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Foreword

The spatial organization of aquatic populations as observed using hydroacoustic methods

The study of spatial structures through acoustic method involves several approaches. The first one is descriptive: its aim is to establish a typology of the spatial organizations, *in order first to be able to study them separately in a more precise way (and if possible to identify the species) and secondly to allow a better general description of the populations observed. The second approach concerns the* study of the behavioural mechanisms *through which the living organisms adopt and maintain these structures in time and space, or may change their organization according to changes in the environment (ecoethology). The third approach is the* determinism of the structures and spatial organization, *i.e. the study of the ecological or physiological reasons that affect the existence or collapse of the structures. Finally a more strictly acoustic approach, consists in measuring the* impact of the spatial structures on the results of acoustic evaluations, *in order to correct the biases on the data and measure the accuracy of the biomass estimate obtained by echo integration.*

Typology of spatial organization

The spatial geometry of the group of individuals can take several forms such as: school, shoal, swarm, aggregation and layer. Each of these categories obeys some environmental constraints, but depends also on the species behaviour and physiology. Their description and classification is useful for determining the specific compositions. We will present here as examples the school and the aggregation.

The school

The school is a temporary gathering of individuals, usually of a single species, a single length class and a single biological stage. The fish present a mutual attraction and various degrees of coordination that allow them to swim in a polarized group.

The experience of scientists as well as of fishermen shows that the structure of a school often permits identification of the species which forms it (Weill *et al.*). The typology of this structure will help to develop an automatic method for species identification using the acoustic characteristics (signature) of the school. As far as pelagic schools are concerned, a few conclusions have been extracted:

– in favourable conditions and in the case of oligospecific communities, species identification through school characteristics is possible;

– although some typical structures may be described for a species, these structures are not stable in time: if the structure is characteristic of a species at one moment, it may be associated with another one in another period of the year (Scalabrin and Massé);

– a single species may present very different structures at a single place and at the same moment. This is the case of the capelin (*Mallotus villosus*) in the Gulf of Saint-Laurent (Quebec), where this fish is present in large layers as well as in dense shoals (Simard *et al.*); these differences are probably linked with small-scale changes in the hydrology or with ethological reactions (presence of predators);

– the schools present both general characteristics, independent of the species or depending on external parameters (proximity to the surface or the bottom), and specific characteristics (Misund). One of the objectives of researches is to discriminate between these two sets of characteristics.

The aggregation

The aggregation also concerns dense gatherings of living organisms, but in areas usually much larger than in the case of schools (at least in the horizontal dimension). Their structure is quite different from that of schools; the species may be numerous, and no coordination in the reactions of the individuals is required. These aggregations seem to be principally related to hydrological variations: the internal waves may be drawn by the layers in the vertical dimension, as well as the thermocline (Baussant *et al.*).

Unlike the case with schools, it is impossible to identify a species from particular characteristics of aggregations. However, it is possible to classify the

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main features of the aggregations. In this case the scientist is not interested in one particular type of organism, but in the global community, which may be linked to environmental characteristics. Two types of aggregation may be interpreted in this way:

- fish aggregations. The classification methods are many, but all of them show the possibility to split the aggregations in several groups according to their acoustical particularities. These groups, named "Acoustic Populations" (Gerlotto), allow later identification of the species constituting them and mapping of the populations;
- plankton swarms. Their identification is also possible, and may help to classify the detections (Baussant *et al.*). Of course in this particular case it is indispensable to link the acoustic data to the hydrological data, which is often the main deterministic factor. The hydrological data are often discrete pieces of information while the acoustic recording is continuous. In this case the high variability of the hydrology at small scale makes difficult the relationship between acoustics and hydrology.

Behavioural mechanisms

The different types of spatial structure correspond not only to environmental constraints, but also to behavioural characteristics of each species. Among these characteristics one of the most important is gregarism. It can be defined as the tendency of animals to constitute coherent social groups, through mutual attraction of individuals within a single species. This coordinate behaviour allows the fish to present organized actions that are biologically favourable to the whole group. This is probably true also for plankton swarms, even though this is not well documented.

