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THE INFLUENCE OF SEASONAL SALINITY AND TURBIDITY MAXIMUM VARIATIONS ON THE NURSERY FUNCTION OF THE LOIRE ESTUARY (FRANCE)

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KEYWORDS: estuarine nursery; disturbance; salinity; turbidity maximum; seasonal variations.

ABSTRACT

In the Loire estuary which is a macrotidal estuary, the river flow and tides induce large seasonal variations in salinity gradients and in location and density of the turbidity maximum. These characteristics influence colonization patterns developed by juveniles of euryhaline fish populations (structure, distribution, density) and the dynamics of benthic communities which constitute their food resources. In some hydrological conditions, the upstream limit of the nursery function may be controlled by the turbidity maximum which induces anoxic conditions: reduction in densities or mass mortalities may be observed.

INTRODUCTION

Estuaries are complex ecosystems where abiotic factors are mainly controlled by the river outflow and tides. Variations of these features are often cyclic and their magnitude depends on climatic conditions (rainfall, wind). When harsh conditions prevail (pollution, dryness), catastrophic events as hypoxia may be observed (MACKAY and FLEMING, 1969). Such a phenomenon may be linked either to eutrophication which corresponds to an enrichment in nutrients (HANSSON and RUDSTAM, 1990; DAY *et al.*, 1989) or to occurrence of an entrapment zone where accumulation of suspended mineral and organic material enhances bacterial activity (BOUCHET *et al.*, 1976; BROSSARD and GALLENNE, 1982; ROMANA *et al.*, 1990; DAY *et al.*, 1989). Magnitude and location of this Maximum Turbidity Zone (M.T.Z.) which are controlled by the hydrodynamics of the system may act on the dynamics of benthic communities and of their predator populations. It is well known that in estuaries, macrobenthic and nektonic species are well adapted to survive in a fluctuating environment. However, when turbid conditions become harmful, different responses of these communities can be observed: emigration, reductions in density or biomass, mass mortalities (ROSENBERG, 1977; SIEGFRIED *et al.*, 1980; SANTOS and SIMON, 1980; GASTON, 1985).

This paper describes the effect of variations of salinity and turbidity conditions on the fluctuations of the nursery function of a macrotidal estuary. Their influence will be considered according to the location and composition of the fish populations in the estuary and the dynamics of the benthic communities they use as trophic resources.

MATERIAL AND METHODS

Study site

The Loire estuary is located on the southern coast of Britanny (France) and is 70 km long between Nantes and the outside limit of St. Nazaire (Fig. 1). Based on mean river flow conditions, the estuary can be divided in four major areas with different haline characteristics. The area (0) is the

