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Impact of cage farming of fish on the seabed in three Mediterranean coastal areas

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The impact of cage culture of marine fish on the benthic environment was investigated seasonally at three commercial fish farms (Cephalonia, Ithaki, and Sounion) established in coastal waters 20–30 m deep, with different types of sediment (from 80% silt to coarse sand) and varying current intensity. A transect of stations in the vicinity of the cages and a control station in each area were sampled for macrofauna and geochemical variables during July, October, and April. Redox potential in the sediment decreased under and near the cages but reached negative values only at the silty sediment site. Organic carbon and nitrogen content of the sediment near the cages increased by a factor of 1.5–5 and ATP content by 4–28 compared with the control. Azoic zones were not encountered, but the macrofaunal community was affected up to 25 m from the edge of the cages. At the coarse sediment sites, abundance and biomass under the cages were 10 times higher than at the control. Diversity indicated that the ecotone was in the vicinity of 25 m from the cages in all cases. *Capitella* cf. *capitata* dominated macrofauna up to 10 m from the cages in two fish farms, whereas the third was dominated by *Protodorvillea kefersteini*. Similar patterns of succession from the impacted to the normal zones were found, although macrofaunal composition differed among sites. Seasonal variability in geochemistry and macrofauna was higher in proximity of the cages. The results indicate that impacts of fish farming on benthos in the Mediterranean vary considerably depending on site characteristics.

Key words: aquaculture, macrobenthos, pollution, sediment chemistry.

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Introduction

Over the last two decades aquaculture has proliferated in the coastal zone, becoming an increasingly important industry. Once considered an environmentally benign practice, fish farming is now viewed as a potential polluter of the marine environment (Findlay *et al.*, 1995). Organic enrichment of the seabed is the most widely encountered impact of culturing fish in cages (Gowen and Bradbury, 1987; Iwama, 1991). A small proportion of the carbon supplied to the fish *via* the feed is retrieved through harvest, whereas a considerable amount reaches the seabed, either as wasted food pellets or as faecal excretions. For salmonids, 29% of carbon (Hall *et al.*, 1990), 23% of nitrogen (Hall *et al.*, 1992) and 47–54% of phosphorus (Holby and Hall, 1991) may be lost in particulate form and end up on the sea bottom. The effects of the enrichment on benthic communities have also been studied in relation to the salmon industry (Brown *et al.*, 1987; O'Connor *et al.*, 1989; Weston, 1990; Kupka-Hansen *et al.*, 1991). The studies gave similar results regarding macrofaunal succession but revealed large differences regarding the spatial extent of the impacts.

Little is known of fish farming impacts in the Mediterranean (Munday *et al.*, 1994), where fish farming of marine species, particularly sea bream (*Sparus aurata*) and sea bass (*Dicentrarchus labrax*), has grown exponentially during the last 15 years. Typical characteristics of the Mediterranean marine environment might result in considerable differences when compared with the patterns induced by the salmon industry: the microtidal regime could affect dispersion of settling organic material; the high temperature could affect