Fish may present two kinds of gregarious behaviour: obligatory gregarism, and facultative behaviour. In the first type gathering in school is indispensable for the survival of the species (Clupeids, for example). The species belonging to the second one may spend part of their life solitary (in particular, in case of presence of predators these species may change to an individual behaviour). Gadoids seem to belong to this group.

It is quite easy to discriminate between school and aggregation when considering them from the ethological point of view. In the case of aggregation, one or several species are gathered according to hydrological conditions (Guillard and Gerdeaux). Contrarily to the school, no social attraction is required to form such groups. We may sometimes encounter a combination of both groups, when the aggregation is made of schools and not of scattered fish. In this last case the gregarism is added to the attraction due to the environment.

It is impossible to consider the spatial structures exclusively as produced by environmental constraints. According to the ethology of the populations, several spatial structures may be the answer to a single hydrological or trophic organization (Simard *et al.*). The behaviour may also present an effect at very large scales, as in the case of migrations, reproduction, etc.

The determinism of the spatial structures

The determinism of the spatial structures is closely dependent on the scale at which the structures are observed. At small scale (1 to 10^3 m), the intra and interspecific reactions (for instance predation) as well as physical microstructures determine the occupation of space. At medium scale (10^3 to 10^5 m), the structures depend on the collective behaviour of the individuals faced with common physiological or ethological needs (nutrition, reproduction), and on hydrological gradients, fronts, topographical discontinuities, etc. At large scale (more than 10^5 m), the main factor is the physiological tolerance of the species to environmental gradients (temperature, for example).

The variability of the structures is much greater in the vertical dimension (some metres) than horizontally (sometimes several tens of kilometres). Such a variability assumes that there exists a convergence in the reactions of almost all the groups (fish, plankton, necton, etc.) to the environment. The determinism of these distributions may have several origins:

- biological. The circadian migrations, which correspond to physiological constraints or to intra or interspecific relationships can be cited here. These rhythms can consist of movements in the water column or in changes in the structuration of the biomass (Guillard and Gerdeaux);
- physical. The main factor affecting the biological structures is that of hydrological discontinuities. The densest aggregations are often observed close to physical fronts: the limit of vertical light penetration, the thermocline and the picnocline, are at the same time attractive features that concentrate the nutritive elements (phytoplankton, prey), and an impassable frontier for some living organisms. Horizontally, the frontal areas produce a similar effect. We may include here also the dramatic changes in hydrological structures produced by storms, which induce an unstable distribution of the organisms. On a longer time scale, small but continuous changes in the hydrological characteristics may have important consequences for the whole ecosystem;
- combined. The preceeding cases apart, spatial structures generally result from combined action of animal behaviour and environmental characteristics. The lunar cycle, for instance, has an impact on the amplitude of the changes in the spatial distribution (such as circadian vertical migration and reproduction). Phototaxism may interfere with the vertical movement of the water and create

areas favourables or unfavourables to life, such as convergence or divergence sectors and upwellings.

Spatial structures and acoustic assessment

The principle of the biomass evaluation and mapping through acoustics consists in interpolating the results obtained from one sampling to the whole area studied (Weill *et al.*). The spatial characteristics and our sampling methods make it difficult (or even impossible) to use classical statistics for such purpose (Simard *et al.*). The use of geostatistics for analyzing the results of acoustic surveys is now currently accepted (especially at GEOSPACE). The main characteristics of the spatial distribution of aquatic organisms show clearly that the density measured is a variable presenting spatial autocorrelation. Therefore the use of variograms for describing the structures is acceptable (Petitgas; Guillard and Gerdeaux; Simard *et al.*). Nevertheless some points needs more investigation, in two domains in particular.

