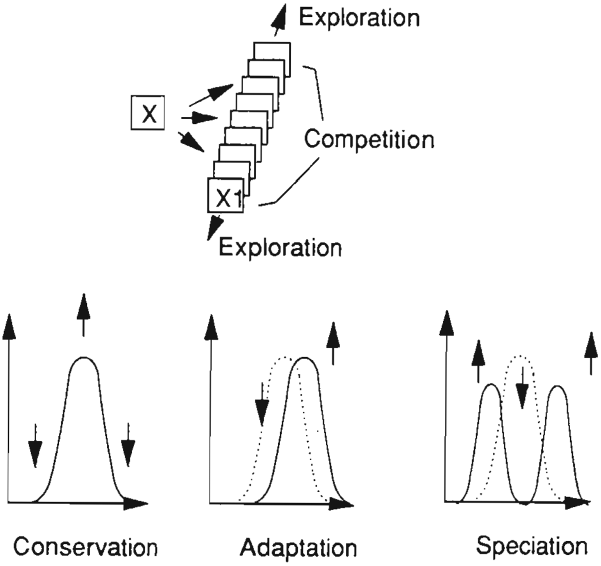


Fig. 3
The explicit presence of «stretching» and «squeezing» generates a latent adaptability.



with each other, since they feed off the same resources, and suffer from the same predators, but there is some «distance» in character space, some level of dissimilarity, at which two populations do not compete with each other.

Initially, a population grows until it reaches the limits set by the competition for underlying resources. At this point, there is a positive pay-off for error makers, who escape somewhat from competition. We could say that although initially there was no «hill» to climb, the population effectively digs a valley for itself, until there is a «hill» to climb on either side of the present character «centroid». However, over some distance in this space the population growth is restricted because of the «competitive shadow» of the original population, and so they diffuse in small numbers up the slope away from the original type. After a certain time, however, small populations arise which are sufficiently different from the original type that they can grow and multiply on the basis of some other resource (fig. 4).