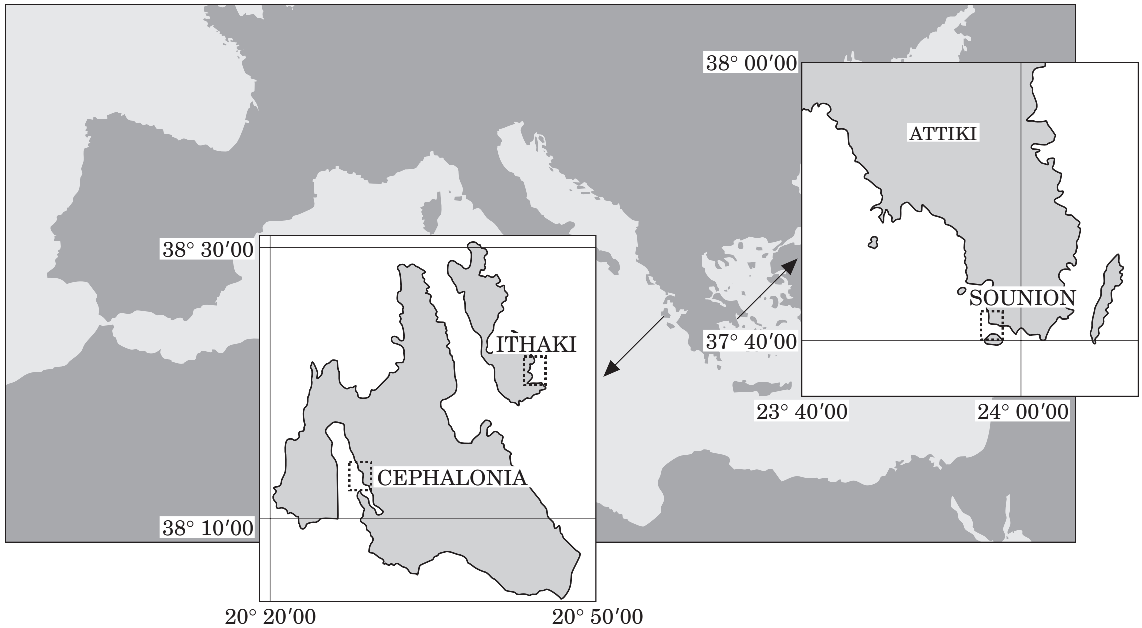

Figure 1. Map showing the location of the three fish farms investigated.

sediment metabolism and oxygen availability; light availability because of more sunshine and water transparency allows for photosynthesis deeper in the water column; and the low-biomass and high-diversity benthic communities adapted to oligotrophic conditions could respond differently to sudden increases in organic content of the sediment.

Previous studies in the Mediterranean have addressed the impact of fish farming on water column chemistry and parasites (Papoutsoglou *et al.*, 1996), the effect on nutrients and plankton (Pitta *et al.*, 1999), the dynamics of sediment accumulation beneath cages (Karakassis *et al.*, 1998) and the recovery process of benthos after cessation (Karakassis *et al.*, 1999). We present data on spatial and temporal variability in sediment geochemistry and macrofauna from three commercial fish farms in Greek coastal waters spanning a wide range of sediment types and hydrodynamic processes.

Methods

Description of areas studied

Sampling for geochemical variables and macrofauna was carried out during three seasonal cruises (July and November 1995 and April 1996) aboard the RV "Philia". Three fish farms were visited, two in the Eastern Ionian and one in the Aegean Sea (Fig. 1), henceforth referred to as Cephalonia, Ithaki, and Sounion, respectively. Cephalonia farm (18–20 m depth) is situated in a semi-enclosed bay connected to surrounding waters by a narrow opening (three miles) at the southern part of the bay. Ithaki farm (20–30 m) is situated in a small embayment at the west coast of Ithaki island; the area is exposed to strong water currents and the seabed is steep, reaching 90 m depth at a distance of only 200 m from the cages. Sounion farm (13–20 m) is situated on the south coast of Attiki, in a strait formed between the coast and a small island, thus being protected from the north and south winds prevailing in the area. Average annual standing stocks were 140, 150, and 120 t for the particular units in Cephalonia, Ithaki, and Sounion, respectively. The average annual carbon input was 126, 135, and 108 t, respectively. The average annual nitrogen input at each site (in tonnes) would be approximately 14% of the respective carbon input. Current measurements through deployment of current meters (over a one-year period) gave average values of 3.5, 2.8, and 6.3 cm s^{-1} for the three farms, respectively (P. Drakopoulos, Institute of Marine Biology of Crete, pers. comm.). Although these values are indicative of the average speed of the currents at mid depth, they do not adequately describe the bottom currents nor the episodic flushes during storms. The coarse sediment in Ithaki and Sounion with median grain diameter (MD) of 0.42 and 0.60 mm, respectively, was typical of the Amphioxus sand biocoenose described by Pérès (1967) as coarse sands and fine gravels under bottom currents (French acronym SGCF). The seabed in Cephalonia was silty (MD = 0.02 mm) and showed the typical characteristics of the biocoenose of terrigenous mud (or VTC) described by Pérès (1967).

