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Upwelling and outwelling effects on the benthic regime of the continental shelf off Galicia, NW Spain

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ABSTRACT

The benthic regime off the Galician coast of NW Spain was surveyed to assess biogenic enrichment from coastal upwelling and detritus outwelling from the rías, large coastal embayments: the Rías Altas along the northern and the Rías Bajas along the western coast, which have intense mussel aquaculture. Sediment samples were collected from 1984 to 1986 and used for geological, microbiological, and macrofaunal studies. Sub-bottom acoustic profiler records and grab and core samples identified two main mud deposits on the western shelf that were aligned north to south and parallel with the coastline. The major axis of the mud deposit, which extended south to the Portuguese border, is associated with the three most southern rías (Arosa, Pontevedra and Vigo) along the western shelf. Sediment particle size analysis showed that sediments on the western shelf were heterogeneous, and grain size increased from the inner shelf to the shelf break. On the northern shelf, sediments exhibited a more homogeneous textural distribution. Sediment organic matter followed a similar pattern with that of particle size. The highest organic matter values, 10%, occurred on the western shelf nearest the Rías Bajas, but these values decreased offshore to between 2 and 4%. On the northern shelf organic matter content was generally less than 4% but with patches of higher organic content.

The composition and structure of macroinfauna on the northern shelf, where seasonal coastal upwelling results in benthic enrichment, showed mainly small, surface feeding, and fast growing polychaetes. In contrast, macroinfauna on the western shelf showed more subsurface, deposit-feeding polychaetes. A main difference between the two shelves is that off the Rías Bajas, besides coastal upwelling, outwelling from the highly productive Rías Bajas, with their intense mussel aquaculture, also enriches the coastal sediment regime with a steady source of organic matter. Although seasonal and interannual variations occurred in the benthic bacteria, their general density distribution followed the pattern of organic matter content and particle grain size seasonally and interannually. The highest numbers of bacteria occurred in the upwelling region off the northern shelf and nearest the Rías Bajas on the western shelf.

Both coastal upwelling and organic outwelling from the Rías Bajas support benthic

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production along the western Galician shelf. The main commercial demersal finfish along this coast is hake, *Merluccius merluccius* and blue-whiting, *Micomesistius poutassou.* The norwegian lobster, *Nephrops norvegicus* is also an important crop, and is more abundant off the Rías Bajas in the finer and organic-rich sediments where there are abundant prey resources of benthic infauna.

1. Introduction

The coastal ocean off Galician NW Spain (43N 9W), an area exhibiting coastal upwelling, supports commercially-important pelagic and demersal fisheries along a narrow (10 km width) shelf, as well as intense raft mussel aquaculture in the rías, large oceanic embayments to the north (Rías Altas) and west (Rías Bajas) of Cape Finisterre. During the last decade there was a cooperative program, FOG (Fisheries and Oceanography off Galicia), involving scientists from the Instituto Espanol de Oceanografía and several U.S. universities, investigating the oceanographic regulatory processes and resultant food chain patterns of this high coastal production. This present study is a part of that larger program.

This coastal area exhibits mesoscale spatial and temporal patterns of upwelling (Wooster *et al.,* 1976; Fraga, 1981; Blanton *et al.,* 1984; McClain *et al.,* 1986; Tenore *et al.,* 1992). Upwelling is common from April through September because of the seasonal migrational pattern of the Azores high and resultant changes in patterns of coastal wind direction. Surface upwelling is more persistent off and north of Cape Finisterre. Because of local geomorphology, upwelled water also intrudes into the Rías Bajas.

Nutrient enrichment associated with upwelled water results in high pelagic productivity on the shelf and in the Rías Bajas (Campos and González, 1975; Tenore *et al.,* 1992). Along the coast there is an important pelagic fisheries, especially off Cape Finisterre. A coastal purse-seine fishery for sardine, *Sardina pilchardus,* typically yields ca. 80,000 metric tons annually along the Galician coast (Porteiro *et al.,* 1986). There is also an important demersal fishery along the Galician shelf, including hake, *Merluccius merluccius,* blue-whiting, *Micromesistius poutassou,* and Norway lobster, *Nephrops norvegicus* (Fariña *et al.,* 1983). In the Rías Bajas, the high primary productivity supports an intense raft culture of the edible mussel, *Mytilus edulis* (Tenore and González, 1975; Pérez and Román, 1979; Blanton *et al.,* 1987). The Ría de Arosa alone produces ca. 100,000 metric tons total wet weight of mussels. The intense culture has profound effects on the ecology of the rías (Tenore *et al.,* 1982). One important result of this mariculture is the high amount of detritus produced from the feces/pseudofeces of the raft mussel community. This results in sediments with high ($>12\%$) organic matter that are easily suspended and transported. Continental shelves, especially those bordered by coastal rivers and embayments, contain sediment deposits of coastal origin. The western Galician shelf off the Rías Bajas is a good example where recent suspended sediments from the coastal zone, rather than erosional materials from the shelf itself, are an important source of

shelf deposition. Because of the high organic content of the sediments resulting from the high primary production and intense mussel aquaculture, the rías can supply a large amount of organic enrichment to the shelf regime off the Rías Bajas by means of outwelling.

Spatial differences of these processes along the land-sea interface of the Galician coast allows us to investigate the effect of enrichment of the shelf sedimentary regime from pelagic production associated with coastal upwelling, and outwelling of organics onto the continental shelf off the Rías Bajas. We studied sediment characteristics, macroinfaunal benthos and bacterial abundance in the sediments of the Galician shelf to ascertain any evidence of enrichment effects on the shelf benthic regime that might support production of local bottom fisheries.

2. Material and methods

From 1984 to 1986 benthic sediment samples were collected over 123 stations located on both the northern and western Galician (NW Spain) continental shelf (Fig. 1) with a Bouma box corer (0.0175 m^{-2} surface area and 15 to 20 cm sediment depth). Overlying water depth at these stations ranged from 48 to 267 m. These samples were used for sediment analysis (grain size, organic matter content), microbiology, and macrofauna studies. Upper sediment layer (surface to 14 m maximum thickness) of recent sediment deposits was also studied by means of sub-bottom acoustic profiling.

a. Geology

High resolution sub-bottom profiling (3.5 kHz), Geopulse and/or Uniboom and side scan sonar was used to study the characteristics of the uppermost layer (0 to 14 m thick) of recent sediments from the inner to the outer shelf, to a maximum water depth of 200 m. Sediment sampling was carried out either with a Shipek grab or a Bouma box corer and piston corer (5 cm diameter and 2 m long). Echoseismic records were obtained with: (1) high resolution sub-bottom profiler (3.5 kHz and 10 Kw transmission power), connected to an analogical precision recorder EPC 3200 on dry paper; (2) high resolution continuous seismic profiler Geopulse and Uniboom (300 joules); (3) sonographs were obtained with a Klein 4000 Side Scan Sonar operating at a frequency of 100 kHz, and two channels were registered on wet paper with a slant range of 150 and 200 m each. Sediment samples were used to correlate sediment type and acoustic response.

b. Sediment analysis and macroinfauna

Particle size analysis was performed by a combination of dry sieving and sedimentation techniques (Buchanan, 1984). Organic matter content of the sediment, reported as %OM was estimated as weight loss of dried (100°C, 24 h) samples after

