

Estimating fish numbers, fishing mortality and migration rates between different spatial zones : the spatial VPA methodology.

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Abstract:

Many works have been carried out to take into account spatial dimension in population dynamics and stock assessment models. But most of these works are based on stocks for which tagging data are available. Consequently, due to the small number of stocks for which those data are available, the movement rate of most of exploited stocks remains unknown. Therefore, spatial approaches remain most of the time impossible in practice.

This paper proposes a method to estimate fish numbers and fishing mortality in discrete spatial zones, and migration rates between these zones. The method needs catches at age and fishing effort by zone data only. It is based on a calculation of the fishing mortality in each zone from the total fishing mortality estimated by VPA. The method takes into account the surface of the stock in each zone. Fishing mortality in each zone is then used by a temporally discrete boxes model to estimate fish numbers and migration rates in each zone.

The method and its underlying hypothesis are tested on several data sets simulated with the advection-diffusion based simulator SHADYS (Simulateur HALieutique de DYnamiques Spatiales).

INTRODUCTION

Current stock assessment and management tools are generally based on population dynamics modelling at the global stock distribution scale. In this way, those methods do not allow spatially heterogeneous assessments.

Yet, spatial heterogeneity plays an essential functional role in the dynamics of fisheries systems and ecosystems in a broader meaning. Accordingly, overfishing concept should be extended to local scales. Thus, a stock may present local overfishing situations with very high local fishing mortality rates, without being in an overfishing state at the global scale usually considered. Such a phenomenon could have important consequences:

- in terms of local biomass depletion (many tuna fisheries for instance - Fonteneau *et al.*, 1997-) : a local zone can be totally swept, even when the global stock is not highly exploited. The recovery time becomes a function of fish movement, of what MacCall (1991) names the stock « viscosity ». Such a phenomenon may have dramatic impacts on stock assessment.

- in terms of local biodiversity: an important genetic heterogeneity can be completely hidden by the stock concept (Cury and Anneville, 1997) (as, for instance the New Foundland cod stock -Brethes, 1996-). A local overfishing could lead to an endemic sub-population extinction.

From another point of view, spatio-temporal modelling and management including effort limitations by boxes (to prevent stocks overexploitation and to limit fleet interactions) or creation of marine refugia (to prevent biodiversity erosion and ecological overexploitation in a broader sense) is more and more used in fishery science and management. This is a reason why many works try to integrate spatial dimension in population dynamics and stock assessment. Most of them deal with stocks with available tagging data. Unfortunately, because of such data scarceness, fish migration rates are most of the time unknown and spatial stock assessment and modelling remain inapplicable in practice. This paper proposes a method to estimate fish abundance and local fishing mortality coefficients in spatial zones and migration rates between these zones. The method only needs data of catches at age and fishing effort by zone. The method takes into account the surface of the stock in each zone.

The method and its underlying hypothesis are tested for two zones on several data sets simulated with the advection-diffusion based simulator SHADYS (Simulateur HALieutique de DYnamiques Spatiales) (Maury and Gascuel, 1997).

I. METHOD

The basic model we use is a discrete model. It is analogous to the boxes model whose differential formulation was presented by Beverton and Holt in 1957, and is based on the assumption of an instantaneous migration of fishes at the end of each time step (Punt *et al.*, 1994). To simplify, equations are written in the whole paper for two distinct boxes but could be easily extended to more boxes.

$$(1) \quad \begin{cases} N_{1,t+1} = N_{1,t} e^{-(F_{1,t}+M_{1,t})} (1-T_{12,t}) + N_{2,t} e^{-(F_{2,t}+M_{2,t})} T_{21,t} \\ N_{2,t+1} = N_{2,t} e^{-(F_{2,t}+M_{2,t})} (1-T_{21,t}) + N_{1,t} e^{-(F_{1,t}+M_{1,t})} T_{12,t} \\ C_{1,t} = \frac{F_{1,t}}{F_{1,t} + M_{1,t}} N_{1,t} (1 - e^{-(F_{1,t}+M_{1,t})}) \\ C_{2,t} = \frac{F_{2,t}}{F_{2,t} + M_{2,t}} N_{2,t} (1 - e^{-(F_{2,t}+M_{2,t})}) \end{cases}$$

with $N_{1,t}$ and $N_{2,t}$, the fish numbers in zones 1 and 2 during time step t ; $F_{1,t}$ and $F_{2,t}$, the fishing mortality coefficients in zones 1 and 2 corresponding to numbers of fish and efforts in each zone during the time step t ; $M_{1,t}$ and $M_{2,t}$, the natural mortality coefficients in zones 1 and 2 during the time step t ; $T_{12,t}$ the migration rate from zone 1 to zone 2 during time step t and $T_{21,t}$, the migration rate from zone 2 to zone 1 during time step t .