Sampling strategy

Using the information from current meters, a transect was established at each site along the prevailing direction of the water currents. Samples were taken at a distance of 0 m (under the cages) and at 5, 10, 25, 50, and 100 m from the edge of the cages downstream. The upstream direction was sampled at a distance of 25, 50, and 100 m from the edge of the cages (henceforth referred to as − 25, − 50, and − 100 m, respectively). A control station was chosen 1 km upstream from the cages at similar depth and sediment type. At Ithaki the control site was deeper (40–45 m) because of bottom topography. From the stations at 50 and 100 m distance at either end of the transect, only geochemical data were analysed. Macrofauna samples at 0, 5, and 10 m from the cages were taken by SCUBA divers using sampling cores of 9.5 cm internal diameter and 15 cm depth of sediment from the water–sediment interface. Five replicates were taken for each sampling station to determine variability within samples. From all other stations three replicate samples were taken by means of a Smith McIntyre grab (0.1 m^2). No macrofaunal samples were taken during the first sampling cruise (July 1995) at the stations close to the farms (0, 5, and 10 m distance).

Redox potential (Eh) was measured in larger core samples at 2 cm intervals from the water–sediment interface by means of an electrode standardized with Zobell's solution (Zobell, 1946). Sediment subsamples for determination of organic carbon and nitrogen content, as well as algal pigments and ATP concentrations, were taken by means of core tubes (2.2 cm diameter). The top 2 cm were sectioned off for analysis and stored deep-frozen, with the exception of ATP subsamples which were processed on board (extraction through boiling with $NaHPO_4$ buffer for 90 s) before being stored.

Total organic carbon and nitrogen in the sediment samples were determined by means of a Perkin Elmer 2400 CHN Elemental Analyzer following the procedure of Hedges and Stern (1984). Algal pigments were extracted with 90% acetone and sediment contents in chlorophyll and phaeopigments were determined according to the method described by Yentsch and Menzel (1963) using a Turner fluorometer (model 112). The ATP content was determined in the extraction solution using the luciferine-lusiferase reaction (Karl, 1980), and the luminescence was measured by means of a LUMAC Biocounter 2010. Dilutions of ATP stock solution were used for preparing regression lines to standardize the method for each sample batch separately. Chl a, organic carbon, and ATP concentrations were calculated with reference to dry sediment weight.

All macrofaunal samples were sieved *in situ* through a 500 μm mesh, and the retained sediment containing macrofaunal organisms was preserved in 10% buffered formalin. Samples were sorted by hand into major taxa (Polychaeta, Mollusca, Crustacea, Echinodermata, Sipuncula, miscellaneous) and specimens were identified to species level. Macrofauna wet biomass (g m^{-2}) was determined separately for each species and each sample.

Data analysis

Abundance Biomass Comparison (ABC) curves were plotted according to the method proposed by Warwick (1986) and the associated W statistic (Clarke, 1990) was calculated for each station and for each sampling cruise using the average values over all replicates at each station. Diversity was calculated by means of the (log_2) Shannon-Wiener index (Shannon and Weaver, 1949). Multidimensional Scaling (MDS) ordination analysis (Field *et al.*, 1982) was performed using the Bray-Curtis similarity index (Bray and Curtis, 1957) to obtain a 2D plot of the spatial and temporal changes in species composition of macrofaunal assemblages at each of the three areas studied. To normalize the data and to avoid skewness, a fourth root transformation was applied on the abundance data prior to calculating similarities (Field *et al.*, 1982). Calculations were done by means of PRIMER software package.