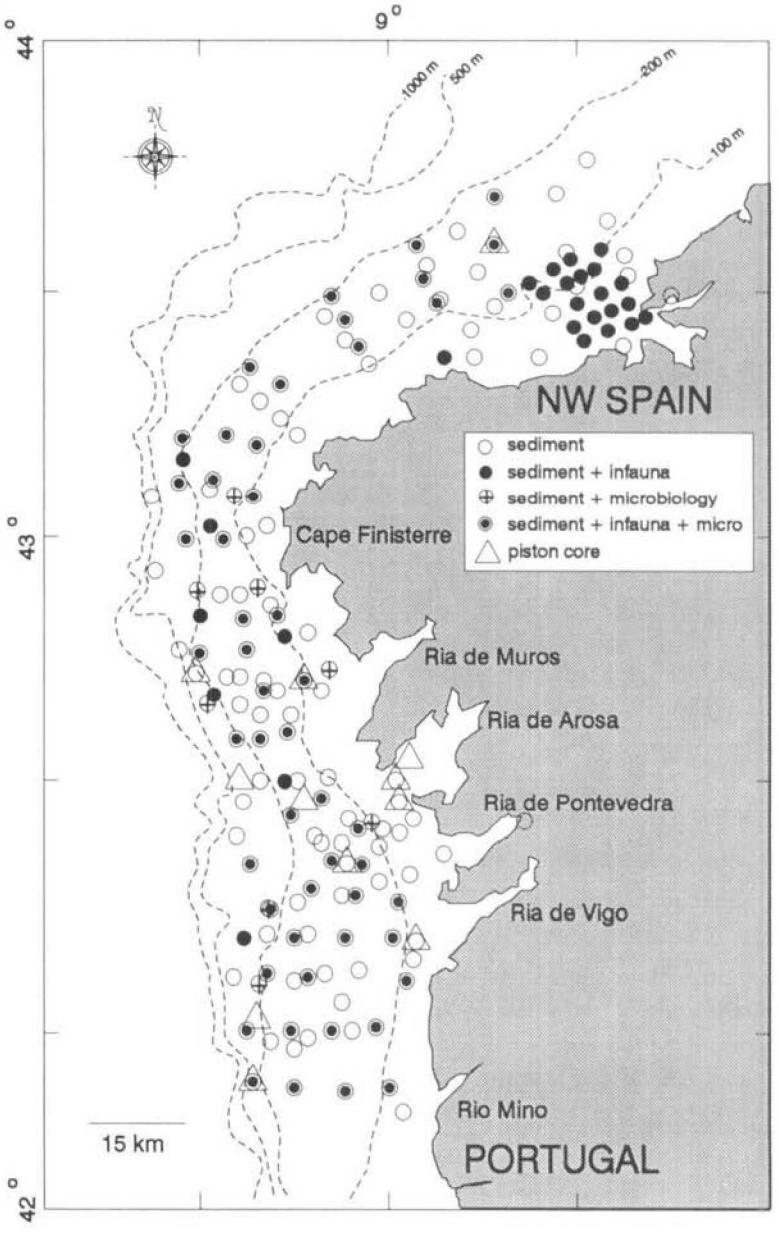

Figure 1. Sampling stations on the Galician shelf (NW Spain). Solid dots show stations for both sediment and macrofauna; open dots show stations for sediment only.

combustion (500°C, 24 h). Macroinfauna samples were sieved through a 0.5 mm sieve, anaesthetized with a methanol solution and then preserved in 5% buffered formaldehyde containing Rose Bengal solution. After each cruise, the preserved samples were sorted, identified to species whenever possible, and wet weight of each

taxa recorded. Correlations of wet weight (WW) to ash-free dry weight (AFDW) were used to estimate biomass. The Morisita index (Morisita, 1959) modified by Horn (1966) was used to calculate faunal similarity among stations, and a cluster diagram was constructed to delimit communities (Southwood, 1971). Diversity was calculated using abundance data with the Shannon function (Shannon and Weaver, 1963), and evenness was estimated as defined by Pielou (1966).

c. Bacteria

Bacteria were enumerated using the acridine orange direct count (AODC) method (Hobbie *et al.,* 1977). Each sediment core was sampled in triplicate and the top 1 cc was preserved in sterile test tubes containing an autoclaved-filtered seawater solution of formaldehyde (AFSW) (2% final concentration). Preserved samples were stored at 4°C until processed within two weeks after the cruise. Samples were sonicated for 5 minutes. Coarse particles were allowed to settle for 1 minute, and 1 ml was diluted 100 times with AFSW. Finally, 2 ml were stained in sterile test tubes for 3 minutes with filtered acridine orange (0.01%) in AFSW. Blanks were run daily. Stained samples were filtered through 0.2 μm Nucleopore filters (2.5 cm), previously stained with Irgalan Black. Maximum vacuum of 15 cm of Hg was applied. The filters were immediately placed on a drop of non-fluorescent immersion oil, a second drop of immersion oil was placed on top, and covered with a cover slip.

Stained bacteria were observed by epifluorescence microscopy (Zeiss standard microscope fitted with an epifluorescence condenser, HBO 50 W lamp, BG 12 excitation filter, FT 510 beam splitter and LP 520 barrier filter). Bacteria were counted at a magnification of 1000× in a minimum of 20 randomly chosen microscopic fields. Only organisms with a clear bacterial shape were counted. Numbers of bacteria per g of sediment (dry weight) were obtained from the mean count per microscopic field, the field area, the actual area of filtration, the volume of sample filtered, the dilution factors, and porosity.

3. Results

a. Geology

The narrow shelf slopes gently seaward and is generally flat, with small-scaled irregularities of rocky outcrops and related coarse-sand shoals in most of the nearshore littoral zone (Fig. 2). The numerous irregularities plotted from the bathymetric studies are caused by a rocky belt running along the entire inner littoral zone of the shelf. In contrast, the middle and outer shelf have little or no relief. On the western shelf, there is a flat consolidated outcropping covered by a deposit of medium grain-sized sand, which is related to a subaerial erosion following a sea level decrease (Dias *et al.,* 1986; Vanney and Mougenot, 1981). At the shelf break, the sedimentary deposits are represented by distal progradational sand units.

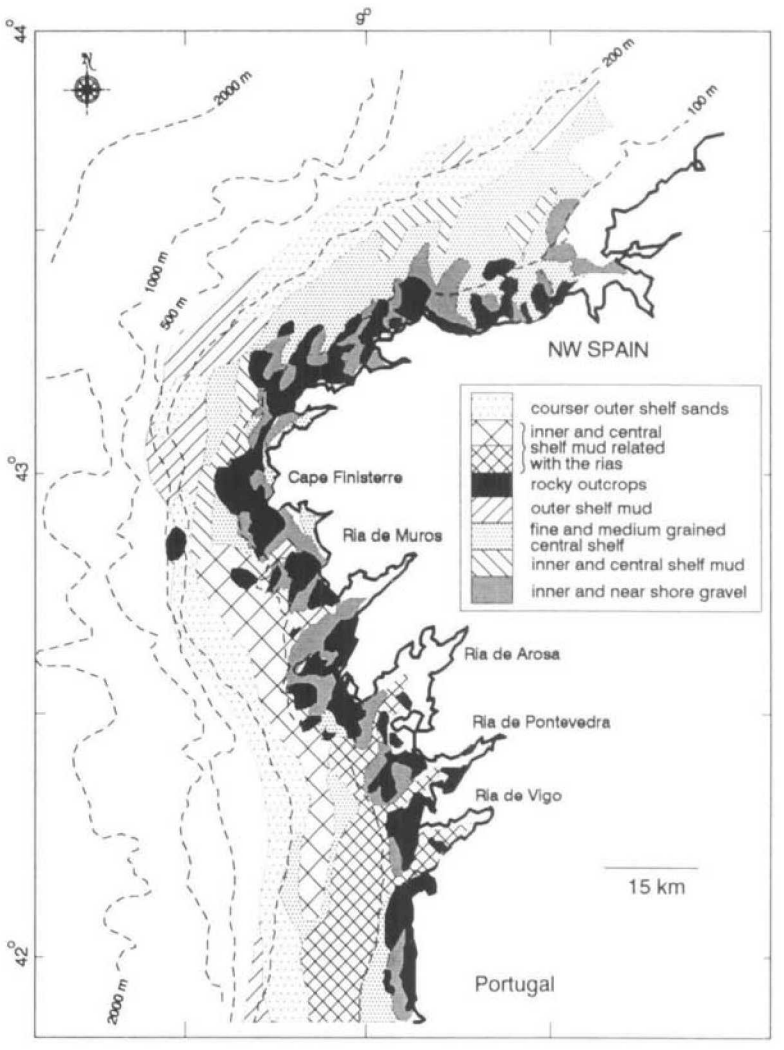

Figure 2. Schematic map of the Galician shelf showing the general distribution of superficial sediment type and rock outcrops.