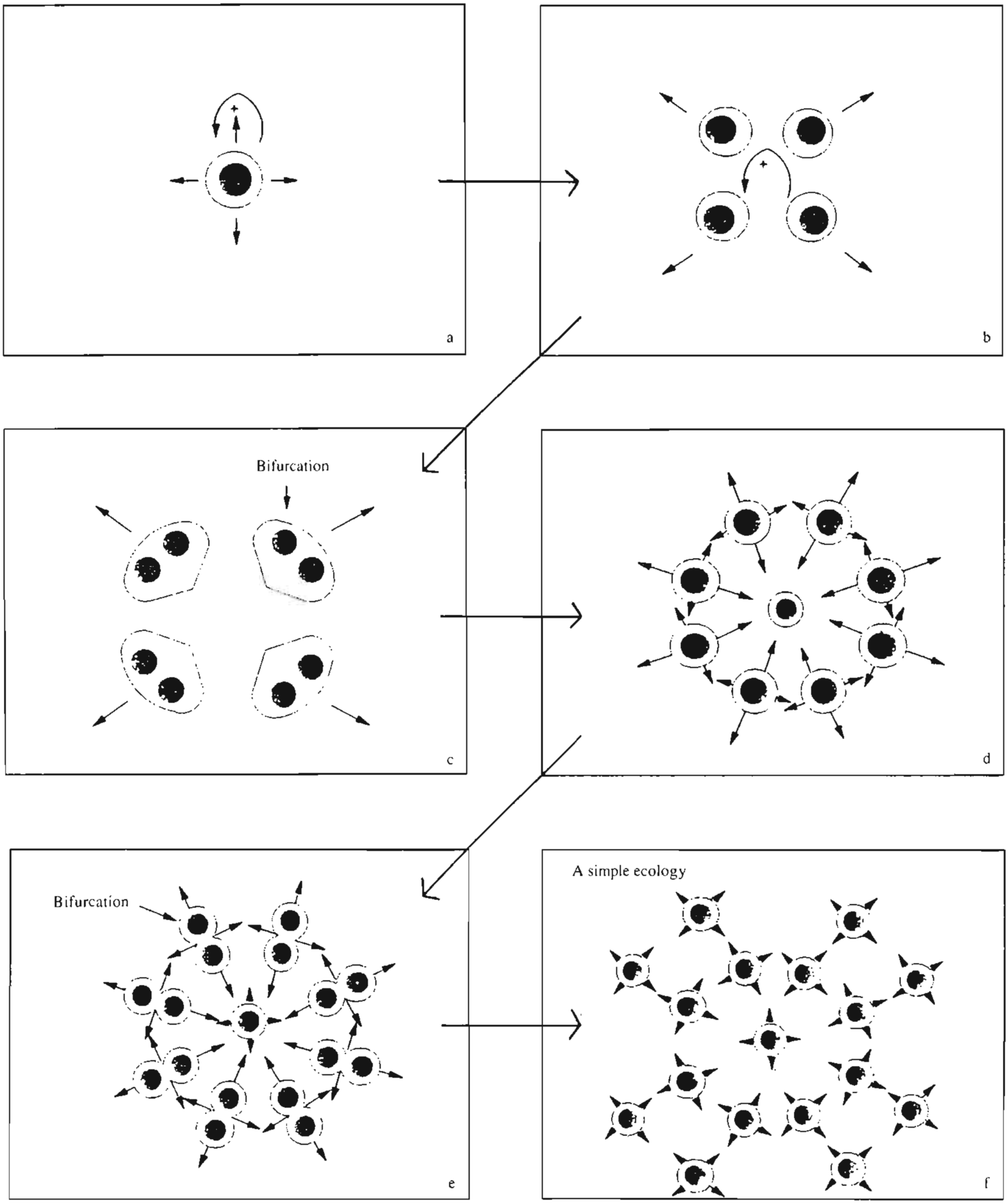
In its turn, this new population increases until it too is limited by internal competition for the limiting resource, and once again there is a pay-off for deviants, particularly for those on the outside of the distribution, as they climb another self-made hill towards unpopulated regions of character space. In this way, well defined populations appear successively, and colonists diffuse out from each of them as they reach a competitive limit, gradually filling character space with a set of populations separated approximately by some distance which is characteristic of the resource diversity which can be tapped.

From a single population our model generates a simple ecology (fig. 4), and a dynamic one since the identity of each population is maintained by the balance between a continual diffusion of deviants outwards into character space, and the differential reproduction and survival that is due to the presence of the other populations. Random events which occur during the "filling" process will affect which populations arise, and so it is not true that the evolution represents the discovery of pre-existing "niches".

Such a system operates beyond the mechanical paradigm, because its response to external interventions can involve changes in structure and of the «identity» of the populations in the system. Harvesting particular populations in such a system, as in fishing for example, will provoke a complex response from the other populations. The identity of each species depends on that of the others, and on the accidents of its particular history. Removing, or severely depleting one or several populations, will therefore set in motion a series of responses, and changes in behaviour of other species which may look very like (and indeed be) a form of learning. Deviant behaviour which hitherto encountered a negative pay-off may instead be reinforced, and in addition the responses may be essentially unpredictable.

Fig. 4

In character space, it is the interaction of populations themselves that creates and constantly changes the «adaptive landscape».



Indeed, events like this may be occuring constantly in the ecosystem, owing to environmental fluctuations of all kinds, and what we need to realize is that we are trying to fish a vast and complex learning system, constantly adapting and responding to all kinds of perturbations, and in the process, itself causing changes in local environments and conditions. Instead of managing equilibria we must manage change.

MODELS OF COMPLEXITY: THE SCOTIAN SHELF FISHERIES

If the preceding sections have helped to clarify why scientific theories about living systems had failed, we need to turn now to the problem of showing that the ideas discussed above can actually help us in a practical way. In order to do this, one of the problems that has been addressed is that of the management of a particular fishery the Scotian Shelf Groundfish fisheries of the' Canadian Atlantic coast.