Results

Sediment geochemistry (Fig. 2)

Redox potential varied considerably among areas, sampling sites and seasons (Fig. 2a). Values at the control sites in Ithaki and Sounion were never <150 mV and values on the transect were always positive, indicating oxidized conditions. At the control site in Cephalonia values never exceeded 60 mV, whereas the sites up to 10 m from the cages had reducing sediments during all sampling periods. At the sites closest to the cages the maximum Eh values were recorded during April and the minimum values during November.

Organic carbon and nitrogen (Fig. 2b, c) concentrations in the sediment were approximately a factor of two higher at 0–10 m distance from the cages in Cephalonia compared to the control site, a factor of 1.5–5 higher in Ithaki, whereas in Sounion there was only a slight increase at 5 m during November and April. The C and N concentrations at the control site in Cephalonia Bay were higher by a factor of two than those in Ithaki and Sounion. This was also the case for the concentrations of algal pigments in the sediment (Fig. 2d, e). In Cephalonia, values at sites in proximity to the cages showed fluctuations above and below the values recorded at the control site and no consistent pattern in pigment concentrations could be discerned. Consistently higher chlorophyll contents were observed near the cages in Ithaki than at the control site during all seasons and consistently higher phaeopigment

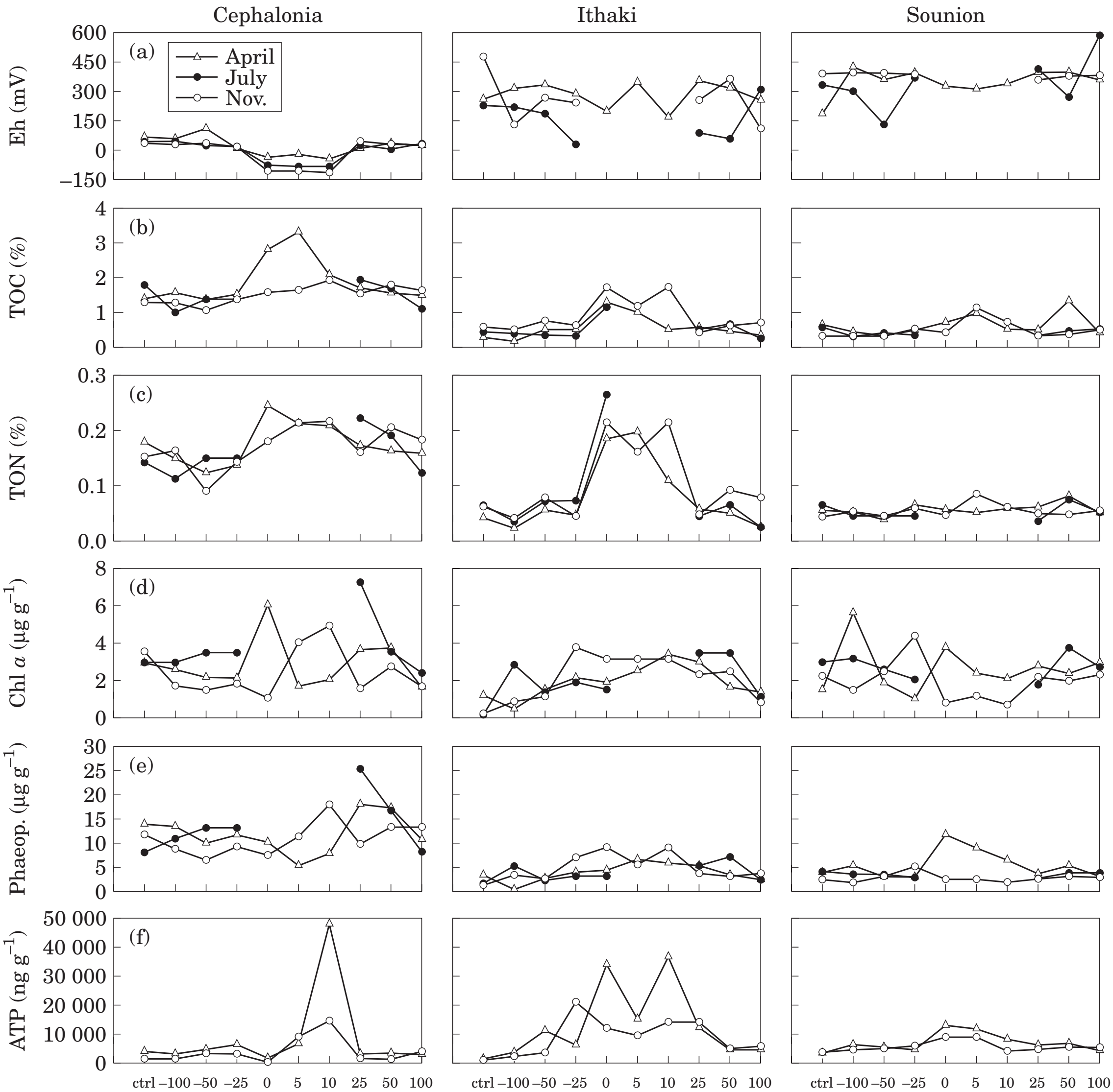