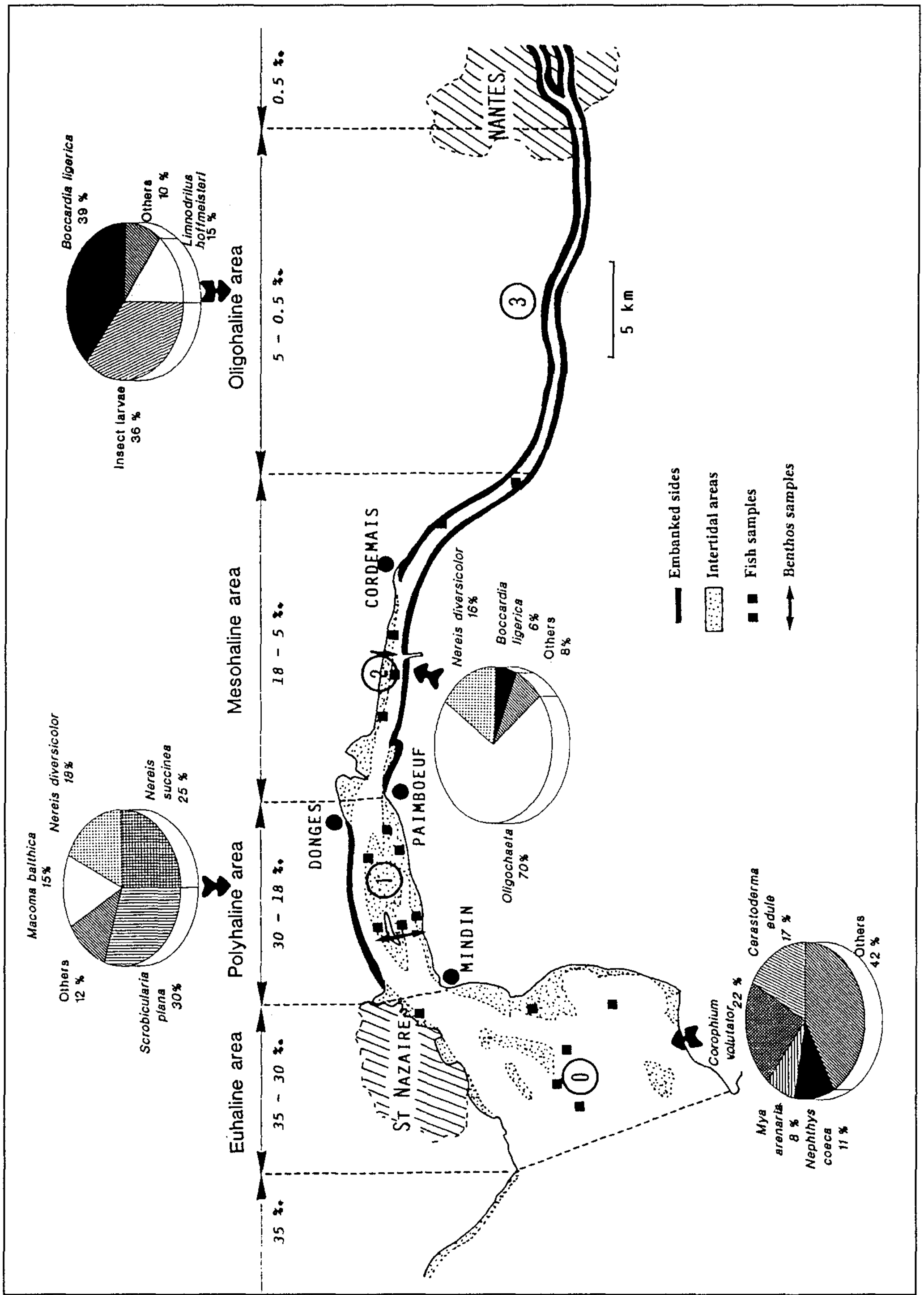

Fig. 1. Map of the Loire estuary with the mean limits of haline areas, the composition of benthic communities (% density), the location of fish and benthos samples.

euhaline zone where benthic communities are dominated by marine species: it corresponds to the lower estuary. The area (1) is the polyhaline zone where large mudflats are inhabited by typical estuarine species. The area (2) is the mesohaline zone where mudflats represent only 9% of the intertidal areas of the estuary and provide about 20% of the benthic production (MARCHAND and ELIE, 1983 A). The two areas (1) and (2) constitute the middle estuary where daily and seasonal salinity fluctuations are maximal. The area (3) is the upper estuary or the oligohaline zone where limnic species are the basic components of the benthos, the river influence being predominant; in this area there are no mudflats, the river being completely canalized.

The present study was conducted from April 1981 to October 1982.

Abiotic characteristics

Daily river flow values were recorded at the Loire Hydrological Office station located at Montjean, 50 km upstream from Nantes. Water quality information, *i.e.* water temperature, salinity and dissolved oxygen measurements were obtained from several locations in the estuary: daily by the Water Quality Service of the Cordemais power station (area 2), and bimonthly by the R.N.O. (areas 0 and 1). Additional data on the spatial distribution of these variables throughout the estuary were recorded in June 1982 by SALIOT *et al.* (1984). The location and the extension of the Turbidity Maximum Zone (TMZ) were estimated from the data collected by GALLENNE (1974) and corrected according to the river flow values observed in 1981-1982. The concentrations of suspended matter given by SALIOT *et al.* (1984) were estimated after filtration on 0.2 μm Whatman glass microfibre filters and expressed as mg l^{-1}.

Fishes

Fishes were caught with a 3 m beam trawl (20 mm mesh size in the cod end) which was towed by a small fishing boat (9 m length) (MARCHAND and ELIE, 1983 b). Seventeen stations were sampled monthly, mainly around the high tide. The sampling sites were stratified according to the accessibility of the mudflats by boat, the water depth and the sediment characteristics. Fished area was estimated for each sample. Numbers and biomass of captured fishes were calculated per hectare. In the laboratory, fish samples were sorted; fish species were counted, weighted and classified according to their age group. From these data, mean monthly density and biomass were estimated per sampled area. At each station, analysis of fish diets showed a strong link between the composition of the gut contents and the composition of the benthic community (MARCHAND and ELIE, 1983b).