No hypothesis is made about the distance between zones or their connexity. The model is not spatially explicit, it is based on the fundamental assumption of homogeneity within each zone (each zone is supposed to behave as a whole).

In order to simplify notations, the case of a single cohort only will be considered in the following of the paper. The method can be easily extended to the other exploited cohorts of the stock. In the case of a single cohort, the time t is redundant with the age.

System (1) has two unknown state variables $N_{1,t}$ and $N_{2,t}$, two measurable output variables $C_{1,t}$ and $C_{2,t}$ and six parameters ($M_{1,t}$, $M_{2,t}$, $F_{1,t}$, $F_{2,t}$, $T_{12,t}$ et $T_{21,t}$). Without external information, natural mortality coefficients $M_{1,t}$ et $M_{2,t}$ can be arbitrarily set as it is normally done in cohort analysis. The fishing mortality applied to the whole stock F_t is estimated by VPA and is used to determine the fishing mortality in each zone $F_{1,t}$ et $F_{2,t}$. By using the catchability per surface unit q' (Laurec and Le Guen, 1981) and the assumption of spatial homogeneity of fish density in each zone⁽¹⁾, we can write:

$$q'_t = q'_{t,i} \cdot S_{i,t} = \frac{F_{i,t} \cdot S_{i,t}}{f_{i,t}}$$

with $S_{i,t}$ the surface covered by the stock in zone i during time step t . Without auxiliary information (scientific surveys), the surface of each box and the effort distribution surface in each zone are used. Because q'_t is constant in space, we can write:

$$\frac{F_{1,t} \cdot S_{1,t}}{f_{1,t}} = q'_t = \frac{F_{2,t} \cdot S_{2,t}}{f_{2,t}}$$

then:

$$(3) \quad F_{2,t} = \frac{S_{1,t} \cdot f_{2,t}}{S_{2,t} \cdot f_{1,t}} \cdot F_{1,t}$$

Using the conservativity of the number of fish ($N_{1,t} + N_{2,t} - N_t = 0$), system (1) gives:

$$(4) \quad g(F_{1,t}) = \frac{C_{1,t} \cdot (M_{1,t} + F_{1,t})}{F_{1,t} \cdot (1 - e^{-(F_{1,t} + M_{1,t})})} + \frac{C_{2,t} \cdot (M_{2,t} + F_{2,t})}{F_{2,t} \cdot (1 - e^{-(F_{2,t} + M_{2,t})})} - \frac{C_t \cdot (M_t + F_t)}{F_t \cdot (1 - e^{-(F_t + M_t)})} = 0$$

with $F_{2,t}$ given by equation (3), $M_{1,t}$, $M_{2,t}$, $C_{1,t}$, $C_{2,t}$ and C_t already known and F_t estimated by VPA.

⁽¹⁾ The catchability per surface unit q'_t is defined as being equal to the local CPUE $U_{s,t}$ divided by the local density $D_{s,t}$, both calculated on a unit surface ds during time t :

$$(2) \quad q'_t = \frac{U_{s,t}}{D_{s,t}} = \frac{U_{s,t}}{N_{s,t}} \cdot ds = q_{s,t} \cdot ds$$

with $N_{s,t}$ and $q_{s,t}$, the fish number and the catchability in the unit surface ds during time t .

Contrary to the catchability q_t , the assumption that the coefficient q'_t is spatially constant at a given time t can be done. Then, catch per unit effort in each zone i at time t can be expressed as follow:

$$CPUE_{i,t} = \frac{C_{i,t}}{f_{i,t}} = \frac{q'_{i,t} \cdot \int_S D_{s,t} \cdot f_{s,t} \cdot ds}{\int_S f_{s,t} \cdot ds}$$

with $f_{s,t}$ the effort in the elementary surface ds at time t .

