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Short term yield and effort impacts of a precautionary management strategy based on marine refugia. Simulations with SHADYS (Simulateur HAlieutique de DYnamiques Spatiales).

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Abstract:

By prohibiting fishing activities on delimited areas, or by creating fully protected marine parks, the use of protected areas (refugia, natural parks, ...) is getting more and more frequent. This paper attempts to show as simply as possible the short term effects of a protected area on fishing yield and on the distribution of fishing effort. For this purpose, different *scenarii* of spatial management have been explored using SHADYS simulator (Simulateur HAlieutique de DYnamiques Spatiales). Following a short presentation of SHADYS, some simulations are conducted, by varying the total area of the protected boxes.

Three characteristic simulated populations are submitted to a box protection management strategy : a resident population, a diffusive one and a migratory one. The distribution of fishing effort is studied in the case of a very deterministic spatial distribution (fishermen spatial is to search the highest level of catches).

It is shown that for diffusive or migratory species, the yield per recruit versus protected surface can reach a maximum. So, protected areas behave like « sources » and exploited areas like « sinks ». For resident populations, the larger the protected area is, the lower the catches per recruit are.

These results raise interesting questions about multispecific management : how to conciliate these different behaviours? Where to locate protected areas (which won't be the same for all species)? How large should they be (is it better to protect one large area or several smaller ones)?...

Regarding the spatial distribution of fishing effort, it is shown that if it is spatially distributed in order to maximise catches, then fishing boats will tend slowly to be distributed all along the boundaries of the protected area.

INTRODUCTION

As all interactions are spatial, the protection of space could be a way to limit interactions between human activities (including fishing) and ecosystems. The rapid development of conservation biology (based on new ecological theories like landscape ecology, biodiversity, ecosystems viability, evolutive biology, ...) prevails for new population and ecosystem management methods. Consequently, the use of protected areas (refugia, natural parks, ...) is one of the most common methods in ground environment management. In marine environment, this method is getting important, by prohibiting fishing activities on given areas or by creating fully protected marine parks.

Because it tries to limit human impacts on ecosystems without really knowing how to mesure them, the use of protected areas is a precautionary approach.
There are two kinds of effects (which are both targeted by precautionary management strategy) resulting from the creation of protected areas :
- short term changes of yield per recruit (Y/R), of stock-recruitment relationship or distribution of fishing effort ;
- long term effects : conservation of the specific and genetic biodiversity, population viability, protection of a genetic pool from anthropic selection, environment protection, ... (Dugan and Davis, 1992).
This paper attempts to show as simply as possible the short term effects of a protected area on fishing yield and on the distribution of fishing effort. In this aim, different *scenarii* of spatial management have been checked with SHADYS simulator (Simulateur HAlieutique de DYnamiques Spatiales). Following a short presentation of SHADYS, some simulations are conducted by varying the total area of protected boxes.

1. PRÉSENTATION OF THE SIMULATOR SHADYS

SHADYS is a spatialized fisheries simulator based on a GIS interface (Savane software ©ORSTOM, 1995). GIS is used in management and handling of spatial information. The modelled ecosystem is made up of subsystems whose dynamics are coupled together. In this way, SHADYS put together three fundamental entities in an explicit spatio-temporal manner :
➊ the environment which is mainly responsible of the spatio-temporal population structuration. From a statistical point of view, the environmental component statistical distribution is neither random (Poisson law) nor uniform. On the contrary, we can observe aggregative structures (patches) or continuous structures like gradients (Legendre *et al.*, 1989). This is what Kolosa *et al.* (1989) named the **structural heterogeneity.** Complex spatial structures result from the combination of various environmental factors exhibiting either a patchy or a gradient distribution. These complex spatial structures can be characterized by :

- the diversity of their various areas (diversity of their nature, of their size, ...),
- their fragmentation,
- their structuration,
- the connectivity of the zones.