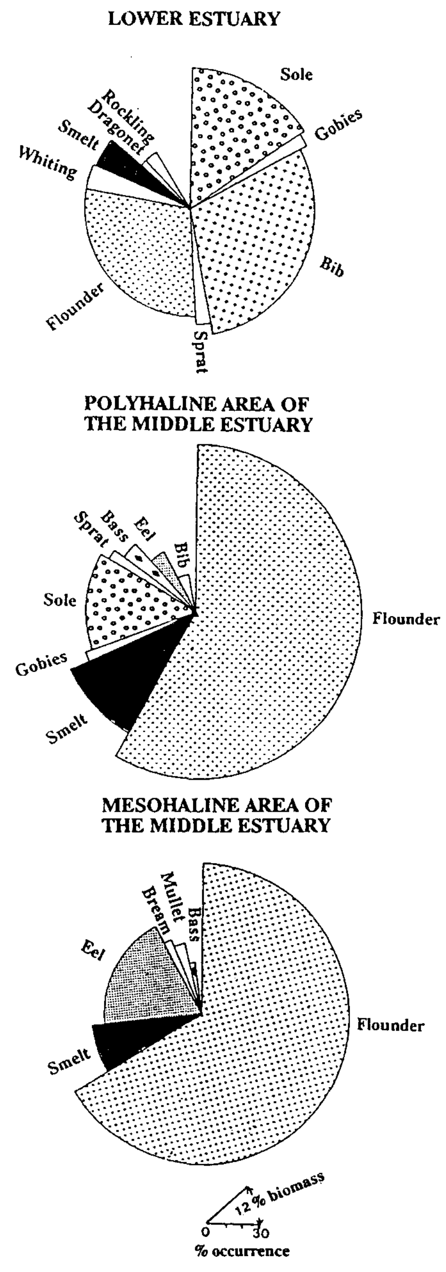

Fig. 2. Composition of fish assemblages in the different areas of the Loire estuary.

Benthic fauna

Macrobenthic fauna was sampled monthly from September 1981 to October 1982 along transects in the mesohaline area (4 stations) and in the polyhaline area (15 stations) in various depth and sediment conditions (MARCHAND and ELIE, 1983a; ROBINEAU, 1986). At each station, 5 replicates were taken using a 11.6 cm diameter core sampler to a depth of 30 cm. In the field, samples were washed through a 1.0 mm sieve and a solution of 5% formalin was added to the residue. In the laboratory, benthic samples were sorted to species level. Animals were counted (Nm^{-2}) and their biomass was measured as g ash free dry weight (gm^{-2}). Mean mensual density and biomass were calculated for each sampled area.

RESULTS

Distribution patterns of demersal fish populations

Mean distribution patterns were estimated from the 19 month cumulated observations (Fig. 2). During the study period, the fish community of the lower estuary was dominated by three main species: the sole (*Solea solea*), the bib (*Trisopterus luscus*) and the flounder (*Platichthys flesus*). In this area, juveniles accounted for 60 to 80% of the populations. In the polyhaline area of the middle estuary, the flounder, the sole and the smelt (*Osmerus eperlanus*) were the main components of the community; juveniles accounted for 70 to 90% of each population. In the mesohaline area of the middle estuary, the flounder was associated to the smelt, the mullet (*Liza ramada*), the bass (*Dicentrarchus labrax*), the eel (*Anguilla anguilla*) and the bream (*Abramis brama*). These populations were almost exclusively composed of juveniles (MASSON, 1987; LARDEUX, 1986). Density and biomass distributions in relation to salinity are shown in Fig. 3. The highest densities (2000 ha^{-1}) were recorded between 10 and 20 ppt. The highest biomass (27 kg ha^{-1}) was recorded at 5 to 10 ppt. These data show that the nursery function is mainly ensured by the middle estuary, *i.e.* the poly- and mesohaline areas of the Loire estuary.

Influence of river discharge on the hydrological conditions of the estuary

In comparison to a 100 year average, variation in river flow during the study period was characterized by very high values in winter 1981/1982 (3500 m^3s^{-1}) and low levels in summer (about 200 m^3s^{-1}) (Fig. 4). The duration of this low level period was normal in 1981: 2 months (August-September), but was very long in 1982: more than 4 months (mid May to late September).