With the assumption of spatial homogeneity of fish density in each zone i ($D_{s,t} = D_{i,t}$), the previous equation can be simplified:

$CPUE_{i,t} = q'_t \cdot D_{i,t} = q'_t \cdot \frac{N_{i,t}}{S_{i,t}} = q'_{i,t} \cdot N_{i,t}$ with $N_{i,t}$, the number of fish in zone i at time t . Such a simplification can be made at the global stock level only under the generally false hypothesis of

equality of fish densities in all zones at a given time t : $CPUE_t = \frac{C_t}{f_t} = \frac{\sum_i C_{i,t}}{\sum_i f_{i,t}} = \frac{q'_t \cdot \sum_i (D_{i,t} \cdot f_{i,t})}{\sum_i f_{i,t}}$.

Equation (4) is solved numerically with the hybrid method proposed by Press *et al.* (1994). When $F_{1,t}$ is assessed, equation (3) is used to calculate $F_{2,t}$. Next, fish numbers $N_{1,t}$ and $N_{2,t}$ are calculated using the catch equations in each zone of the system (1).

The only remaining unknown parameters are $T_{12,t}$ and $T_{21,t}$. But system (1) is still not identifiable, as far as infinity of couples $(T_{12,t}, T_{21,t})$ can be a solution. It is under-determined and must be simplified (*i. e.* : a relation between $T_{12,t}$ and $T_{21,t}$ has to be found). For this, fish movement is supposed to have two components: a random one D_t (diffusion) which is spatially isotropic (brownian motion) and depends only on age and time t , and a deterministic one T'_t (advection) which is spatially directed (Okubo, 1980 ; Deriso *et al.*, 1991 ; Kleiber and Fonteneau, 1994). With such assumptions, transfer coefficients $T_{12,t}$ and $T_{21,t}$ can be expressed as follows:

$$(5) \quad a \begin{cases} T_{12,t} = D_t + T'_{12,t} \\ T_{21,t} = D_t \end{cases} \quad \text{or} \quad b \begin{cases} T_{12,t} = D_t \\ T_{21,t} = D_t + T'_{21,t} \end{cases}$$

$T'_{12,t}$ and $T'_{21,t}$ can not be simultaneously positive because advection is considered as an homogeneous and univocal phenomenon. Now, the unknown parameters are: $(D_t, T'_{12,t})$ or $(D_t, T'_{21,t})$. In the present study, the coefficient D_t is supposed to be estimated with an auxiliary method (Kleiber *et al.*, 1994 ; Porch, 1996), neglected compared to $T'_{i,t}$ or bounded in an intervall. Migration rates at terminal age $T_{12,T}$ and $T_{21,T}$ are supposed to be equal to values at the previous time step : $T_{12,T-1}$ and $T_{21,T-1}$. For all the other time steps, equations (1) and (5) are used to estimate $T_{12,t}$ and $T_{21,t}$:

$$\begin{cases} T_{12,t} = \frac{N_{2,t+1} + N_{2,t} \cdot e^{-(F_{2,t} + M_{2,t})} \cdot (D-1)}{N_{1,t} \cdot e^{-(F_{1,t} + M_{1,t})}} \\ T_{21,t} = D_t \end{cases}$$

If $T_{12,t} \leq D_t$ ($\Leftrightarrow T'_{12,t} \leq 0$ which is impossible by definition), symmetrical equations are used to estimate $T_{12,t}$ et $T_{21,t}$.

II. TESTING THE METHOD

The simulator SHADYS (Simulateur Halieutique de Dynamiques Spatiales) (Maury and Gascuel, 1997) allows to simulate the dynamic of a fishery spatially and temporally heterogeneous at a very fine spatial and temporal resolution. In order to check the spatial VPA method, SHADYS output (catches, fishing efforts and fish densities) are aggregated monthly on two zones of different size. The spatial VPA method is applied to simulated data. In order to test the method, assessment results from the spatial VPA are compared to the fish numbers $N_{\text{zone, month}}$ from SHADYS (such data are unknown in reality). Simulations are run for a single cohort during ten years (120 months and 720 SHADYS time steps) (fig. 1 and 2).