Work was begun in 1985 on building an integrated dynamic model, which would help clarify the issue of sustainability, of potential fleet sizes and technology, and also of management methods. These have been described elsewhere (Mc Glade and Allen, 1985; Allen and Mc Glade, 1986; 1987a)) in some detail, and so we shall only deal very briefly with the model equations. However, here we shall describe the software that was prepared for this application.

Two models were developed. The first was a very simple non-spatial, single species model of the Haddock fisheries of the Scotian Shelf. The interaction diagram is shown in figure 5.

The Single Species Non-Spatial Model

The equations used on the software disk were more complicated than those reported in the previous literature and are given in Appendix 1.

The complex behaviour of these equations have been presented already, but the software package developed for use by management has not. First a parameter changing page appears, so that other data could perfectly well be inserted. Instead of the biological parameters of haddock, otherspecies could be inserted. Similarly, the fleet characteristics could be modified to correspond to the gear technology, speed and hold size of fleets as varied as hand rowed pirogues to deep sea, ocean going industrial trawlers.

When the program is run questions concerning the management strategy to be explored appear on the screen. For example, the imposition of fishing quotas, of licence limitation by fleets and of closure of the fishery can be explored. Effects such as the delay between a stock estimate and the application of a TAC can be tested, as they may be of 2 or 3 years.

As an example of the kind of simulation that is possible, in figure 6 we see two 40 year runs which compare the effects of having no controls, and with quotas imposed corresponding to maximum sustainable yield.

Other policies can be compared to these by using the samè random seed so as to give rise to the same sequence of recruitment fluctuations. Clearly, however, the simulation shown in figure 6 must not be considered as a prediction, since a different sequence of random disturbances leads to a different set of results for our 40 year run.

In fact, if the program is run without management for a variety of "seeds", a wide spectrum of results are possible. The average of these can be calculated, and in fact corresponds roughly to the values obtained for the 40 year run shown in figure 6. However, certain stochastic sequences give very different results. The upper extreme gives fleets and stocks about twice that of average, with 3 times the catch, and the lower extreme giving about half average.

A clear idea of the "average" of these dynamics can be obtained by running the model for 1000 years. This merely allows a good exploration of the effects of the environmental noise, and hence gives a good estimate of the average result, but is little help for really making policy for the next 5 or 10 years say.

This simple program can be used for testing the probable effects of other policies, such as fixing prices, subsidising fishermen, restricting technology etc. and for getting a good idea of what kind of effect these policies may have. Similarly, it could equally well be recalibrated for other fisheries such as those of West Africa, and used to explore the policy issues there.

The Multispecies, Multifleet Spatial Model

This more complex model describing the complex behaviour of boat movements, information flows between fleets, and the spatial dynamics of the different fish stocks. The connection with the discussion about evolutionary systems becomes much clearer here. The model has already been described in some detail and so we shall not repeat the details here. The main components are:

- an equation for the stock of each species in each spatial zone. It contains ecological interactions, biological parameters of the species, and the fishing mortalities caused by the different fleets and gear types fishing in the zone;
- an equation for the change in fleet size as a result of profitability, and also the fleet movements between zones based on imperfect information about relative profitabilities, home ports, hold sizes, etc;
- a price equation per fish species based on the imbalance between supply and demand.

One of the important ideas that arose from this model was that successful fishing was impossible over the longer term, if short term behaviour was optimal. In other words, fleets which behaved too rationally, «cartesians», were not successful, and boats with some non-rational strategy, «stochasts», were required in order to generate new information. Fishing, like the rest of life, has too opposing requirements: efficient behaviour and the need to make discoveries.

Let us describe the different options that the program

Fig. 5

The interactions of the single species non-spatial model.