These fluctuations had a direct impact on the location of the haline front (Salinity = 0.5 ppt) and of the Maximum Turbidity Zone (M.T.Z.) (Fig. 5). At high tide, the fresh water limit reached the

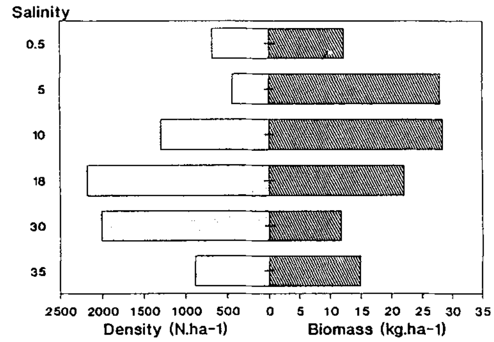

Fig. 3. Distribution of fish densities and biomasses according to haline conditions in the estuary (19 month observations cumulated).

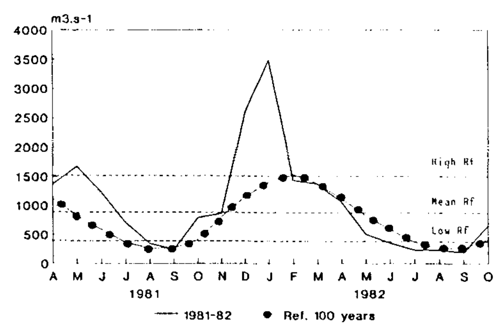

Fig. 4. Variations of the Loire river flow during the survey period compared to mean values calculated over a century.

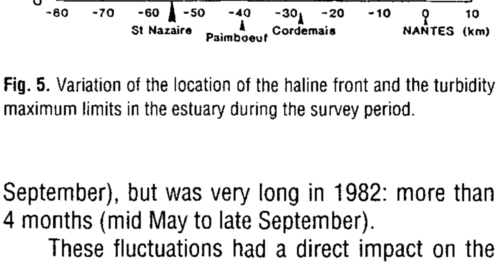

Fig. 5. Variation of the location of the haline front and the turbidity maximum limits in the estuary during the survey period.

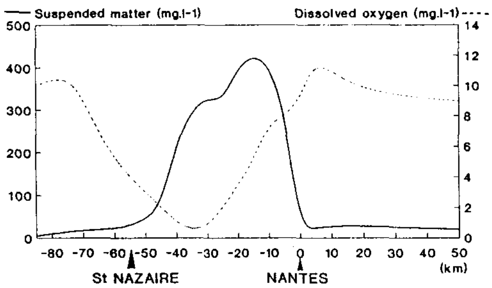

Fig. 6. Spatial distribution of suspended material and dissolved oxygen concentrations in the Loire estuary in June 1982 (from SALIOT *et al.*, 1984).

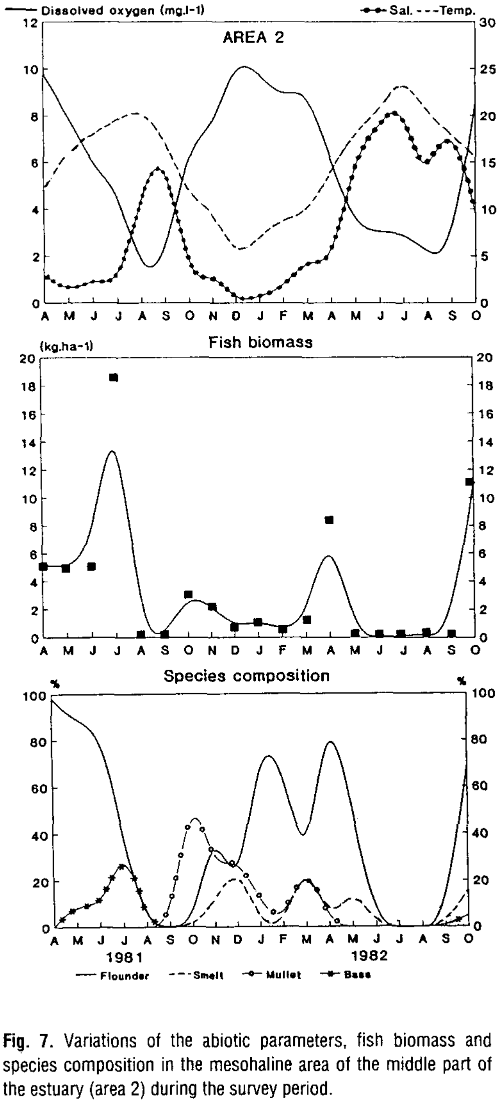

Fig. 7. Variations of the abiotic parameters, fish biomass and species composition in the mesohaline area of the middle part of the estuary (area 2) during the survey period.