By this way, we analyze the reliability of the spatial VPA estimations in the case of a spatially heterogeneous fishery. We focused on three main characteristics of the fishery:

- the more or less migratory behaviour of the stock,
- the fleet capacity to fish in high density zones (which is mesured with a « determinism coefficient » varying from 0 for a fleet whose effort is randomly distributed, to 1 for a deterministic fleet fishing only on the highest density point),
- the method used to estimate the surface occupied by each sub-stock (either the surface occupied by the effort which is probably smaller than reality, or the surface of each spatial box probably larger than the surface actually occupied by the stock).

Results of these simulations are shortly presented here with the help of annotated figures.

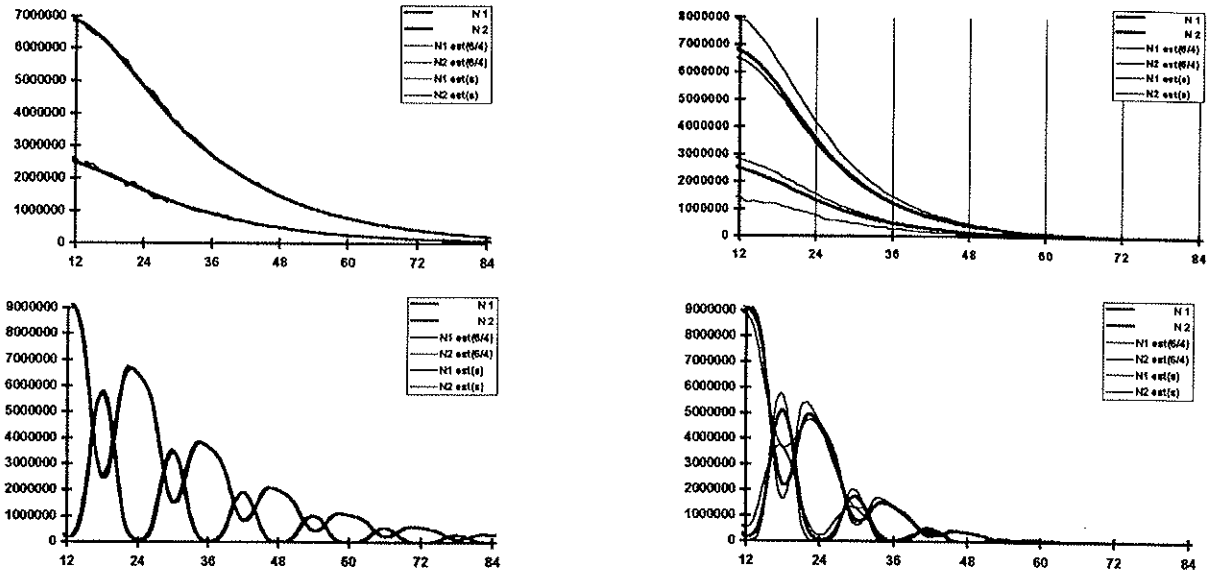


fig. 1 : The spatial VPA methodology is applied to catch data simulated with the simulator SHADYS. Estimated fish numbers are compared with simulated ones. On the top, case of a non migratory stock, and on the bottom, case of a seasonal migratory stock. On the left, case of a « random » fleet (assessments correspond almost exactly with simulated reality), on the right, a « deterministic » fleet (assessments diverge from simulated reality). The use of each box surface to estimate the stock surface in each area is noted 6/4 and the use of the effort surface is noted s.