Figure 2. Geochemical parameters as measured in the sediment at the control sites (C) and at various distances (m) from the cages (negative distances are in upstream direction of the main currents) for the three fish farms by season: (a) redox potential; (b) organic carbon; (c) nitrogen; (d) Chl a; (e) Phaeopigments; (f) ATP.

concentrations up to 10 m distance from the cages in Sounion during April.

The concentration of ATP in the surface sediment layer (Fig. 2f) showed a consistent and conspicuous increase over the background values in the proximity of the cages. Except for the station under the cages in Cephalonia (where ATP concentrations were very low during both November and April), content at stations up to 10 m distance from the cages was a factor >10 higher compared with the respective control site. ATP at stations near the cages was increased by a factor 12–28 compared with the control site in Ithaki and by a factor 3–4 in Sounion.

Macrofauna (Figs 3–5)

A total of 28 235 individuals, belonging to 366 species were identified. Macrofaunal abundance (Fig. 3a) at stations up to 10 m from the cages was higher than the control in Ithaki and Sounion by a factor ranging from 20–120 and 5–10, respectively. Biomass also increased by a factor higher than 10 (Fig. 3b). In Cephalonia, abundance and biomass during November were impoverished up to 10 m distance, whereas they increased above the levels of the control site during April. In all three farms, the 25 m station showed slightly higher abundance than the control site during all samplings. In