area 2 in winter (35 km downstream of Nantes) and retreated upstream to Nantes in summer. The evolution of the M.T.Z. limits followed the same pattern: its occurrence was permanent in the estuary but according to the river discharge, it reached the lower estuary in winter 1981/82 or extended 10 to 30 km upstream into the middle and upper estuary in summer. So, whereas the polyhaline area (1) was little affected by this physical disturbance, the mesohaline and oligohaline areas were inside the M.T.Z. from July to November in 1981 and from April to October in 1982, *i.e.* during the main period of nursery function (spring-summer).

Comparison of the spatial distribution of the suspended matter with the dissolved oxygen concentrations in the estuary in June 1982 (SALIOT *et al.*, 1984) (Fig. 6) shows that low levels of oxygenation in the water column were linked to high turbidity: hypoxia occurred when 300 to 400 mg l^{-1} suspended matter concentrations were observed in the estuary, more precisely at 20 to 40 km downstream from Nantes. These results indicate that at the head of the estuary and in the upper part of the middle estuary, oxygen deficiency may occur in summer during several months when the river discharge is low and when temperature is increasing.

Effects of oxygen deficiency on fish populations

In the upper part of the middle estuary which was inside the M.T.Z. during most of the spring-summer period, oxygen deficiency conditions occurred mainly when salinity and temperature increased over 15 ppt and 18°C respectively (Fig. 7a): 3 mg l^{-1} from May to July 1982 and less than 2 mg l^{-1} in August and September 1981 and 1982. In such catastrophic conditions, decrease in fish biomass was concurrent with the hypoxia: from 13 kg ha^{-1} to 0 kg ha^{-1} in August 1981 and from 5 kg ha^{-1} to 0 kg ha^{-1} in May 1982 (Fig. 7b). Renewed occurrence of fish in this area coincided with the improvement of the oxygen conditions observed in October. Concerning species composition (Fig. 7c), the impact of oxygen deficiency affected mainly the flounder which is the dominant species of the community and also the bass which is normally present during summer time (like in spring and early summer 1981). These data demonstrate that when an early and protracted oxygen depletion period occurs in the mesohaline area of the Loire estuary, this area can not play its full role of nursery, the mudflats being out of reach of the fish for a long time.

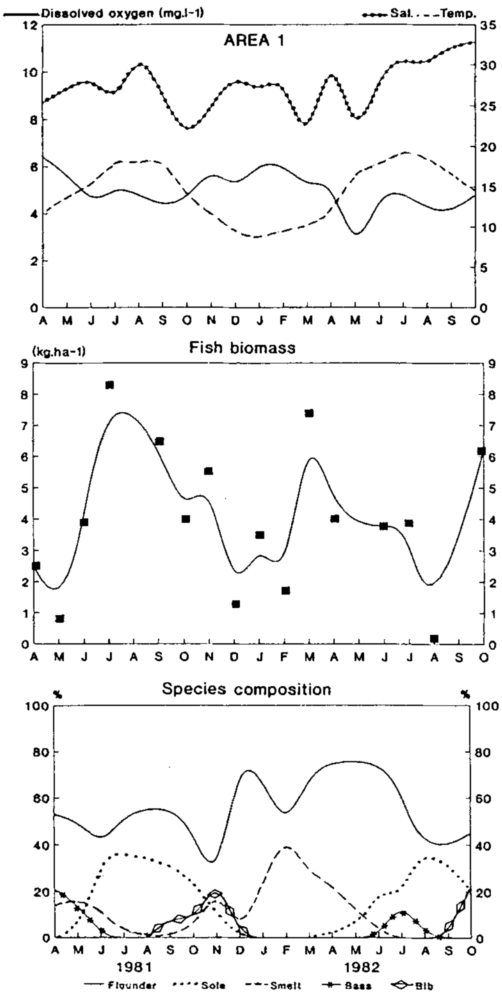

Fig. 8. Variation of the abiotic parameters, fish biomass and species composition in the polyhaline area of the middle part of the estuary (area 1) during the survey period.