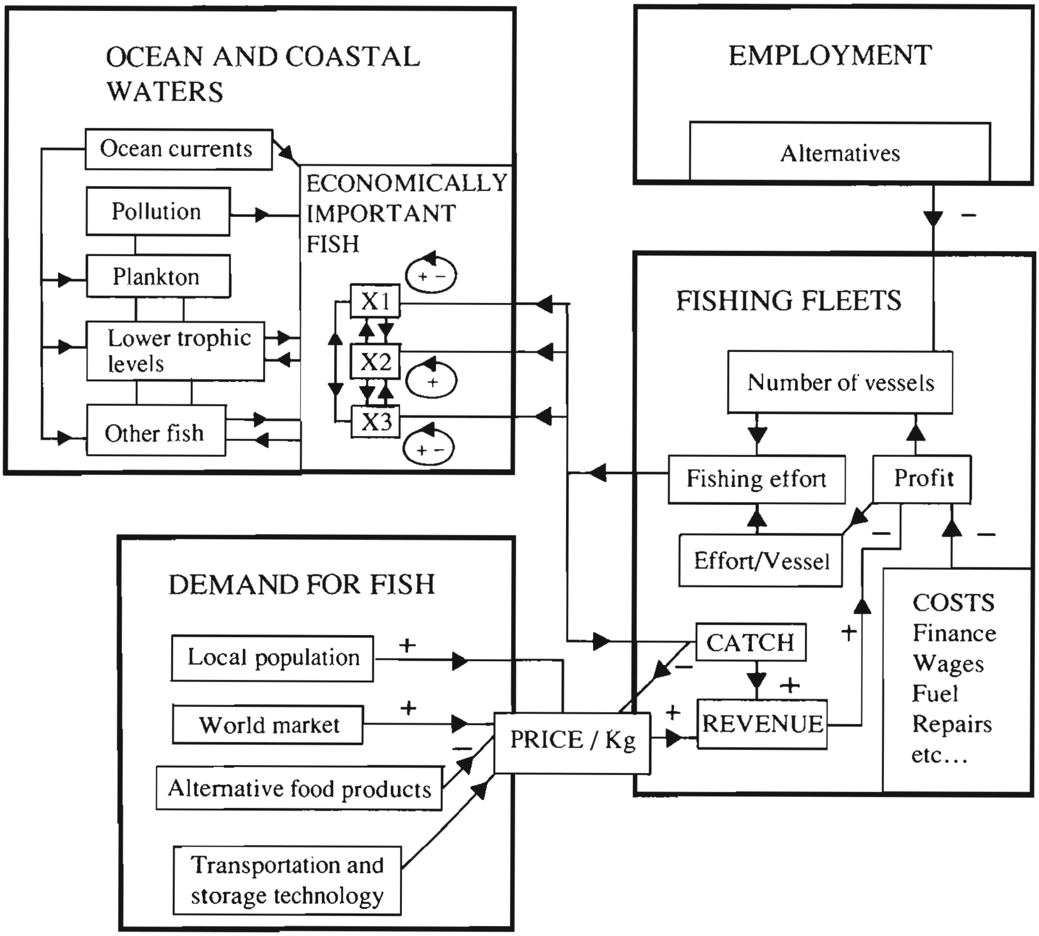
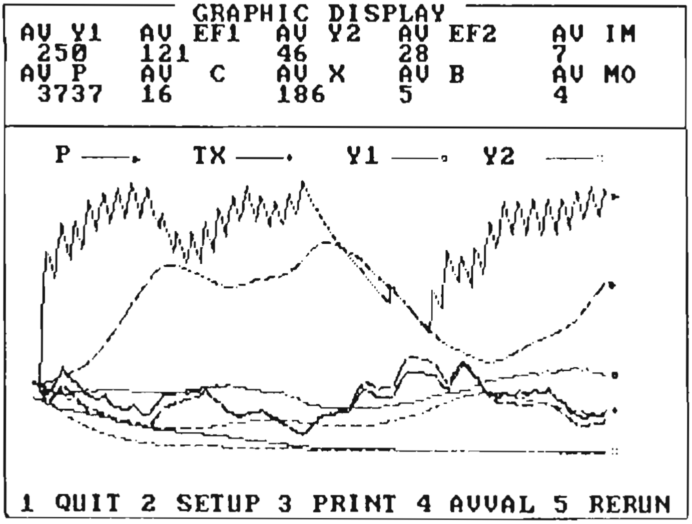


Fig. 6

TAC quotas lead to price rises that put the system in a state of chronic management. Consumers subsidise (in prices) a larger fishing industry, although the boats are tied up for 4 months a year.