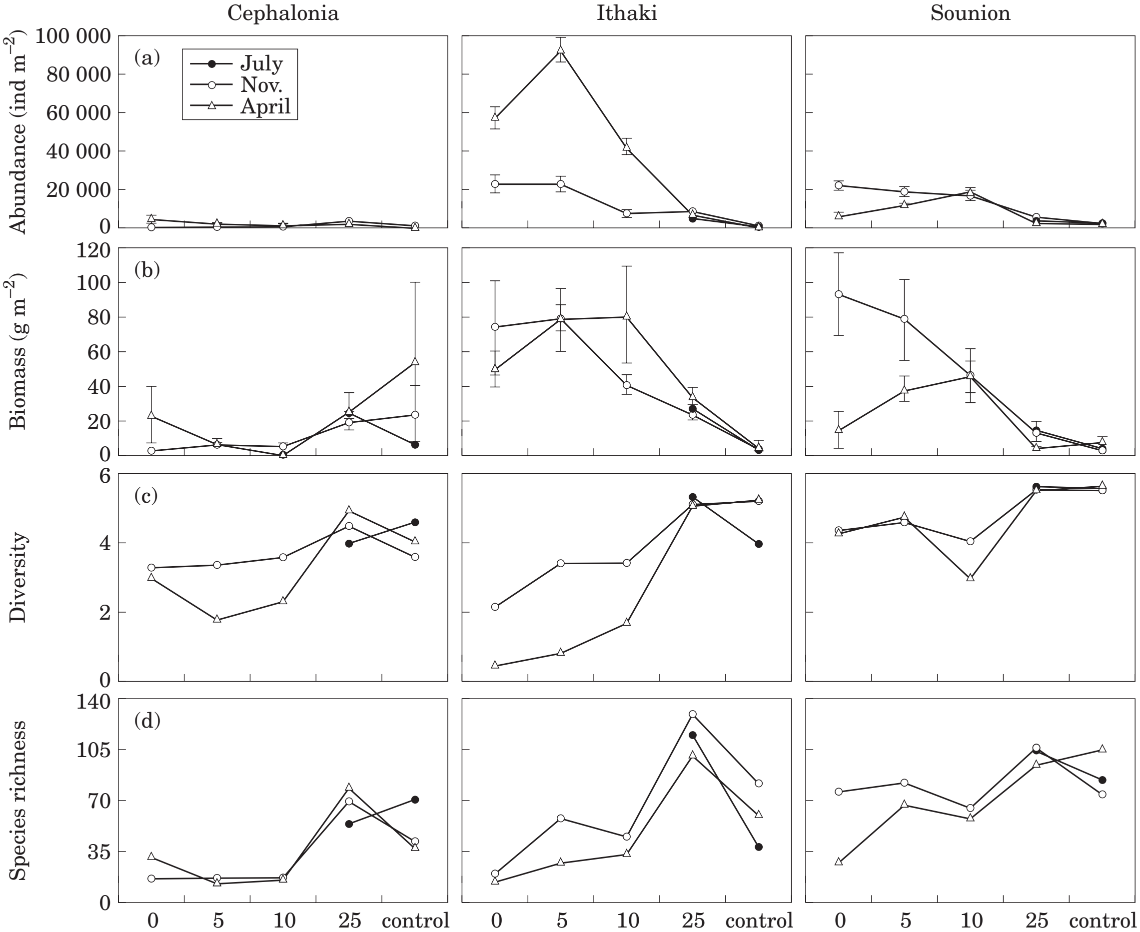

Figure 3. Macrofauna characteristics at the control sites (C) and at various distances (m) downstream of the cages for the three fish farms by season: (a) average abundance (± se); (b) biomass (± se); (c) Shannon-Wiener diversity index; (d) species richness.

terms of community structure (Table 1), the three areas showed a pattern of spatial change with distance from the cages. At Cephalonia and Ithaki, in most stations up to 10 m, the macrofauna was dominated by *Capitella* cf *capitata*, during both seasons. At the stations close to the farming site in Sounion, *Capitella* was present but in low proportions (<1%) in most samples, whereas *Protodorvillea kefersteini* and *Cirrophorus lyra* comprised more than 20% of the total abundance up to 10 m. *P. kefersteini* also reached high abundance in Ithaki (at 5 and 10 m) during November when it comprised more than 40% of the macrofauna. At the other end of the enrichment gradient, the polychaete *Tharyx heterochaeta* was consistently found at the control sites and the 25 m stations, but never near or under the cages.

The Shannon–Wiener diversity index and species richness (Fig. 3d, e) in Cephalonia and Ithaki increased with distance from the cages up to the 25 m station, which in most cases was characterized by more diverse fauna than the control site. In Sounion, diversity and the number of species along the transect remained roughly comparable to the control site. The numbers of species at 0, 5 and 10 m are not strictly comparable to those at 25 m and the control station because the sampled area and therefore sample sizes were smaller. Nevertheless, numbers of individuals identified and counted in each set of five cores were in most cases higher than those obtained from three grabs at the control site. Therefore, numbers of species provide only an indication of the minimum species richness present at each station. Even under the cages, at least 15 (in Sounion, 27) species were encountered, which is not typical for the polluted zone as described in Pearson and Rosenberg (1978).