The spatial heterogeneity

The spatial distributions are highly heterogeneous: very often it appears that more than 50% of the biomass is concentrated on 1 or 2% of the surface. Two schemes may be described: distribution with or without transition (Petitgas; Misund). The structures without transition are mainly the fish schools, those with transition are the aggregations, but may also be constituted by some more complex structures such as the series scattered/school/aggregation/school/scattered. These structures depend also on the species: the sardine of the Bay of Biscay often presents transitionless structures while in the same area the anchovy distribution is progressive (Scalabrin and Massé).

The kind of spatial distribution of the densities may strongly influence evaluations. Some distribution laws present particular characteristics, and sometimes the central limit theorem is not applicable (Fréon *et al.*). When the acoustic data obey such a law, that means, for instance, that the usual sampling scheme is no useable, and that an increase of the sampling effort would not increase the precision of the results. In such cases, it may be better to take into consideration parameters other than the density (Marchal and Petitgas).

The time variability

It can be observed at various scales. It can be deterministic (rhythmic, or not), random or factual (i.e. with a random apparition but a deterministic process once the event has happened). Practically we can consider two major cases:

– the circadian rhythm. If we consider separately the day and night acoustic data, we may note that there is a strong difference between the mean densities calculated for these two periods, the night data often being higher (at least for tropical stocks). Several explanations are proposed: fish behaviour (migrations, avoidance), presence of different populations by day and by night (vertical migrations, plankton) or statistical effect of the density distribution. In this last case, the difference in the density histogram obtained by day and by night is responsible for the variability in the evaluation (Fréon *et al.*);

– the variability with time interval. This concerns the changes that are observed in density and spatial distribution when coming back to a single point after a time interval. This variability can have several reasons: biological (movements of the animals during the time interval considered); or technical: the narrow band echo sounders usually used may introduce errors in the estimates (Samb *et al.*). This time variability can appear even with very short time intervals. The difference of speed and direction between the movements of the fish and the survey vessel is the most important factor. The biological structures mobe either in a passive way (accompanying the water mass, at speeds usually lower than one knot), or actively (fish schools, migrations) at one or two knots. They are still slow compared to the vessel speed, which is between 6 and 10 knots. However, when considering the speed of the structures in the direction perpendicular to the transects direction, this difference becomes low, and sometimes insignificant. This variability has consequences at two levels:

– on the structure analysis. The data collected along a transect are continuous in space and time. The spatial drift affects the description of the large-scale structure, but has no influence on the microscale description. A variogram calculated in the direction of the transects describes the structures without any bias produced by the time variability;

– on the mapping. The image obtained may be blurred when the structures have moved during the survey (migrations) or when the vessel comes back to prospect a second time to an area. We may note that in any case the map is always a biased representation of the truth, as the sampling is not synoptic for the total area.

Nevertheless the map of the structures is more reliable than that of the densities. Effectively the density depends on the rare high values recorded, usually from schools. The evaluation of the number of schools in a given area is much easier and more precise than the evaluation of the mean density of the schools (Marchal and Petitgas).

Conclusion

The distribution of individuals in coherent structures is one of the most remarkable characteristics of pelagic organisms, at sea as well as in freshwater ecosystems. These distributions, although they favour the exploitation of pelagic stocks by fishermen, for instance, make their study by "traditional" methods difficult (plankton or fish sampling by nets). The introduction of acoustic methods of investigation allows a synoptic view to be obtained of the three-dimensional structures of the populations and their combination with hydrographical observations, thus an understanding of the relationship between population distribution and environment. Indeed these methods are the only ones that allow a real continuous spatial observation of the structures. The work of GEOSPACE has shown how large an amount of information can be extracted from the acoustic data. It is clear that the understanding of the detailed mechanisms which induce the spatial organization, and particularly gregarism, is the first step towards an integrated study of the relations between environment and total biomass. Therefore the working group has decided to favour the study of gregarism of pelagic species. This is the topic that will be discussed in the coming years at the annual meeting of GEOSPACE.

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