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               GRAPHIC DISPLAY
AV Y1    AV EF1    AV Y2    AV EF2     AV IM
 250     121       46       28         7
AV P     AV  C     AV X     AV B       AV MO
 3737    16        186      5          4
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offers. Selecting the first option allows a choice of the number of fish species, of the number of fleets, as well as the frequency and detail of numerical and graphic printouts. For each selection, the position of the cursor brings up a line of explanation concerning the parameter in question, as well as limits to its value. For the Random seed, 0 corresponds to no fluctuations in recruitment of the fish, while numbers between 0 and 1 give rise to particular sequences of fluctuations.

The second option allows the biological parameters of the fish stocks to be inserted, or modified, as well as some ecological information concerning the niche-overlap of the species with the others. In addition, the catchability of a species with respect to a particular fleet gear type can be set. By moving the cursor around, changes in biological parameters catchabilities and initial unit price can be made.

The third option allows the different parameters which characterize a fleet to be adjusted. For example, parameters can be set concerning the rate of response of fleet fishing capacity to profit and loss, and also the different fixed and variable costs that characterize the boats. One important point is that while the "cost/unit dist" used in the equations is a real cost, as experienced in fact by the boats, there are also other costs (Interzone, returning to port) which depend on the "estimates" that skippers make of these. Clearly, the spatial strategy actually executed not only depends on reality but on the perceptions and beliefs fishermen have about it. It is interesting therefore to be able to explore the effects of different cognitive maps on the fishery.

Mobility concerns how fast the "migration" between fishing zones can occur, which may be limited by both physical and cognitive factors. Speed, however, is simply related to the speed of the boat and how long it takes to get a full hold of fish back to port, and to turn the boat around. The "home port" locates the place of landings of the fleet and is the focus for the "distance to port" calculations. The model also allows for a variable degree of randomness in the fleet movement.

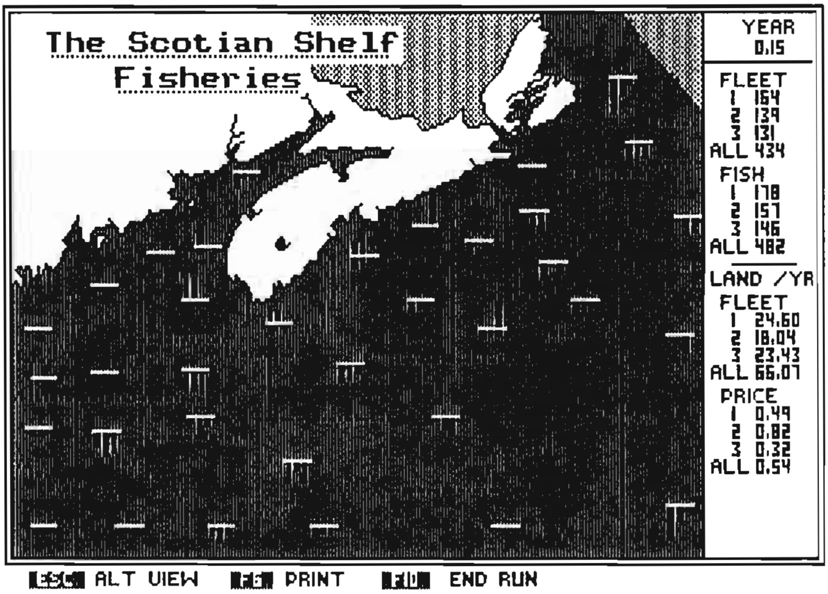
Another important term which was discussed a great deal in the earlier publications concerns the "rationality" of the boats in a particular fleet. This could either be an average value expressing perhaps the strategy of the fleet owners, or it could be broken down into the different strategies of constituent groups. The "rationality" parameter corresponds to two factors:

- the degree of unanimity of "response" of the fleet (i.e. its homogeneity);
- the actual weight each member attaches to the information he is receiving concerning "expected revenues" in other zones.