Two large provinces, north and west of Cape Finisterre, of bottom sediment types can be distinguished. The extension and position of the sand and mud deposits on each province are determined by the relative values of water flow and associated near-bottom suspended material. North of Cape Finisterre, a shelf sand blanket dominates. There are some anomalous mud patches that seismic records show to be up to 17 m thick. West of Cape Finisterre, on the inner and middle shelf, a mud or muddy sand layer 1 to 14 m thick dominates. There are some exposed sandy mud areas having no surficial muds (Fig. 3). Grab samples and sub-bottom profiling

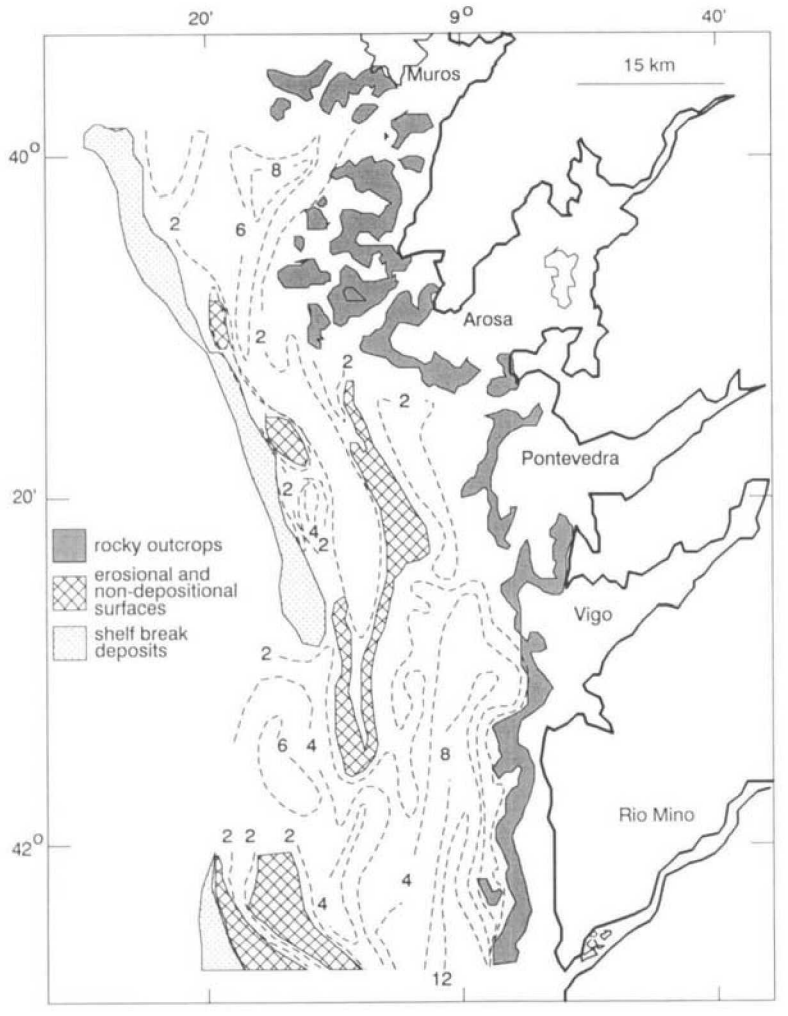

Figure 3. Schematic isopach map of the Galician shelf mud Holocene deposits, based on 3.5 kHz sub-bottom profiling records. 1: rocky outcrops; 2: erosional and no depositional surfaces; 3: shelf break deposits. Contour lines in meters.

records show that these sandy-mud areas are exposed by a "window" in the shelf mud blanket (Rey and Díaz del Río, 1987).

A schematic isopach map of the western shelf based on sub-bottom profiler records, grab and core samples displays the thickness of the mud shallow layer shallow layer (Fig. 3). From this map two axes of maximum thickness can be inferred, whose main direction is oriented on a N-S axis subparallel to the coastline, and separated by an area of no deposition of mud. One of these sedimentary bodies is related to the Rías de Corcubión and de Muros; the other, having a greater thickness,

is associated with the Rías de Arosa, de Pontevedra and de Vigo. The latter extends to the River Limia, south of the Portuguese border (Dias and Nittrouer, 1984; Rey and Díaz del Río, 1987).

b. Macroinfauna

i. Particle size analysis and organic content of the sediment. Data on mean particle size and organic matter of surface sediments from previous investigations on the Rías Bajas (López-Jamar, 1978, 1981, 1982; Tenore *et al.,* 1982; López-Jamar and Cal, 1990) illustrate land (rías)-sea (shelf) coupling, and have been included in the maps of spatial distribution of surface sediment characteristics (Figs. 4 and 5). On the western shelf, sediment particle size increases from the inner part of the Rías Bajas towards the shelf. Inner shelf sediments are silty, with a mean particle size diameter generally ranging from 4 to 6 Φ. Middle shelf sediments have a higher proportion of sand, with a mean particle size diameter ranging from 3 to 4 Φ. Outer shelf sediments are even more sandy, with a mean particle size diameter of 2 to 3 Φ (Fig. 4). On the other hand, the northern shelf has a more homogeneous sediment distribution. Most of the area is composed of fine muddy sand, with a mean particle size diameter ranging from 2 to 3 Φ. Off the Rías Altas there is an area having a coarser sediment (<1 Φ).

The distribution of organic matter content (% AFDW) of surface sediments follows a similar pattern to that of mean particle size (Fig. 5). Highest values appear in the inner part of the Rías Bajas ($>10\%$). Relatively high values appear in the inner shelf off the Rías Bajas ($>6\%$), with lower values toward the open sea. In the northern shelf, organic matter content is generally lower ($<4\%$), although there are several sediment patches having higher values.

ii. Benthic species composition and community structure. A total of 272 taxa comprised of polychaetes (180), molluscs (43), crustaceans (26), and echinoderms (12) were identified from the samples. Because some taxa were identified only to a high taxon level (Phylum, Family or Genus), the total number of taxa is conservative. The complete taxonomic list is available from the senior author.

A first attempt to identify communities using cluster analysis revealed a very high similarity among most of the stations, mainly caused by the great ubiquitousness and abundance of the polychaete, *Prionospio malmgreni.* The result of the cluster analysis, after eliminating this species, also shows a high similarity, but several cluster groups can be distinguished (Fig. 6). We have related these groupings with environmental variables, such as depth and sediment characteristics. All of these groupings but one are numerically dominated by *P. malmgreni.*

Cluster groups A, B, and C have similar species composition and structure, as well as environmental characteristics (Table 1). Sediment at the sites of these samples ranges from fine muddy sand to sandy mud, and organic content is moderate. Small spionids (*Prionospio malmgreni, P. cirrifera, Pseudopolydora paucibranchiata*), para-