Based on the ABC criteria, the macrofaunal community at the control stations in all areas must be considered undisturbed during all cruises (Fig. 4). Also, at none of the other stations the typical pattern of disturbed communities was observed. Only moderate disturbance was observed at stations near the cages but not during all seasons. During all cruises, the 25 m

Table 1. Average relative abundance (%) per station of macrofaunal species comprising more than 5% of the total abundance at any one station over all sampling cruises (+: presence <1%; C: Crustacea, M: Mollusca, P: Polychaeta, Ph: Phoronida, S: Sipunculida). Species are arranged by decreasing average abundance at the stations in proximity to the cages (0, 5 and 10 m) and increasing average abundance at the control sites.

		Cephalonia					Ithaki					Sounion				
Species/distance (m)	Area	0	5	10	25	Ctrl	0	5	10	25	Ctrl	0	5	10	25	Ctrl
Capitella capitata	P	45	53	28	+		75	51	46	8	+	1	+	+	1	+
Protodorvillea kefersteini	P	3			+		+	23	22	11		19	8	14	9	4
Cirrophorus lyra	P							2	2	7	+	11	25	45	4	2
Ophryotrocha sp.	P	4	5	23	+					+	+	1	+	+		+
Neanthes caudata	P	10	1		+		10	4	5	+	+	2	1	+	+	
Aricidea fragilis	P	1	1	7	5	+				+						
Prionospio fallax	P				+	+	+	1	+	3	+	9	7	2	5	4
Tellina incarnata	M	2	3	5	8	+										
Gammarella fucicola	C											2	6	3	3	
Malacoceros tetraceros	P	1	1				6				+					
Spiochaetopterus costarum	P	+	6	4	2	+		+	+	+	+	+	+	+	+	+
Aricidea cerrutii	P							1	+	2		7	5	6	4	3
Demonax tenuicollaris	P									8				+		
Caprella acanthifera	C													+	6	
Heteromastus filiformis	P	2	+	1	10	2	+	+					+			
Phoronis sp.	Ph	+			5	3		+	+	+	+	+	+	+		
Magelona minuta	P				+	+		+		6				+	+	4
Sternaspis scutata	P				1	5										
Glycera rouxii	P		+	2	+	+				1	6	2	3	2	4	4
Lumbrineris gracilis	P	+		1	9	7	+	+	+	2	3	2	2	+	+	2
Tharyx heterochaeta	P				+	1				2	2				+	5
Syllis hyalina	P				+	+	+	+	+	+	2	+	+	+	+	7
Aspidosiphon muelleri	S						+	+	+	2	10					
Corbula gibba	M	1	2	1	2	14					+			+		
Mysella bidentata	M	2	1	3	13	17		+		+	+	2	1		+	
Levinsenia gracilis	P	+		1	2	4			+	1	11			+	1	+
Nephtys hystricis	P				3	16				+						+
Cumulative abundance (%)		72	74	76	61	72	94	87	79	59	39	60	62	79	42	39