This is an important parameter - and realistic movement seems to correspond to values between 3 and 8 (for Cartesians) and .75 to 3 for Stochasts.

Using the fourth option, the amount of each type of fish, and of each fleet present in a zone can be changed. The "fish" are given in thousands of tons. Also, we can change the "carrying capacity" of the zone, which sets a limit to the total fish population that it can support.

Fig. 7
The graphical output of our dynamic, spatial fishing model.



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YEAR
 0.15
FLEET
 1  164
 2  139
 3  131
ALL 434
FISH
 1  178
 2  157
 3  146
ALL 482
LAND /YR
FLEET
 1  24.60
 2  18.04
 3  23.43
ALL 66.07
PRICE
 1  0.49
 2  0.82
 3  0.32
ALL 0.54
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This maximum population will depend on the degree of niche overlap that has been put into the model, and clearly, if this is total then the carry capacity is the limit on total population. If there is no overlap then each population could attain the carrying capacity separately.

At any time, the simulation can be interupted and the parameters of the species, fleets or spatial zones can be modified and the simulation continued. In this way, the effects of increasing fishing effort, pollution accidents, changing marine environment, improved fishing gear, greater/lesser, fixed/variable costs etc. can be explored.

Various management options for the simulation can be set, and the complex response of the fishermen and of the ecosystem can be studied. Two basic strategies of management can be applied. Either fishing quotas can be set, or limits can be imposed on fleet size through licenses.

The model described here has parameter values corresponding to those of cod, haddock and pollock, being fished by fleets of trawlers and longliners - which have the costs, mobility and fishing power based on the real data taken from the 1984 overcapacity study carried out by Fisheries and Ocean, Canada.

A typical black and white rendering of a colour screen is shown in figure 7. As the simulation proceeds, the longliners are gradually eliminated by the trawlers, as the process of locating and exploiting successive fish aggregates continues. Between about 5 and 12 years fleet landings fall to a very low value (20ktons) but they recover after that. After 20 years the fishery is as healthy as it was initially, except that the Longliners have been eliminated.

The program can be used to study the effects of different fleet strategies, and of cooperation, information sharing, or of pure competition.

Fleets of "cartesian" trawlers, with a rationality of 5, can be ranged against fleets of «stochasts», and information exchange can be allowed or disallowed. Composite fleets made of «cartesian» troops and «stochastic» scouts can be run against each other, and successful strategies revealed.

If the ESC button is pressed during a simulation, a second screen appears showing the aggregate values of fish stocks, fleet numbers and catch. It is interesting to note that this tells us that catch and stock size are not simply proportional, but instead obey a complex relationship reflecting the state of knowledge and communication among fishermen. Pressing ESC again brings back the map.

The program allows, using the input/output option, previously stored files containing parameter/initial condition sets to be loaded, and also for saving existing situations and parameter values.

The essential point that emerged form the fishing model was that success in fishing, as in life, requires two almost contradictory facets of behaviour. First, the ability to organize one's behaviour so as to exploit the information available concerning "net benefits" (to be rational) which we have called "Cartesian" behaviour. More surprisingly, however, a second ability is required, that is to be able to ignore present information and to "explore" beyond present knowledge. We have called these kinds of fishermen "Stochasts". The first makes good use of information, but the second generates it! At the root of creativity is always this second type.

In the short term it is always true that the more "rational" actor must outperform the less, and therefore that for example taking steps to maximise present profits must, by that yardstick, be better than not doing so. Nevertheless, over a longer period the best performance will not come from the most rational but instead from behaviour which is some complex compromise.

For example, a fleet of Cartesians which goes where available information indicates highest profits will in fact lock into zones for much too long, remaining in ignorance of the existence of other, more profitable zones simply because there is no information available concerning "other zones": "You don't know what it is you don't know".

New information can only come from boats which have "chosen" not to fish in the "best" zones, or who do not share the concensus values, technology or behaviour, and hence who generate information. They behave like risk takers, but may or may not see themselves as such. They may act as they do through ignorance, or through a belief in some myth or legend. Whatever the reason, or lack of it, they are vital to the success of the fishing endeavour as a whole. It is their exploration that probes the value of the existing pattern of fishing effort, and lays the foundations for a new one.