In the polyhaline area (Fig. 8) which was at the downstream boundary of the M.T.Z., it was noticed that the nursery ability of this area might be also affected but to a lesser extent: it was observed that the estuarine recruitment of juveniles was disturbed from early May in 1982 when an oxygen sag occurred (less than 4 mg l^{-1}); it remained at a low level until the end of the summer with poor water quality conditions (4 to 5 mg l^{-1}). As for the species composition of the fish assemblage, no changes were observed: the flounder was the main component all year long and was associated either to the sole during the spring and summer periods or to the smelt and the bib in fall and winter.

Although fish biomass is highly variable in an estuary, these data suggest that a poor water quality may have an impact on the nursery function of the middle Loire estuary as low oxygen levels constitute a barrier to the fish estuarine migration.

Comparison of the fish biomass distribution in the whole ecosystem in July 1981 (without oxygen depletion) and in July 1982 (hypoxia) (Fig. 9) shows that an upstream shift of the biomass maximum may occur with an accumulation of juveniles at the downstream limit of the M.T.Z. in more suitable oxygen conditions (Fig. 9).

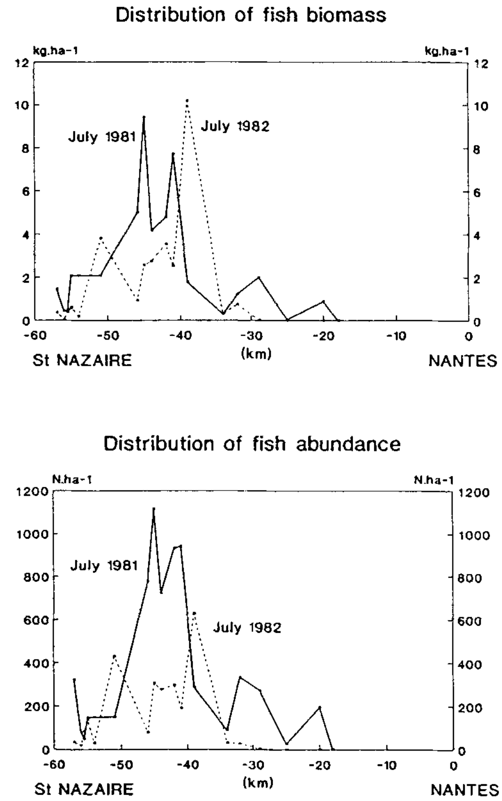

Fig. 9. Comparison of the distribution of fish biomass and abundance in the estuary in summer conditions, July 1981 (without hypoxia) and July 1982 (with hypoxia).

Effect of disturbance on the benthic trophic resources

In the upper part of the middle estuary (area 2), the evolution of the benthic populations was marked by high biomass of oligochaeta in winter

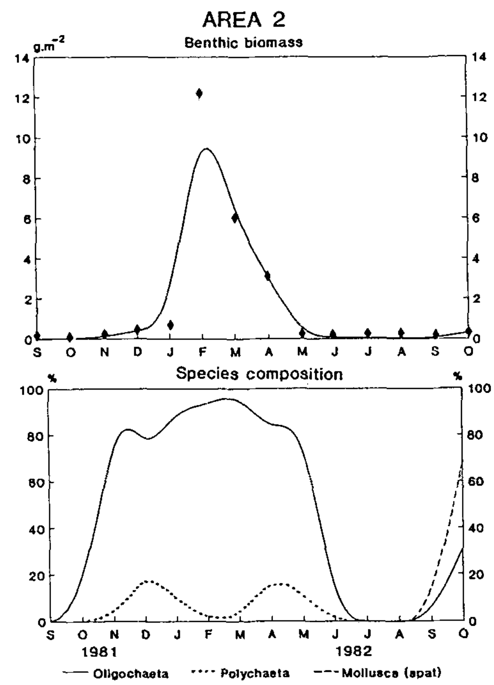

Fig. 10. Variation of benthic biomass and species composition in the mesohaline area of the middle part of the estuary (area 2) during the survey period.