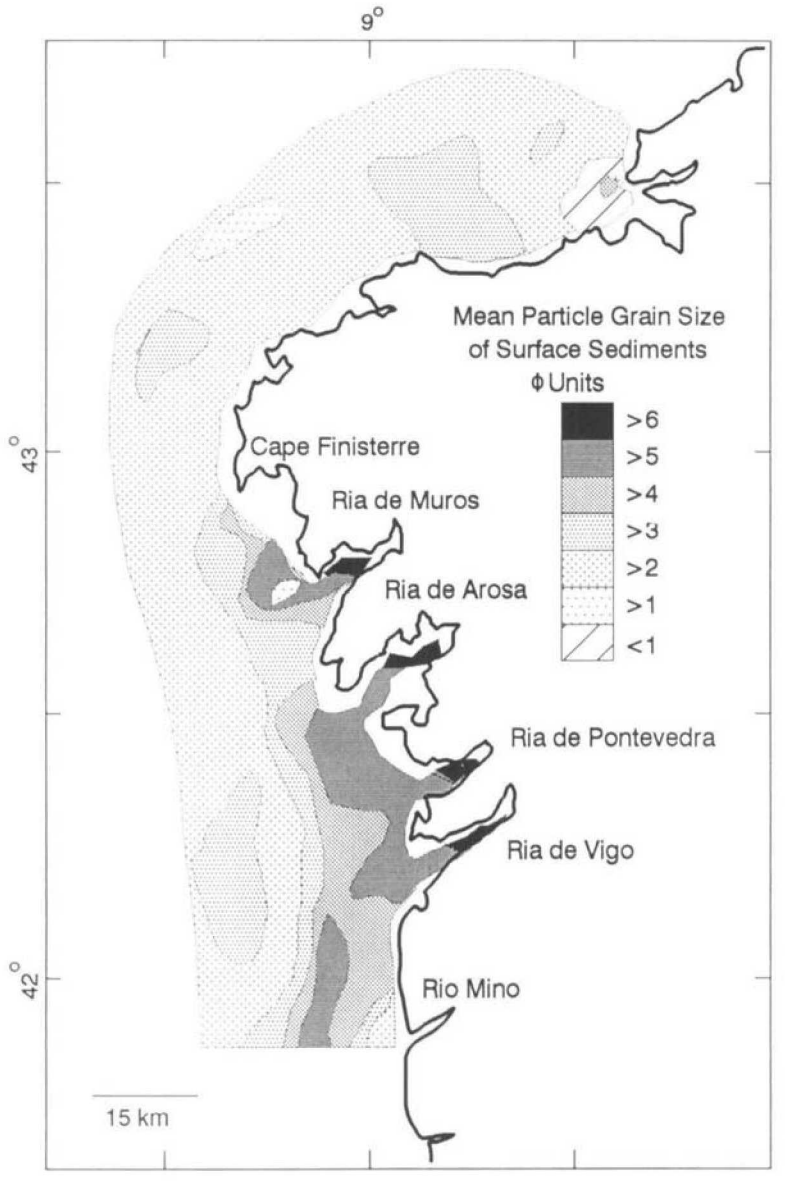

Figure 4. Spatial distribution of mean particle size (Φ units) of surface sediments of the Galician shelf (NW Spain).

onids (*Paraonis gracilis, Paradoneis lyra, Aricidea* sps.) and the cirratulid, *Tharyx marioni* dominate numerically most of the stations. The polychaetes, *Nephtys hombergi* and *Glycera rouxii,* dominate benthic biomass. The stations forming these three groups are distributed throughout most of the study area, except the inner part of the western shelf and off the Rías Altas. Group A is mainly formed by the middle and

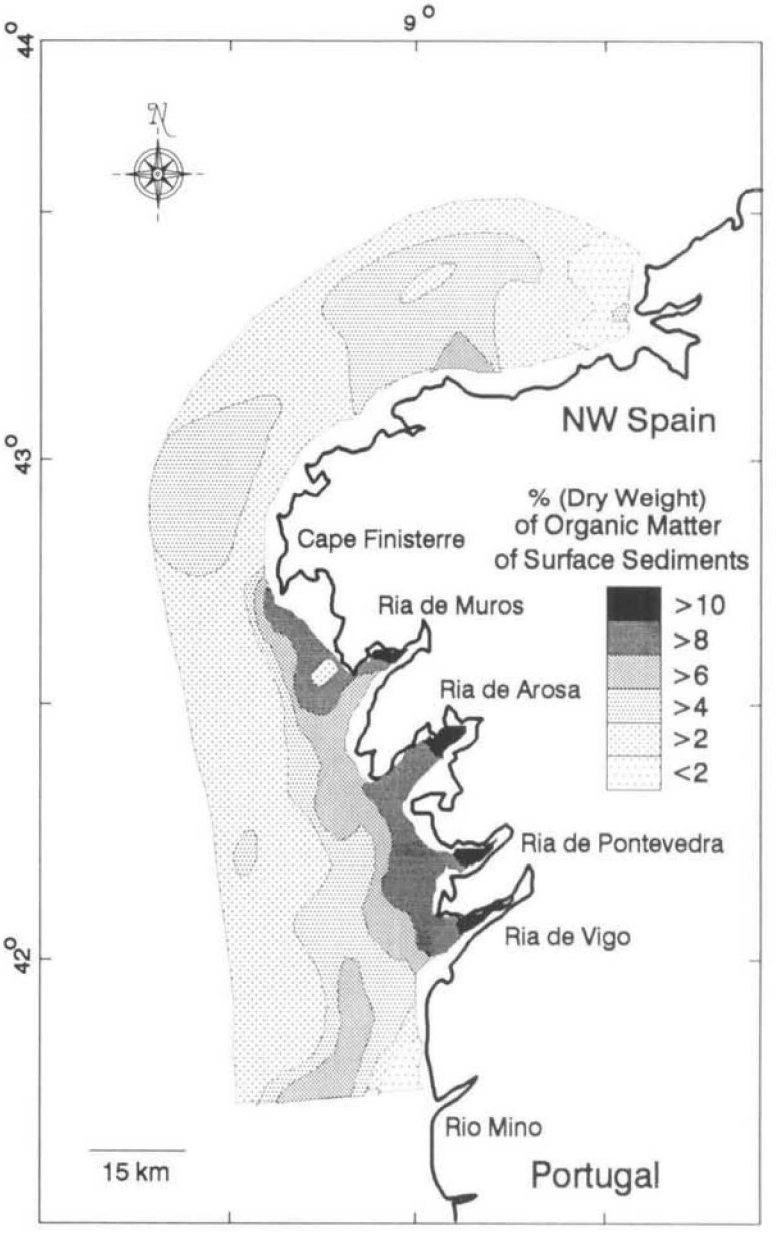

Figure 5. Spatial distribution of organic matter content (% OM of sediment dry weight) of surface sediments of the Galician shelf (NW Spain).

outer shelf stations off the Rías Bajas and the inner area off Finisterre; stations of Group B are distributed in the middle shelf area, and Group C is formed by the outermost stations. However, the stations of Groups B and C are always located off and northward of the Ría de Arosa (Fig. 7).

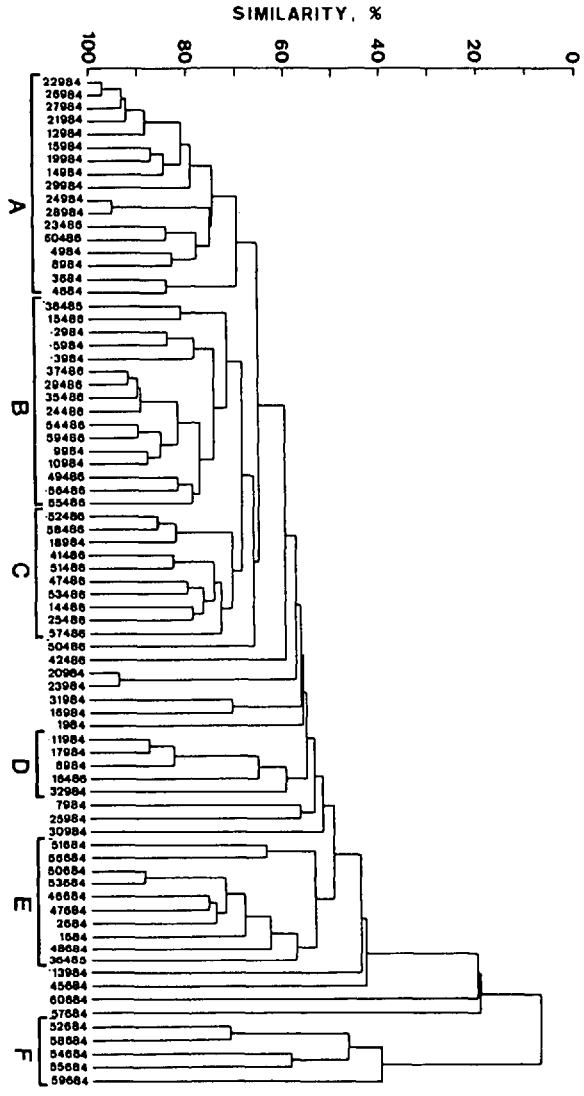

Figure 6. Dendrogram showing clustering of stations based on macroinfaunal similarity among macroinfauna stations of the Galician shelf.

The stations of Group D are mainly distributed along the inner shelf off the Rías Bajas. The sediment is usually finer and organic content is higher than those of the other community groups. Although small spionids and paraonids are still numerically dominant, the proportion of larger, burrowing polychaetes (*Sternaspis scutata, Notomastus latericeus*) is higher; these two species dominate benthic biomass.