SHADYS allows to vary the heterogeneity of artificial environmental landscapes drawn from marine benthic biotope. The landscape structure is generic enough to be transposed to other types of biotopes.
At each time step, a monotonous gradient moves through space with a sinusoïdal speed. It can be considered as a model of a seasonal variable such as temperature for instance. For convenience sake, we name it thermic gradient. Patches are distributed in space. They can, for instance, represent rocky zones spread over a muddy bottom. In SHADYS, patches distribution is either connective or not. The thermic gradient is fully connective.
Spatial structuration, distribution, diversity and fragmentation of patches can be varied according to discrete levels in SHADYS. A self-referencing process, analogous to a fractal surface development, is used to generate these heterogeneity levels and to make them vary with a single parameter. Then, patch distribution is randomly perturbed to avoid a too important symmetry (fig. 1).

At each point of space, what we name the « biotic affinity » of the environment (**functional heterogeneity**, local fitness as it is perceived by fish) is estimated from the structural landscape. The biotic affinity is represented as an altitude : the lower the altitude is, the stronger the biotic affinity is and the more favourable the place is (fig. 1).

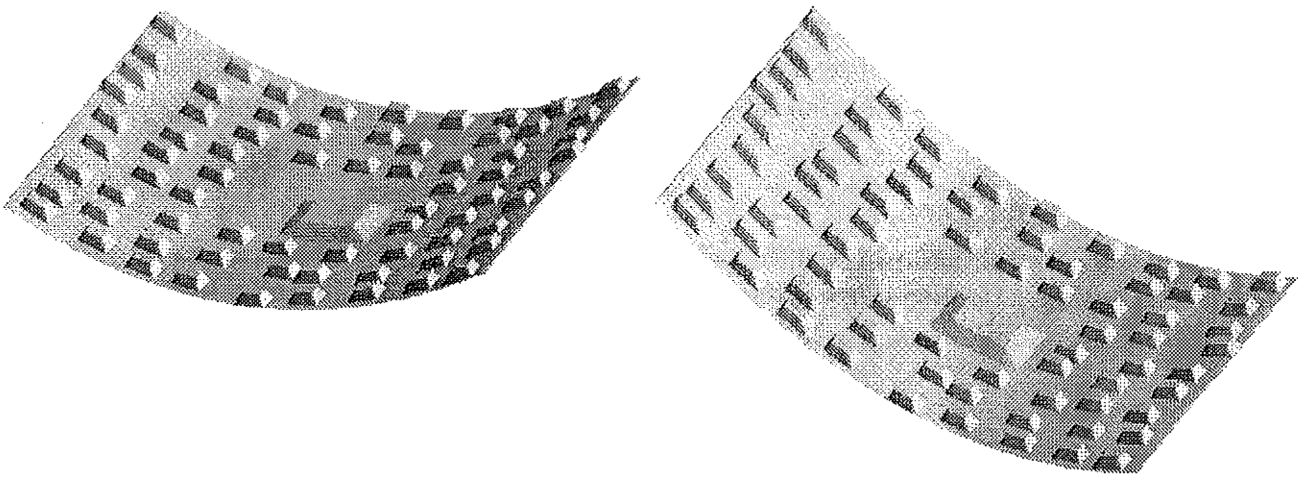

fig. 1 : A SHADYS output : the « vital landscape numerical model » (VLNM) which combines patch and gradient heterogeneity. The higher the altitude is, the more unfavourable the environment is : as a liquid, fishes flow to the valley's bottom of the VLNM. Their movement is determined by the information they locally have on the environment. The VLNM shown on the figure is connective (the population moves into a connective matrix). In a non-connective matrix, holes would have replaced bumps. On the left, VLNM for the first january, on the right, for the first april.