As information is generated concerning the existence of new, rich fishing grounds, so the value of this starts to fall as the news spreads, and exploitation rates increase there. We see a cyclic pattern in the discovery of value in a zone, the spread of information and with it the saturation or exhaustion of the discovery, calling for fresh explorations (Allen and Mc Glade, 1987b). The model can be used either as an overall management tool, linking ecosystem, fleet technology and behaviour, and the market, or for the benefit of any particular fleet wishing to improve its performance.

LEARNING HOW TO FISH

The approach described above can in fact be completely inverted. Instead of supposing that we know, from observation, the parameters which characterize the fishing strategies of different fleets, we can use the model to discover robust fishing strategies for us.

To do this, we can run many fleets simultaneously (our current software will run up to 8) from identical initial conditions. The fleets differ, however, in the values of the parameters governing their fishing strategy, and whether or not they spy on, and copy some other fleets. A slightly modified version of the model will reinforce the more effective strategies, and gradually eliminate the others, and by including a stochastic change in strategies for losing fleets, our model will gradually evolve sets of compatible behaviours. Each of these will be effective in the context of the others, not objectively optimal. In addition, such a system can adapt to changed external circumstances, and could be used to show us "robust heuristics" for the exploitation of renewable natural resource. This is clearly similar in aim to the work on "learning algorithms"(Holland, 1986; Miller, 1988)).

The software which we have developed has several potential areas of application. The first is certainly in understanding and teaching how complex systems involving humans really operate. The pattern of fishing effort at any time cannot be "explained" as being optimal in any way, but instead is just one particular moment in an unending, imperfect learning process involving the ocean, the natural ecosystem and the fishermen.

Many interesting ideas can be explored using the model, by for example, comparing the evolution of two fleets which are identical in all but one respect. In this way strategies can be studied, and the real complexity of the system glimpsed, as the mutual interdependence of human behaviour is made clear. The model is instructive on many levels, revealing the weakness of our oversimplistic intuitions concerning what is good and what is bad, and how to intervene in a complex, evolving system.

In practical terms, the software is proposed as a prototype version showing for the Scotian Shelf fisheries, what could be developed more generally for any others. It provides the basis for a policy exploration tool which allows the consequences of different regulations on policy options to be estimated, taking into account the response both of the human participants of the system as well as of the ecological environment.

In this way, the further, practical extensions of the work developed here will provide a real improvement in the management of fisheries, and in maintaining and improving their sustainable long term exploitation.

DISCUSSION

Instead of viewing evolutionary dynamics as the progress of a population up a given (if complex) landscape, our models show how the landscape itself is produced by the populations in interaction, and how the detailed history of the exploration process itself affects the outcome. Paradoxically, uncertainty is therefore inevitable, and we must face up to this.

Long term success is not just about the solving of optimization problems, but also about the optimization problems posed to the other parts of the system. An ecology consists of selfconsistant "sets" of populations, both posing and solving the problems and opportunities of their mutual existence.

Innovation occurs because of non average individuals and initiatives, and whenever this leads to an exploration into an area where positive feedback outweighs negative, then growth will occur. We assign "value" afterwards. It is only when we wish to rationalize what we see that we insist that there was some pre-existing "niche" which was revealed by the supply. The future, then, is not contained in the shape of the hills, since they are fashioned by the explorations of climbers.

Does this mean that there is no overall effect of evolution? Is no function (thermodynamic?) maximised or minimised by it, which would characterize climax ecosystems and mature societies? Indeed, do «climax» ecosystems and «mature» societies really exist or is evolution actually continuing under an apparently stable envelope?

The answer suggested by our work is that stability is a mask that hides evolutionary potential. Only if deviant behaviour is constantly suppressed by selection do the existing structure and organization appear to be stable. But, in fact, there is a pool of hidden adaptability in the system, which allows the ecosystem to adjust and restructure in an organic and non-mechanical way. Sustainability is linked to these properties of hidden adaptability rather than to the attainment of some stationary, stable optimal. Evolution gives rise to a nested hierarchy of spatio-temporal structures, from microbes to Gaia, which continue to evolve.