The stations of Groups E and F are located off the Rías Altas, along the northern shelf. Group E stations occupy the outer area, in sediments ranging from fine sand to

Table 1. Water depth, sediment characteristics, species number, diversity, evenness, abundance, and biomass of the 6 macroinfaunal cluster groups

	Cluster Groups					
	A	B	C	D	E	F
Max. depth	190	108	246	168	142	86
Min. depth	100	119	115	96	62	59
Avg. depth	135	156	205	120	114	71
Max. org. matter	6.30	4.40	5.87	8.34	4.56	1.94
Min. org. matter	2.10	2.10	2.43	3.51	1.24	0.42
Avg. org. matter	3.70	3.43	4.04	6.64	2.72	1.09
Max. species number	61	52	62	33	49	40
Min. species number	27	32	26	26	33	32
Avg. species number	45	39	43	30	41	36
Max. diversity (H')	4.21	4.49	4.91	3.93	4.87	4.64
Min. diversity	2.15	1.55	3.25	2.20	3.37	2.59
Avg. diversity	3.48	3.37	4.28	2.71	4.15	3.87
Max. evenness (J')	0.79	0.84	0.90	0.78	0.88	0.90
Min. evenness	0.42	0.31	0.69	0.44	0.63	0.50
Avg. evenness	0.64	0.64	0.80	0.55	0.78	0.75
Max. abundance ($n m^{-2}$)	15636	10024	5532	7692	5372	2480
Min. abundance	2195	1657	1326	2080	1772	1166
Avg. abundance	6031	4011	2469	4512	3020	1897
Max. biomass (g m^{-2} AFDW)	4.0	2.6	1.6	6.6	5.3	2.3
Min. biomass	0.2	0.2	0.1	0.9	0.7	1.1
Avg. biomass	2.2	1.2	0.8	3.4	2.4	1.7

sandy mud and with an organic content low to moderate. Spionids and paraonids are numerically dominant, but small capitellids are abundant as well. The burrowing polychaetes, *Euclymene oerstedi* and *Notomastus latericeus,* dominate benthic biomass. Group F stations are located in the inner part of the shelf off the Rías Altas; their sediment is composed of medium to coarse sand, with a very low organic content. Small capitellids are numerically dominant, whereas the onuphid polychaete, *Hyalinoecia bilineata,* dominate benthic biomass. This group is characterized by the presence of species typical of lose sand sediments: *Glycera lapidum, Aonides oxycephala, Protodorvillea kefersteini,* and *Echinocyamus pusillus.*

iii. Biomass and diversity. Biomass values (g AFDW m^{-2}) ranged from 0.1 to 6.6. Although spatial distribution of biomass reveals a high degree of patchinness (Fig. 8), the highest values correspond to the stations located off the Rías Bajas, mainly off the Ría de Muros. Relatively high values occur also in the northern shelf off the Rías Altas. The lowest values occur in the outer shelf, specially in the northern part. In general, higher biomass values correspond to a higher organic content of the sediment. Polychaetes contribute *ca.* 79% and echinoderms 8% to total biomass. Other groups are poorly represented.

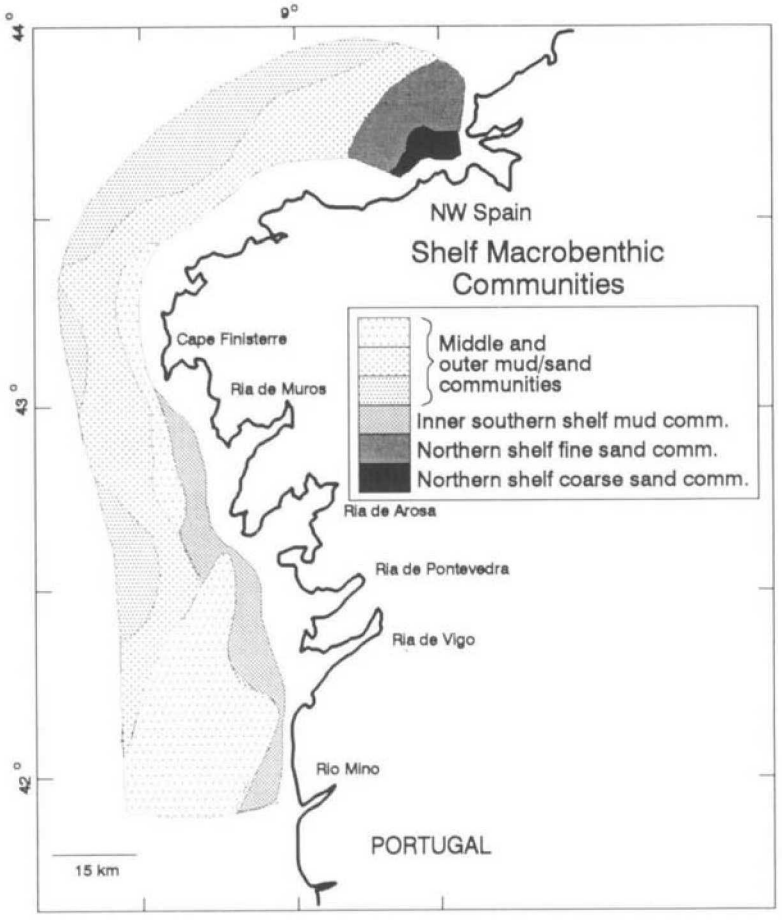

Figure 7. Spatial distribution of the macroinfauna cluster groups on the Galician shelf.

Diversity (H') ranged from 1.55 to 4.91. In general, lower values are related to a great dominance of the polychaete, *Prionospio malmgreni,* which causes evenness (J') to be very low. Spatial distribution of diversity shows no meaningful pattern.

iv. Polychaete feeding guilds. Polychaetes accounted for most of total abundance and biomass, so a knowledge of their feeding habits will help to characterize community function. Fauchald and Jumars (1979) defined the concept of "feeding guild" based on food, feeding habits, and locomotory patterns. This concept has proved to be useful in characterizing the role of polychaetes in benthic ecosystems. In this paper we have grouped the feeding guilds of Fauchald and Jumars into 5 main feeding groups: burrowers (subsurface deposit-feeders), carnivores, filter-feeders, herbivores, and surface detritus-feeders (Fig. 9).

Based on abundance data, surface detritus-feeders numerically dominate the five cluster groups (62 to 97%). Carnivores are the second most dominant group (1 to

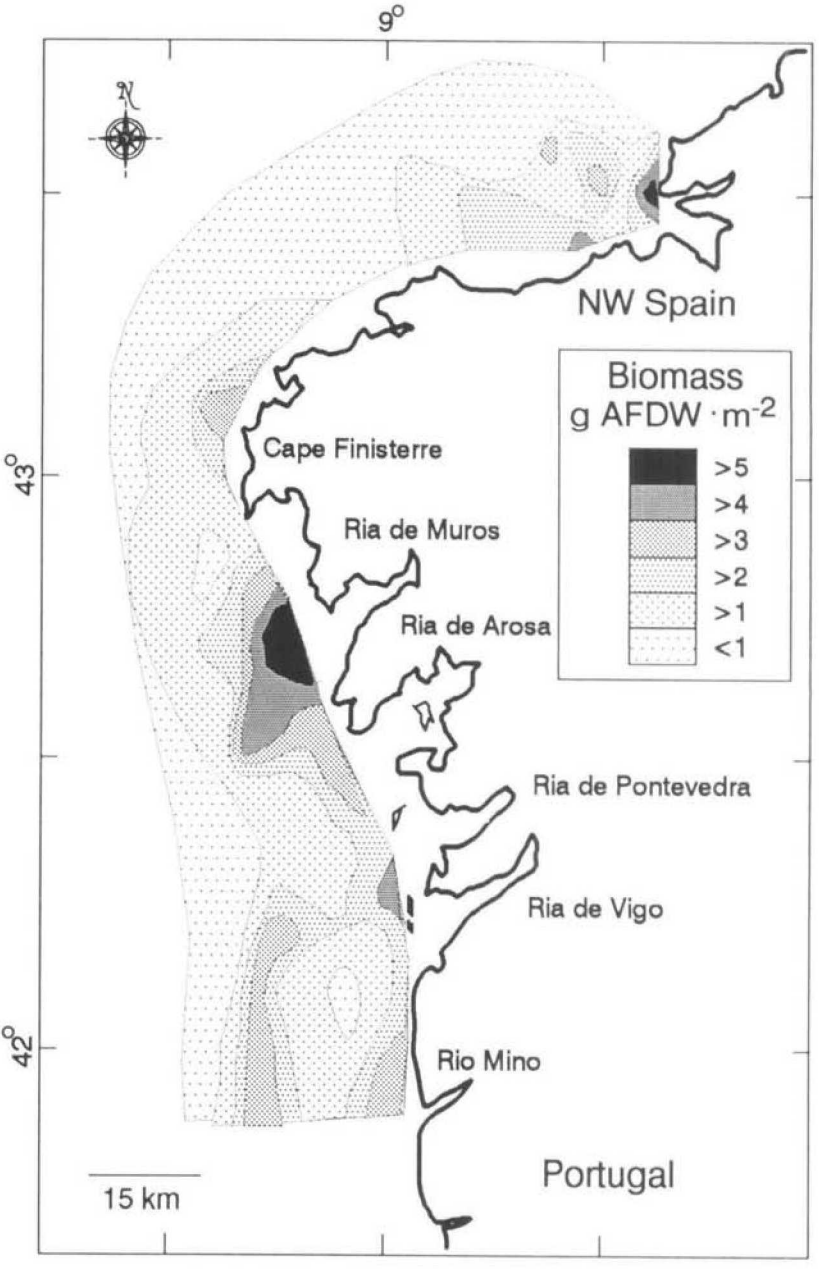

Figure 8. Spatial distribution of macroinfauna biomass (g m^{-2} ash-free dry weight) on the Galician shelf.