❷ An advection-diffusion-reaction model is used to represent the spatial dynamic of recruited stages. In such a model, movement has a random component (diffusion) and a directed one (advection). The model is based on a partial differential equation, continuous in time and space (Okubo, 1980 ; Sibert and Fournier, 1994) :

$$(1) \qquad \frac{\partial N}{\partial t} = \frac{\partial\left(D.\frac{\partial N}{\partial x}\right)}{\partial x} + \frac{\partial\left(D.\frac{\partial N}{\partial y}\right)}{\partial y} - \frac{\partial(uN)}{\partial x} - \frac{\partial(vN)}{\partial y} - (M+F).N$$

with $N=N_{x,y,t}$ the fish density at point (x, y) at time and age t, $D=D_{x,y,t}$ the diffusivity coefficient, $u=u_{x,y,t}$ and $v=v_{x,y,t}$, the advection (directed movement) coefficients, $M=M_{x,y,t}$ the natural mortality coefficient and $F=F_{x,y,t}$ the fishing mortality coefficient.
Numerical solving of equation (1) is done on a 10 000 cells (100x100) square grid. All the forcing parameters are potentially variable in space. According to the subsystems coupling organization, the environment **functional heterogeneity** is constraining their spatial and temporal variation :

$$u_{x,y,t} = -\frac{\partial(pv_{x,y,t})}{\partial x} \text{ and } v_{x,y,t} = -\frac{\partial(pv_{x,y,t})}{\partial y}$$

with $pv_{x,y,t}$ the vital potential at point (x, y) and time t which is defined as the opposite of the biotic affinity $ab_{x,y,t}$ (« fitness » of the environment) (fig. 1) corrected by a density-dependent effect with a generalized « constant slope » equation (MacCall, 1991) :

$$pv_{x,y,t} = -ab_{x,y,t}.\left(1 - \frac{N^{\gamma}_{x,y,t}}{K_{x,y,t}}\right)$$

with γ a constant and $K_{x,y,t}$, the local carrying capacity (proportional to $ab_{x,y,t}$).

❸ A n ships fishing fleet is simulated. Fishing gear selectivity is the same for all boats and is defined with a curve whose parameters can be modified. At each time step, each boat is fishing in a cell chosen in a given fishing zone. A coefficient α is used to characterize the ship fishing strategy. At each time step, each fisherman is supposed to explore randomly a fraction α of the total number of spatial cells and exercise one's fishing effort in the most abundant cell he finds (Gauthiez, 1997). α varies from 0 to 1. If $\alpha=0$, the fishing effort is attributed randomly, if $\alpha=1$, abundance of fishes in all cells are known from the fishermen and the fishing effort is exerted on cell with the highest abundance of the space.

2. SIMULATION STUDY

Different simulations are conducted, based on a mid-heterogeneity level and a connective landscape. Fishing pressure corresponds to a 1000 ships fleet, randomly distributed in space ($\alpha=0$), and fishing mortality level is high (growth overfishing).

2.1. Case of a resident stock

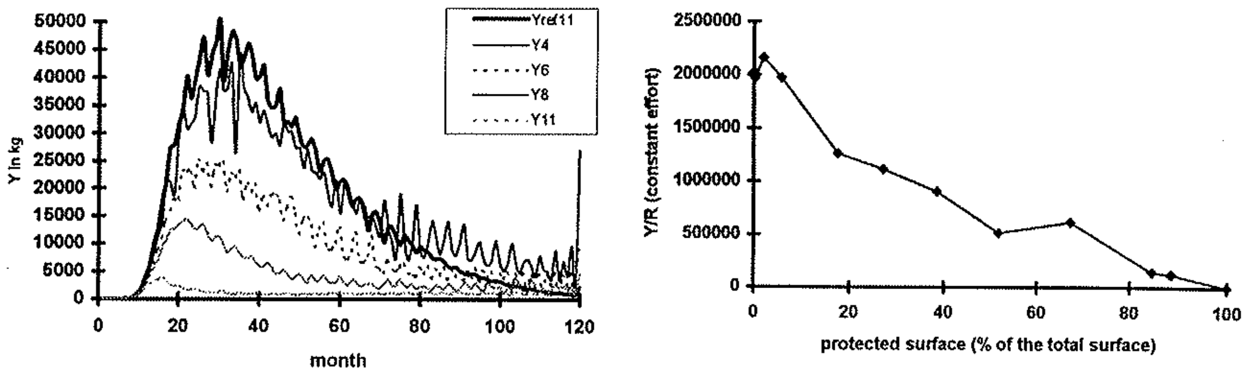

fig. 2 : On the left, a single cohort yield curve as a function of time for different surface values of the protected zone ($Y/R_{ref.}$: no protected zone ; Y_4 to Y_{11}, increasing surface of the protected zone). On the right, cumulated yield versus the protected surface.