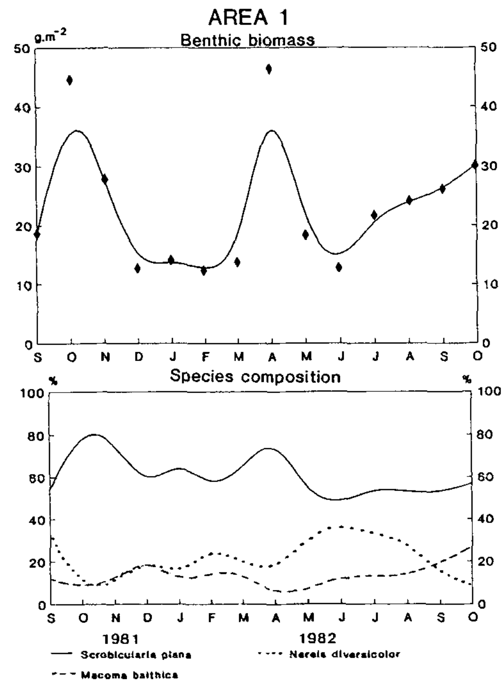

Fig. 11. Variation of benthic biomass and species composition in the polyhaline area of the middle part of the estuary (area 1) during the survey period.

and a net decrease in early spring 1982 when oxygen conditions became unfavourable (Fig. 10). After a period of substrate defaunation (May to September), recolonization proceeded rapidly with an assemblage of oligochaeta and spat of molluscs (*Scrobicularia plana*) whose adults are located in the polyhaline area.

In the lower part of the middle estuary (Fig. 11), variations in biomass were less pronounced: after a net decrease in early spring 1982, it seems that the impact of low oxygen conditions in summer 1982 was weak, a progressive increase in benthic biomass being observed throughout the summer time. As for fishes, no variation in species composition was observed.

These data indicate that both fish and benthic populations are affected by an oxygen depletion mainly in the upper part of the middle estuary.

DISCUSSION

Temperate estuaries are known to provide important nursery habitats for euryhaline fishes and crustaceans which find large food resources in the warm and calm areas (HAEDRICH, 1983, POMFRET *et al.*, 1991). Abundance and species composition of these assemblages are cyclic with high concentrations of juveniles in Spring and Summer when salinity and temperature are at their maximum (DAY *et al.*, 1989). In the Loire estuary, the nursery function follows a typical pattern with the progressive landward extension of fish populations on feeding grounds when low river discharge allows salt water intrusion into the middle estuary (DESAUNAY *et al.*, 1980; MARCHAND and ELIE, 1983b). However, this pattern can be modified by disturbances linked to abiotic conditions (pollution, climatic changes) or to biological features (fluctuations in stock size) (DAY *et al.*, 1989; DE BEN *et al.*, 1990). One of these disturbances may be associated with the turbidity maximum whose extent depends on the suspended matter load of the estuary. In most estuaries, this turbidity maximum is located at the freshwater-brackish interface which is the meeting point of the river and tidal currents (the 'stagnation point') (McLUSKY, 1981). This entrapment zone is usually located in the upper part of an estuary. In the Loire estuary, the turbidity maximum (total content varying between 3 to 5.10^5 tons) extends not only in the upper estuary but also in the middle estuary over 20 to 40 km in areas where salinity varies between 15 and 20 ppt. In the Loire estuary, dynamics of the turbidity maximum are well documented (GALLENNE, 1974; BROSSARD and GALLENNE, 1982; ANONYMOUS, 1984). At neap tides, this turbid mass settles onto the bottom where it constitutes a thick mud layer. When the river discharge is at its lowest, this bottom layer whose height varies between 2 and 3 meters, is more than 20 km long and is composed of very dense material (100 to 300 gl^{-1}). When the river is in spate, water currents increase and erosion induces reduction of its length and thickness to 5 km and to 1 m respectively. At spring tides, resuspension of the particulate material previously settled induces an increase of water turbidity with concentrations that may be 10 times that observed in neap tides conditions. Such mechanisms, which were also described in other estuaries (MASKELL, 1985), induce a decrease in water quality which can have repercussions on the biology of the estuarine populations.

Concerning the planktonic primary production in the Loire estuary, SALIOT *et al.* (1984) and RINCE (1983) observed that the main production area was located upstream from the entrapment zone and provided large quantities of dissolved oxygen in the limnic area (D.O. concentrations: 10 mg l^{-1}). RINCE (1983) and ANONYMOUS (1984) showed that the M.T.Z. constitutes a physical obstacle in which the upstream primary production is accumulated, degraded (high concentrations in phaeopigments) and mixed with the urban and industrial effluents discharged into the estuary (ANONYMOUS, 1984). Some authors described the M.T.Z. as being an important area of secondary production. Such a role was described by DODSON *et al.* (1989) in the Gulf of St. Lawrence where retention of typical estuarine planktonic species (smelt larvae *Osmerus mordax, Neomysis americanus, Gammarus* sp.) is ensured by the specific hydraulic conditions occurring in the stagnation point of the estuary. However, in most cases, high zooplanktonic densities were observed upstream the M.T.Z. as in the Gironde estuary (CASTEL and FEURTET, 1987) and in the Loire estuary (RINCE, 1983) with massive populations of the detritivorous Calanoid Copepod *Eurytemora hirundoides* populations.