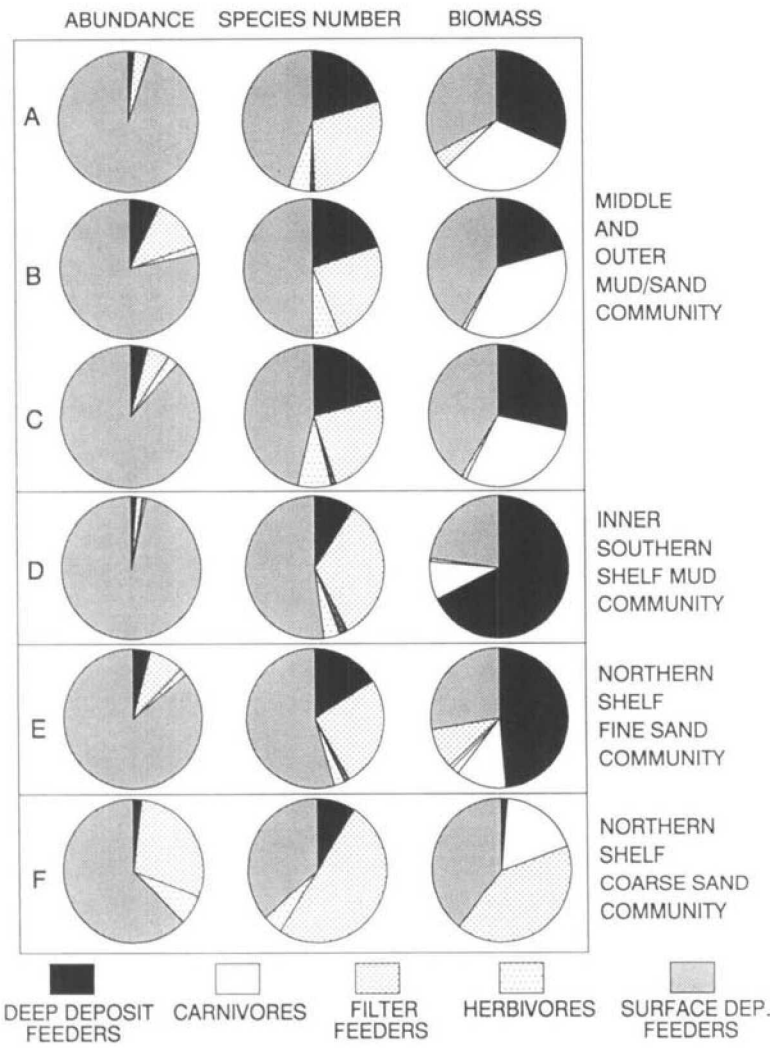

Figure 9. Distribution (abundance, species number and biomass) of polychaete feeding guilds in the macroinfaunal communities of the Galician shelf.

29%); their abundance is low except in cluster Group F. Burrowers occur generally in low densities ($<7\%$) and the rest of the groups are even less abundant.

Based on species richness, surface detritus-feeders are also dominant (36 to 54%). Carnivores are important as well (24 to 50%), being the most diverse group in cluster Group F. Burrowers (9 to 21%) are relatively important, and the rest of the groups are poorly represented.

Based on biomass, there exist clear differences among the cluster groups. Groups A, B, and C have a similar equal distribution of surface detritus-feeders, carnivores,

and burrowers. Group D (stations off the Rías Bajas) is dominated by burrowers (68%), and the proportion of surface detritus-feeders and carnivores is less important (23 and 9%, respectively). Group F is dominated by herbivores and surface detritus-feeders share most of total biomass (41 and 39%, respectively), followed by carnivores (18%).

In summary, small detritus-feeders numerically dominate the macroinfaunal communities of the Galician shelf. Carnivores, though less totally numerically abundant, do have a relatively high species number. The relative proportion of feeding groups, based on biomass, is more evenly distributed, except in cluster Group D (stations located off the Rías Bajas), where burrowers are dominant.

c. Bacteria

In June 1984, shelf sediments between Cape Finisterre and Ría de Vigo contained 0.2 to 0.7 billion bacteria g^{-1} dry wt. of sediment (Fig. 10a). Highest numbers of bacteria occurred on the northern near-shelf off Cape Finisterre. On the western shelf, bacteria increased south along the Rías Bajas, where the highest numbers occurred off the Ría de Vigo. The number of bacteria decreased offshore. However, numbers increased north along the western shelf break, where the highest numbers occurred off Cape Finisterre.

Shelf areas nearest the rías with 4 to 8% organic matter contained the highest numbers of bacteria (Fig. 10b). Farther offshore, organic matter decreased to 2 to 4%, and the number of bacteria declined. Off Cape Finisterre, where shelf sediments contained 4.5% organic matter, numbers of bacteria remained high. Bacteria correlated with percentage of organic matter and grain size (increasing Φ) in shelf sediments (Fig. 12, 6/84).

In September 1984, shelf sediments from Cape Finisterre to the River Miño contained 1.3 to 3.2 billion bacteria g^{-1} dry wt. (Fig. 10c). Although concentrations were about four times higher than in June 1984, the spatial distributions of bacteria over the entire shelf were similar to June 1984 distributions; i.e., highest numbers of bacteria occurring in shelf sediments nearest the Rías and shelf sediments off Cape Finisterre.

The distribution of bacteria also followed the distribution of organic matter content of sediments over the shelf (Fig. 10d). Again bacteria showed a positive correlation with the percentage of organic matter (Fig. 12, 9/84). Highest numbers occurred in areas that contained high organic matter ($>6\%$), whereas in offshore sediments where organic matter decreased to 4%, numbers of bacteria were lowest. In sediments off Cape Finisterre, where 4% organic matter occurred, numbers of bacteria were as high as those found off Ría de Arosa. Bacteria also correlated with increasing Φ (decreasing grain size) and percentage of silt (Fig. 12, 9/84).

In April 1985, the distribution of sediment bacteria over the western shelf was similar to that of the previous fall. Numbers of bacteria decreased from 2.83 billions