By reducing the fraction of the stock available to the ships, the space protection induces (for a resident population) **a global decrease of yield per recruit**. This statement must nevertheless be moderated. Indeed, increasing the protected surface does not increase linearly the protected fraction of the stock. For instance on fig. 2, Y/R sometimes increases slightly when the protected surface increases. This is mainly due to the spatial heterogeneity of the population. At that portion of the curve (65% of the total surface), the increase of the refugia surface covers an inhabited zone. Consequently, the stock is not less available but the effort is concentrated on the non protected area and the production rises.

2.2. Case of a diffusive stock

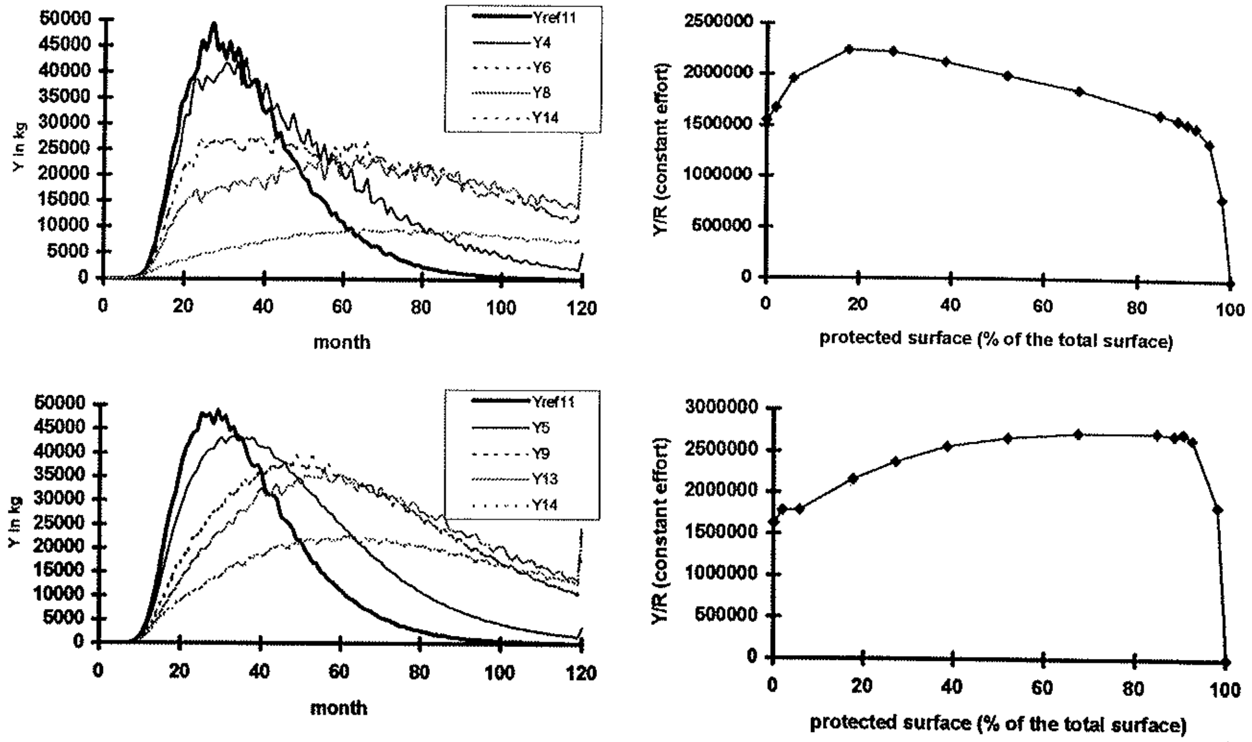

fig. 3 : On the left, a single cohort yield curve as a function of time for different surface values of the protected zone ($Y/R_{ref.}$: no protected zone ; Y_4 to Y_{14}, increasing surface of the protected zone). On the right, cumulated yield versus the protected surface. Up: middle level of diffusion, bottom: high level of diffusion.