The Maximum Turbidity Zone may also be considered as a 'sewage treatment plant' where decomposition of organic detritus is ensured by micro-organisms: oxygen conditions are suitable just seaward and landward of the turbidity maximum. However this positive role may be disturbed when inputs of organic and mineral material reach a critical level. Thus dredgings which are realized for shipping channel maintenance may have a detrimental effect on the fauna by increasing the volume of suspended material (CYRUS and BLABER, 1988; DAY *et al.*, 1989): in the Loire estuary, dredging volume increased twofold between 1975 and 1980 (ANONYMOUS, 1984); industrial and urban wastes which are not correctly treated contribute to increase in the organic loading of the water and the sediment. These harms, which are linked to man's activities, are conducive to an increase of the spatial and temporal extent of hypoxia.

Several authors showed that no relationship exists between dissolved oxygen concentrations and salinity (POMFRET *et al.*, 1991) and that the oxygen depletion is all the more catastrophic when high temperature conditions occur in the entrapment zone (MACKAY and FLEMING, 1969). So hypoxia (indeed even anoxia) may become a recurrent event as soon as the unfavourable conditions of river flow, tide, turbidity and temperature occur concommitantly in the upper and the middle parts of an estuary.

In estuaries, macrobenthic and demersal populations are well adapted to turbidity. CYRUS and BLABER, 1987a,b showed that turbidity can play a significant role in determining the distribution of juvenile fishes in an estuary. Turbidity may prevent interspecific and intraspecific predation by reducing the light intensity in the nursery area. Moreover, in turbid areas, muddy substrates which are located in sheltered and shallow areas, supply large food resources which may be attractive for juvenile fishes. In the Loire estuary, distribution patterns of fishes show that they are mainly concentrated in areas with large trophic resources (MARCHAND and ELIE, 1983b). However this pattern is disturbed when oxygen deficiency conditions occur: fishes escape the hypoxic areas and accumulate in areas where oxygen conditions are suitable. It is obvious that the limit of the nursery function which would progress upstream in summer with the intrusion of salt water into the estuary, is controlled by the oxygen deficiency zone. Such a pattern was observed by POMFRET *et al.* (1991) in two U.K. estuaries where a summer depletion of dissolved oxygen occurred: the poor water quality constituted a barrier to fish migration, even for the flounder which was not recorded at oxygen levels below 5 mg l^{-1}. In the Loire estuary where conditions may be more severe (less than 4 mg l^{-1} during a 20 week hypoxia in 1982), the reduction of available feeding areas concern not only this species, but also the bass, the smelt and the sole.

To hypoxic conditions, macrobenthic communities which constitute food resources for fish juveniles respond by cyclic reduction in biomass or mass mortalities (SANTOS and SIMON, 1980; GASTON *et al.* 1985; GASTON, 1985; MARCHAND and GASCUEL, 1988; MARCHAND and DENAYER, 1991). One of the biological characteristics of areas which are periodically subject to disturbances, is that benthic communities are constantly modified with succession of species and variations in abundance (GASTON *et al.*, 1985; MARCHAND and GASCUEL, 1988). Although the dominance of oligochaeta is an indicator of a high organic pollution in the Loire middle estuary, oligochaeta populations constitute trophic resources which are used by several fish species (MARCHAND and ELIE, 1983b). Since their high recovery rate, their total disappearance in hypoxic conditions is not really catastrophic (SANTOS and SIMON, 1980): the disturbed areas can rapidly recover their trophic function as soon as the hydrological conditions improve.

Such disturbances, which may become cyclic with an increasing frequency linked to climate changes and man's activities, can affect not only the nursery function of an estuary by reducing availability of the feeding grounds to juveniles but also its role as a transit way for amphihaline species: in the Loire estuary, periodic mass mortalities of mullet (*Liza ramada*) are observed in August-September when subadult fishes leave the fresh water areas to breed in sea water. In this case, fish are unable to go through the turbidity maximum and die by asphyxia (SAURIAU, 1990; SAURIAU *et al.*, 1991).

At the moment, because of the regular degradation of the Loire water quality, we consider that the fate of both functions of the estuary, *i.e.* nursery area and transit way, are seriously endangered.

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