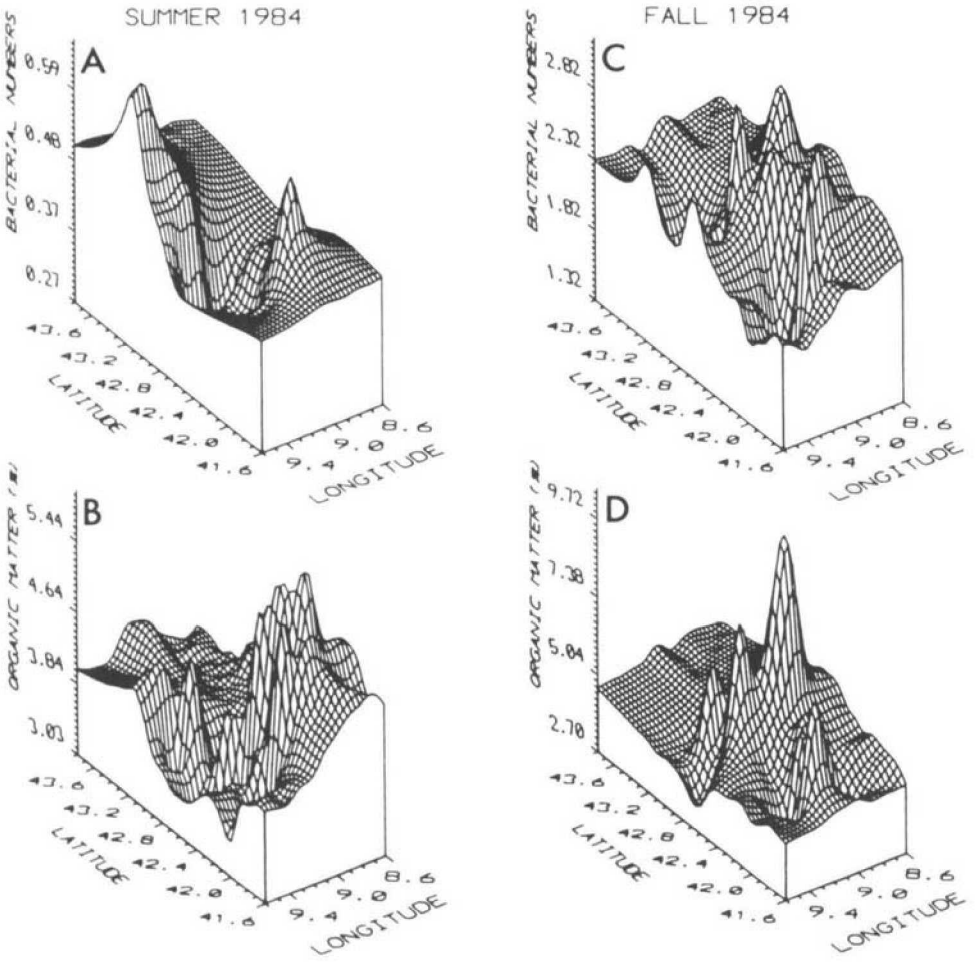

Figure 10. Latitude and longitude variation of bacteria and percent organic matter in the sediment of the Galician shelf. A and B: summer 1984; C and D: fall 1984. Unit for bacteria: billions cells per cubic centimeter of wet surface sediment.

cells along the western coast to 0.63 billion cells g^{-1} dry wt. offshore (Fig. 11a). Along the shelf break from off the Ría de Arosa towards Cape Finisterre, cells numbers again increased. Shelf sediments off Cape Finisterre contained about 10% organic matter. The distribution of bacteria again agreed with previous patterns of organic matter (Fig. 11b).

In March 1986, numbers of bacteria showed a spatial pattern that was similar to previous seasons and years. Bacteria ranged from 0.3 to 1.5 billion cells g^{-1} dry wt. (Fig. 11c) with highest numbers occurring near the Ría de Arosa. Bacteria decreased offshore where again bacteria increased north along the shelf break towards Cape Finisterre. Bacteria on the northern shelf were again as high as numbers found on

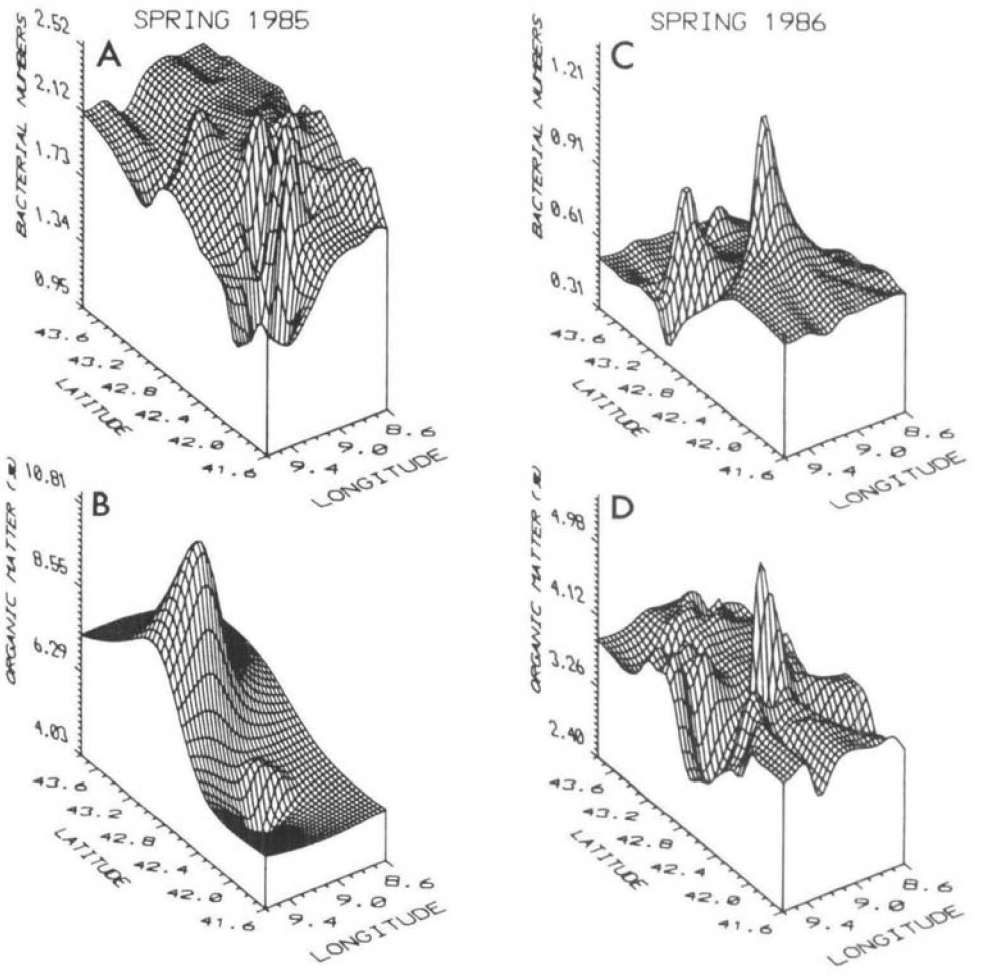

Figure 11. Latitude and longitude variation of bacteria and percent organic matter in the sediment of the Galician shelf. A and B: spring 1985; C and D: spring 1986. Unit for bacteria: billions cells per cubic centimeter of wet surface sediment.

the western shelf. Bacteria correlated with organic matter, grain size and percentage of silt + clay (Fig. 12, 4/86).

4. Discussion

Upwelling on the continental shelf off Galicia is more persistent off Cape Finisterre, although it occurs also over other areas of the shelf and upwelled water intrudes into the Rías. One result of the associated enhanced water column production is enrichment of the shelf sedimentary regime. Moreover, the shelf off the Rías Bajas receives an additional enrichment caused by outwelling of organics from the Rías, either via water column or bedload transport. An important proportion of

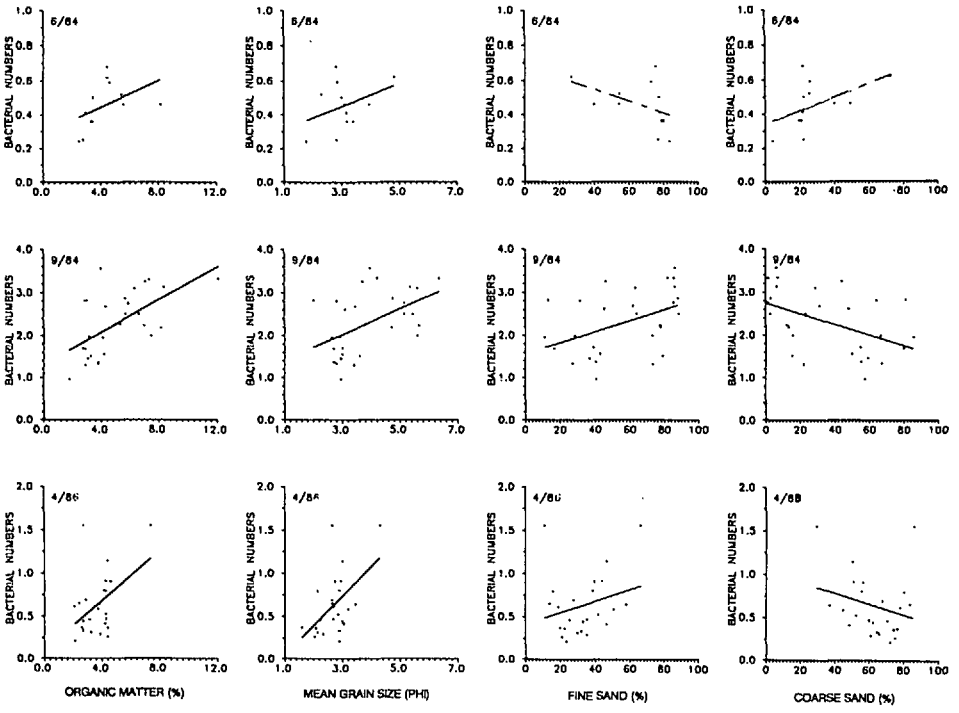

Figure 12. Relation between numbers of bacteria (billions cells per cubic centimeter of wet surface sediment) to percent organic matter, mean grain size (Φ), percent fine and coarse sand. First row: June 1984; second row: September 1984; third row: April 1986. The linear regression lines, where solid, had r^2 values varying between 0.48 to 0.68 and $p < 0.1$.