The consequences a marine refugia will have on yield per recruit depend on the diffusivity level of the considered stock. Nevertheless, in most cases, the yield per recruit of an overfished diffusive stock sharply increases before falling down to zero when the protected surface increases (fig. 3). In this case, the effect of a protected area is a decrease of the effective effort at constant nominal effort (decreasing overall catchability). The more protected the fish is, the later (older and bigger) it will be caught.

2.3. Case of a migratory stock

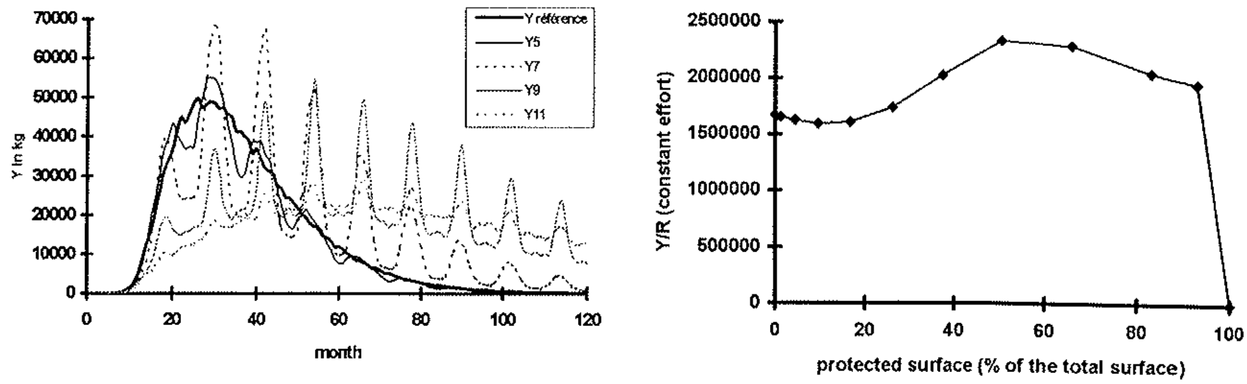

fig. 4 : On the left, a single cohort yield curve as a function of time for different surface values of the protected zone ($Y/R_{ref.}$: no protected zone ; Y_5 to Y_{11}, increasing surface of the protected zone). On the right, cumulated yield versus the protected surface.

For migratory or diffusive species, the curve of yield per recruit versus protected surface reaches a maximum. The main difference between them is the Y/R temporal variability induced by migrations (the population is alternately inside and outside of the refugia -fig. 4-). The solution for stabilizing the production could be a moving refugia following stock movements, or a long refugia protecting the population whatever its position is.

2.4. Multispecific approach

Because each population will have a specific response to a given protected zone, it is necessary to use a multispecific approach. In this paragraph, we analyze for a given situation the impact of marine refugia on the yield per recruit of two different populations as a function of the protected surface.