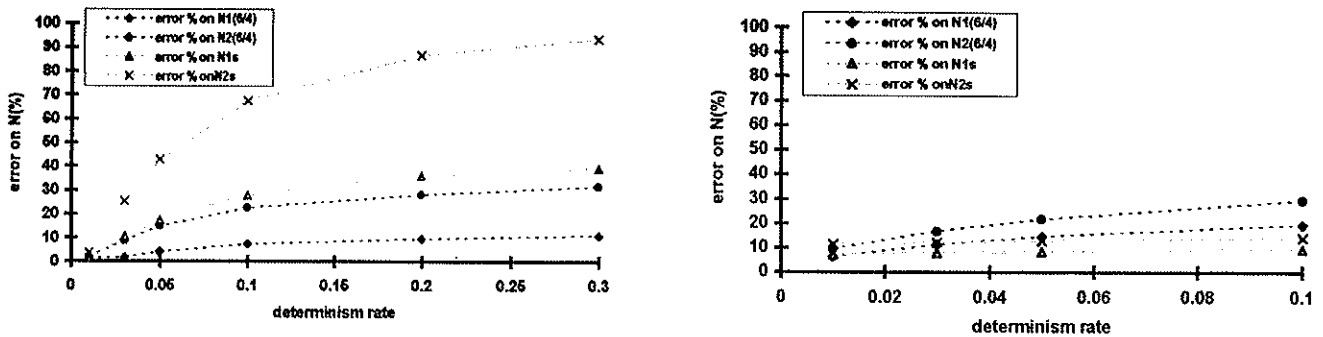


fig. 2 : Mean error on the estimated fish numbers as a function of the « determinism coefficient » (fleet capacity to locate and to harvest the high fish concentrations; see text) by using effort surface or boxes surface to estimate stock surface in each box. On the left, case of a diffusive non migratory stock, on the right, case of a migratory stock.

The more the fleet behaviour is deterministic, the more the error is high but curves converge to an asymptotic maximum. Depending on the considered case, either the use of box surface or effort distribution surface gives the best results. In all cases, these two methods allow to limit the results between a high and a low estimation.

III. DISCUSSION

The relationship between commercial vessels CPUE and stock abundance is generally not a simple linear function. Many well known phenomena lead to a non linear relationship between CPUE and fish abundance. They are generally attributed to the resource spatial heterogeneity and to the fishermen search behaviour (Clark *et al.*, 1979 ; Hilborn and

Walters, 1987 ; Hilborn and Walters, 1992 ; Gauthiez, 1997). The consequences of such phenomena on the spatial heterogeneity of catchability at age q_t (and more precisely on the variability of the catchability by surface unit $q'_{t,z}$ at a given time t between different given zones) are less studied.

The catchability q'_t generally varies with stock abundance (its variations are density-dependant) and with fishermen behaviour (Hilborn and Walters, 1992 ; Gauthiez, 1997). Because fish density is spatially heterogeneous, catchability $q'_{z,t}$ also varies in space. These aspects are not detailed here, but it is important to keep in mind the potential consequences of violation of the spatial catchability $q'_{z,t}$ homogeneity hypothesis. Such hypothesis is not a problem in the ideal case of a fleet fishing randomly on the whole stock distribution area: catches per unit effort in each zone $CPUE_{t,z}$ tend to be proportional to fish abundance in each zone $N_{t,z}$ (apart from the surface). Conversely, in the case of a fishing fleet using a high density research strategy, catch per unit effort in each zone will not be proportional to $N_{t,z}$ but to $D_{t,z}$, the mean density of the fish concentration or the density of the highest fish concentration if the fishermen are able to locate it. In such conditions, three cases must be distinguished:

- ① The stock is quite homogeneous at all spatial scales. In this case, local CPUE are proportional to local biomass and the method is not biased.
- ② The stock is spatially heterogeneous at various spatial scales and concentration density increases at constant surface when the biomass increases. Then, local CPUE stays proportional to local biomass and the method has few bias.
- ③ The stock is spatially heterogeneous at various spatial scales and concentration surface increases at constant density when the biomass increases. Then, local CPUE are not proportional to local biomass. Such phenomena may lead to important bias in assessment results.

CONCLUSION

The proposed method enables to estimate local parameters which are usually estimated at the global stock level (fish numbers and fishing mortality coefficients). Simulations show that in many cases the method is reliable. It seems to be biased when simultaneously fishing effort is highly deterministic and fish density is highly heterogeneous and density dependent. Different statistical tools such as mean/variance relationship (Gauthiez, 1997) or geostatistical selectivity curves (Petitgas, 1994) may allow to identify such « dangerous » cases. In those cases, the use of different stock surface estimates allows to bound spatial VPA outputs between a high and a low value.

Keeping in mind the « dangerous » cases, the method enables, on the one hand, to detect local overfishing phenomena when such phenomena remain invisible with a global analysis. On the other hand, estimating local fishing mortality and fish migration rates allows to use boxes models of population dynamics. Such models are necessary to assess spatial management measures (boxes, refugia, ...).

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