this organic matter from the Rías is produced by biosedimentation from the intensive mussel raft culture, especially in the western-most of the Rías Bajas, and especially in the Ría de Arosa. This type of shelf enrichment caused by estuarine outwelling has been reported for the Georgia Bight off southeastern U.S.A. (Hanson *et al.,* 1981).

The sedimentary structures of the western shelf are strongly modified by the export of a large amount of fine material exported from the Rías Bajas. Most of the bottom of the Rías Bajas is occupied by a very fine sediment (Lopez-Jamar, 1978, 1981, 1982; Lopez-Jamar and Cal, 1990). Geological data suggest that the mud bodies of the western Galician shelf are related to suspended fine material coming out from the Rías Bajas, which is deflected southwards by the general prevailing bottom water currents. The lateral and vertical distribution of the mud suggest that two different water masses move parallel to the coastline, carrying fine materials advected from the Rías Bajas. However, because of the lack of precise hydrodynamic data on the shelf bottom, the general hydrodynamic regime is inferred from sedimentary patterns. The influence of the Rías Bajas is more evident in the inner and middle part of the western shelf, where the mud deposits are superimposed on

the general geological features of the continental shelf. This accumulation of fines has been going on since late Quaternary times (Rey and Medialdea, 1989). By contrast, the northern part of the Galician shelf has a more sandy sediment with a lower organic content. The northern shelf does not communicate with large embayments such as the Rías Bajas.

The community structure of the infaunal benthos of the Galician shelf is also affected by these two different sources of enrichment. The northern and western shelf, especially off Cape Finisterre, is dominated by a low-successional infaunal assemblage, characteristic of episodic enrichment of surface sediments. The relation of upwelling enrichment with benthic communities dominated by opportunistic species has been addressed by Tenore *et al.* (1978) and Hanson *et al.* (1981) as observed on the Georgia southeastern U.S. continental shelf. On the Galician shelf, enrichment from upwelling production reaches the sea bed in pulses, and thus benthic organisms (mainly small surface detritus-feeding polychaetes) are specialized in exploiting such irregular events. By contrast, the sediment off the Rías Bajas is enriched not only from upwelling, but also from the organic matter advected from the Rías. This more regular source of organic material causes an increase in the proportion of subsurface deposit-feeders in the infaunal community, which are typical of a higher successional stage.

Bacterial numbers in surface sediments were within the range of 0.1 to 10 billion cells g^{-1} dry wt., found on other continental shelves (Griffiths *et al.,* 1978; Cammen, 1982; Meyer-Reil, 1983; Newell and Fallon, 1982; Hobbie *et al.,* 1987). In deep sediments off NW Spain, Rowe and Deming (1985) reported that numbers of bacteria were nearly an order of magnitude lower than on the shelf. The observed spatial patterns of bacteria varied seasonally and interannually but support the relative importance of the two different sources of organic matter and benthic regimes on the northern and western shelves of Spain. Numbers are generally higher off Cabo Villaño and off the Rías Bajas.

No relationship has been found between the sediment distribution, bacterial abundance, and macroinfaunal communities of the Galician shelf with the distribution in abundance of the main commercial demersal fishes: hake (*Merluccius merluccius*) and blue-whiting (*Micomesistius poutassou*). The spatial density distribution of these two fishes does not vary much in this area (Sanchez *et al.,* 1991). However, the sampling strata used for the finfish surveys are not designed to investigate such mesoscale distributional patterns. Furthermore, the Galician shelf is affected by heavy overfishing that might obscure smaller-scale distributional patterns.

The diet of blue whiting and juvenile hake consists mainly of epibenthic crustaceans (*Solenocera* spp. and mysids); adult hake feed mainly on blue whiting (Olaso, 1990). Thus both these two fish species, while not directly, are nevertheless indirectly affected by the benthic enrichment outwelling from the Rías Bajas. In the case of the

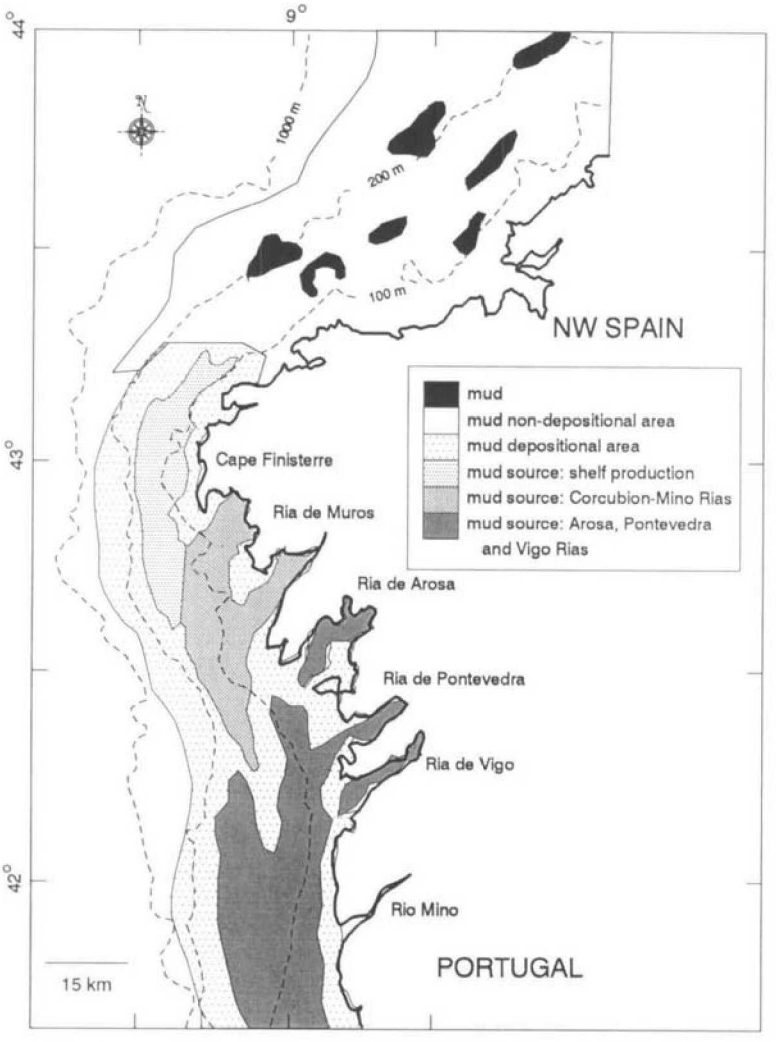

Figure 13. Map illustrating the land-sea interaction of coastal upwelling and outwelling from the Rías Bajas on the distribution and source of mud deposits along the Galician shelf off NW Spain.

other main commercial fisheries, the abundance of the norwegian lobster, *Nephrops norvegicus,* is much higher in the area of fine, organic-enriched sediments influenced by outwelling from the Rías Bajas (Fariña, pers. comm.). The diet of the norwegian lobster consists mainly of macroinfaunal organisms (polychaetes, molluscs and crustaceans) (Thomas and Davidson, 1962; Baden *et al.,* 1990), *N. norvegicus* abundant in the enriched sediments off the Rías Bajas.

The relation, whether direct or indirect, of this coastal demersal fisheries to

coastal upwelling and outwelling illustrates the importance of oceanographic processes in regulating benthic food chain processes at the land-sea interface (Fig. 13).

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