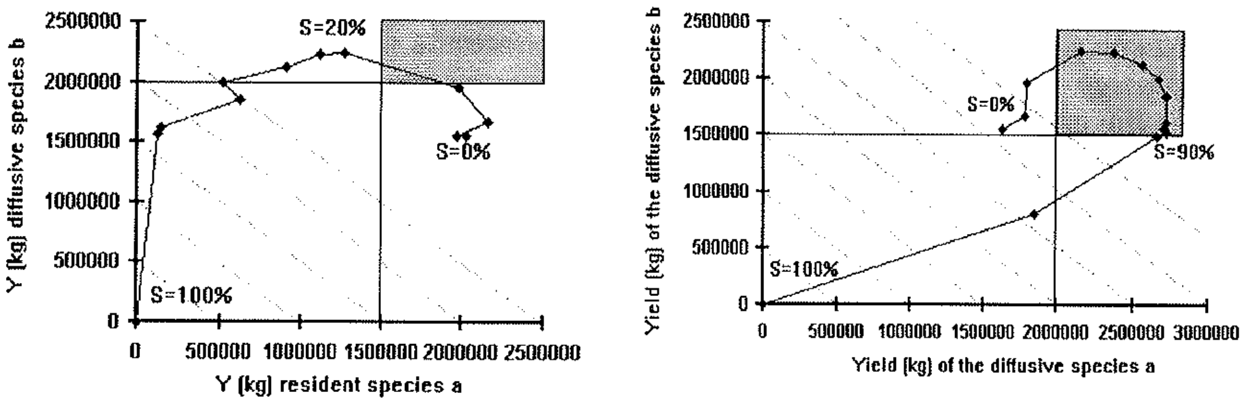

fig. 5 : Multispecific spatial management scenarii : an increasing size protected zone is simulated (from 0% to 100% of the whole surface) (in grey, the line of equal total yield). Curves correspond to a given location of the refugia. On the left, a resident species (a) and a diffusive one (b) : when the size of the refugia increases, the resident population yield decreases very quickly and the yield of the diffusive species increases and reaches a maximum for a protected zone near 20% of the total surface. On the right, two different diffusive species : gains are substantial for both species and for the whole until 90% of the whole surface is protected. The grey domain represents the satisfaction domain on arbitrary constraints on each species production.

2.4. Fishing effort distribution

In this paragraph, the influence of a marine refugia on the general characteristics of the fishing effort distribution is studied. For that purpose, the studied fishing fleet is supposed to have a research strategy towards the highest fish density zones, the places where highest yields are found. Fishing effort distribution is presented on fig. 6.

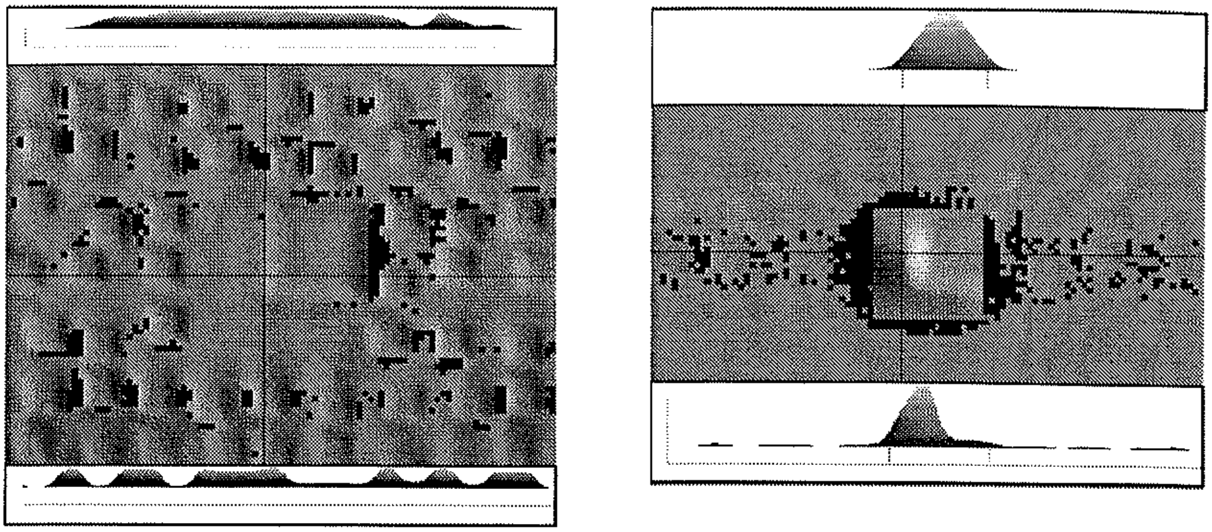

fig. 6 : In grey, the fish population distribution (on the top, section along the vertical axis, on the bottom, section along the horizontal axis). At the beginning of the simulation (on the left), the population is little exploited and it covers heterogeneously the whole space according to VLNM's constraints. At the end of the simulation (on the right), the highly exploited population is concentrated in the protected zone. The fishing effort distribution is deterministic. Fishermen (in black), looking for highest fish density, are distributed in the whole space at the beginning of the simulation, and they progressively concentrate their effort around the refugia where they find the highest fish density.