In human systems, at the microscopic level, decisions reflect the different expectations of individuals, based on their past experience. The interaction of these decisions actually creates the future, and in so doing fails to fulfill the expectations of many of the actors. This may either lead them to modify their (mis) understanding of the world, or, alternatively simply leave them perplexed. Evolution in human systems is therefore a continual, imperfect learning process, spurred by the difference between expectation and experience, but rarely providing enough information for acomplete understanding. It is this very "ignorance", or multiple misunderstanding, that allows exploration, and hence learning. In turn the changes in behaviour that are the external sign of that "learning" induce fresh uncertainties in the behaviour of the system, and therefore new ignorances. This offers a much more realistic picture of the complex game that is being played in the world, and one which our models can begin to quantify and explore.

Instead of the classical view of science eliminating uncertainty, the new scientific paradigm reveals a world of inevitable uncertainty. But, rather than viewing this with dismay, our new understanding of evolutionary processes tells us that this is quite natural and normal. Evolution is not necessarily progress and the future is not preordained, it is created from our differing beliefs about it. This is why it will always be full of surprises, and in this situation the first step towards wisdom is the recognition that this is so, and the second is to develop and make use of mathematical models which capture this truth.

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APPENDIX 1

The fish equations are:

$$dx_1/dt = bx_3*(1 - B/C.C.) - m_1*x_1 - x_1/\tau - x_1*s_{1i}*e_i*y_i /(1+s_{1i}tau_iB)$$

$$dx_2/dt = x_1/\tau - x_2/\tau - m_2*x_2 - x_2*s_{2i}*e_i*y_i/(1+s_{2i}tau_iB)$$

$$dx_3/dt = x_2/\tau - m_3*x_3 - x_3*s_{3i}*e_i*y_i /(1+s_{3i}tau_iB)$$

where:
x_j (j= 1,2,3) are the 3 age cohorts of the haddock stock - 0 to 2yrs; 2 to4 yrs and 5+ yrs.
τ = time of cohort span
B = total haddock biomass
C.C. = total haddock «carrying capacity», which was put equal to the largest amount ever observed.
m_j (j=1,2,3) = the mortality rate for each age class.
s_{ji} = intersection rate between haddock j and fleet i. (Catchability)
tau_i = the time for 1 boat to deal with 1 unit (1000 tons) of haddock.
e_i = effort per boat i. ($0< e_i <1$)

The equations governing the behaviour of the fishing fleets involved not only the numbers of boats fishing for haddock, but also the effort per boat. In fact, we know that if necessary, fishermen can and do double their effort, and therefore management that does not take this into consideration could misjudge the effective fishing effort by 100%.

The number of boats of fleet i is changed by the profitability of fishing.

$$dy_i/dt = r_i*y_i*(Rev_i/costs_i -1)$$

where:
y_i is the number of boats of fleet i fishing for haddock
r_i is a rate of response to profit or loss.
Rev_i = the fishing revenue of fleet i (catch rate for i * price/ton).
Catch rate for i = $s_{ji}*e_i*x_j/(1 + s_{ji}*tau_i*B)$
$Costs_i$ = the costs incurred by fleet i (fixed + variable).
Fixed costs are boat repayments, docking, insurance etc.
Variable, are crew, fuel, maintenance etc.

$$de_i/dt = eps_i*e_i*(costs_i/Rev_i -1) + eta_i*(.5 - e_i)$$

where eps_i and eta_i are rate parameters for i.

Revenue depends on the price of haddock, and this depends in turn on the balance of supply and demand.

$$dp/dt = al*p*(Demand/supply - 1)$$

where:
Demand = market at price p = $MA*(p/p_o +eps*(p/p_o)^4)^{el}$
MA = the initial market
p_o = the initial price
el = the elasticity of demand
eps is a parameter linked to the rate of fall of demand with price.
Supply = total catch rate for all fleets.