In the case where fish population is diffusive and fishermen have a « deterministic » strategy (research of the highest fish density), the effort distribution ineluctably evolves to a distribution along the refugia boundaries. In the refugia, fish spatial density follows a gaussian distribution (apart the landscape structure, that is the consequence of isotropic diffusion with open frontier).

DISCUSSION - CONCLUSION

It is shown that if fishing effort is spatially distributed in order to maximize catches, then fishing boats will tend slowly to be distributed all along the boundaries of the protected area. Such phenomena have been observed along the North sea protected zones by Rijnsdorp *et al.* (1996). It could have important consequences in terms of local impacts on the ecosystem and in terms of technical interactions between ships.

We show that for diffusive or migratory species the concept of « **space overfishing** » is meaningful because the yield per recruit versus the protected surface can reach a maximum before decreasing. Thus, there is a non null optimal domain of protected surface for a given fishing pattern, a given effort and a given location of the refugia (different works lead to similar conclusions : Attwood and Benet, 1995 ; Clark, 1996). In these conditions, protected areas behave like « **sources** » and exploited areas like « **sinks** » (Pulliam, 1988 ; Pulliam and Danielson, 1991). For resident populations, on the other hand, the larger the protected area is, the lower the catches per recruit are.

These results raise interesting multispecific management questions : how to conciliate these different behaviours? How to locate protected areas (which won't be the same for all species)? Where and how large should they be (is it better to protect only one large area or several smaller ones)?...

Trying to answer these different questions requires developing and using spatial assessments and modelling methods which are not yet familiar.

RÉFERENCES

Attwood C. G., B. A. Bennett 1995. Modelling the effect of marine reserves on the recreational shore-fishery of the south-western cape, South Africa. *S. Afr. J. mar. Sci.* 16: 227-240.

Clark C. W. 1996. Marine reserves and the precautionary management of fisheries. *Ecological Applications.* 6(2): 369-370.

Dugan J. E., Davis G. E. 1992. Applications of marine refugia to coastal fisheries management. *Can. J. Fish. Aquat. Sci.* , Vol. 50: 2029-2042.

Gauthiez F., 1997. Structuration spatiale des populations de poissons marins demersaux. Caracterisation, consequences biometriques et halieutiques. Thèse de doctorat.

Kolosa J., Rollo C. D. 1989. Introduction : the heterogeneity of heterogeneity : a glossary. *in* Ecological heterogeneity, Kolosa J. and S. T. A. Pickett (eds). Ecological studies n°86. Berlin : Springer Verlag.

Legendre P., M.-J. Fortin 1989. Spatial pattern and ecological analysis. *Vegetatio* 80: 107-138.

Okubo A. 1980. Diffusion and ecological problems : mathematical models. Biomathematics Vol.10. Springer-Verlag. 254p.

Pulliam H. R., 1988. Sources, sinks, and population regulation. *American Naturalist.* 132:652-661.

Pulliam H. R. Danielson B. J., 1991. Sources, sinks, and habitat selection : a landscape perspective on population dynamics. *American Naturalist.* 137:S50-S66.

Rijnsdorp A. D., A. M. Buys, F. Storbeck, E. Visser 1996. Micro-scale distribution of beam trawl effort in the southern North Sea between 1993 and 1996 in relation to the trawling frequency of the sea bed and the impact on benthic organisms. ICES CM 1996/Mini: 11.

Sibert J. R., Fournier D. A. 1994. Evaluation of Advection-Diffusion Equations for Estimation of Movement Patterns from Tag Recapture Data. Proceedings of the first FAO expert consultation on interactions of pacific ocean tuna fisheries. Vol. 1. R. S. Shomura, J. Majkowski and S. Langi (eds) FAO fisheries technical paper 336/1 326pp.