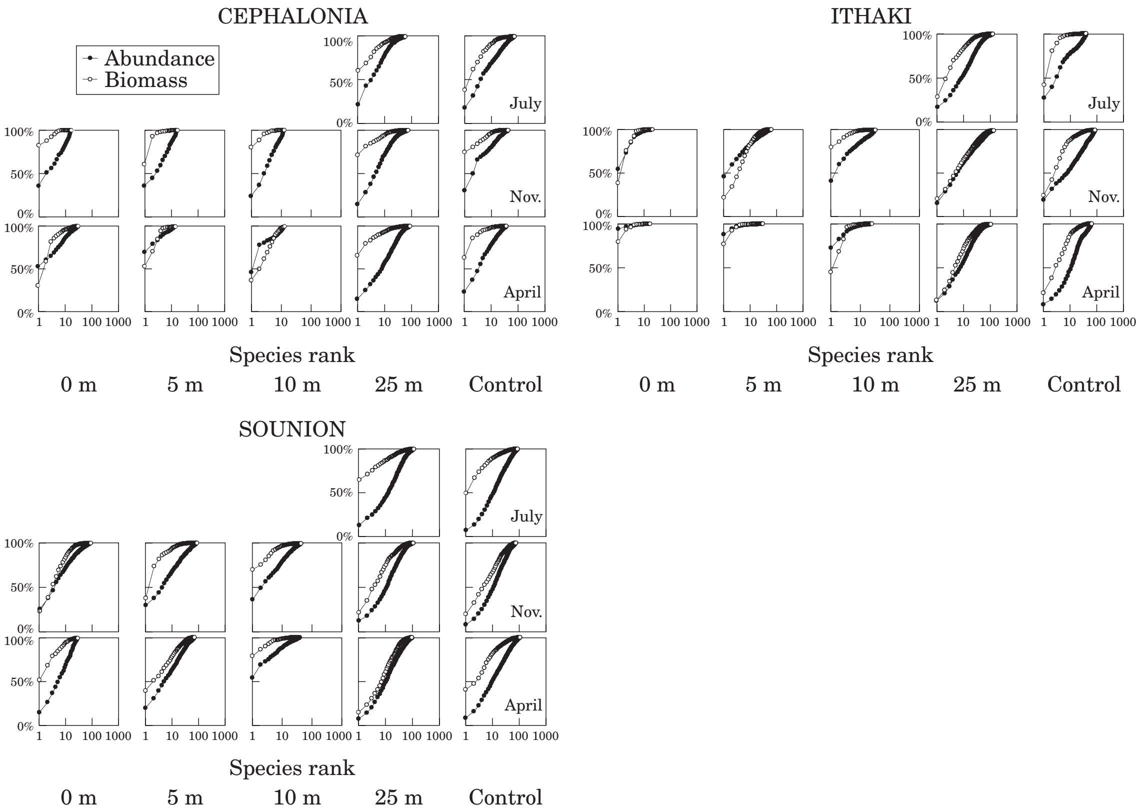

Figure 4. Abundance-biomass comparison curves at stations located at 0, 5, 10, and 25 m from the cages as well as at the control site, for the three fish farms and by season.

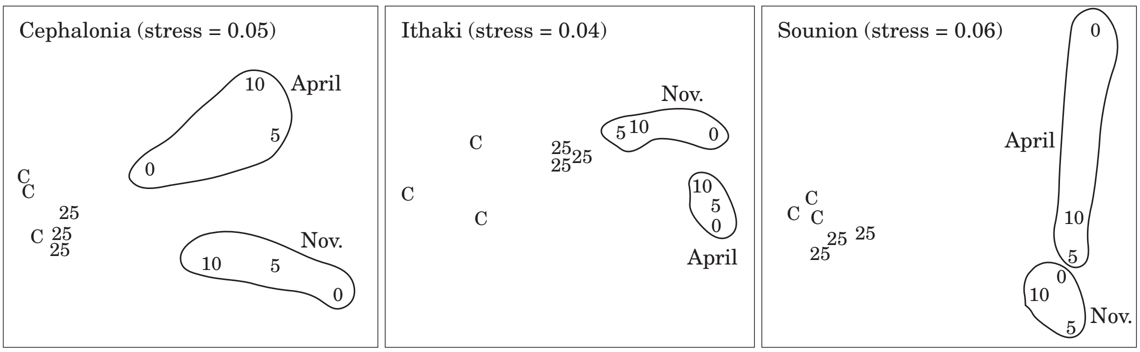

Figure 5. MDS ordination plots derived from species-abundance data for the three areas investigated (numbers indicate distance from the fish farm; C: control site).

station in Cephalonia was undisturbed. At the other two farms with coarse sediments, the 25 m station appeared to be moderately disturbed during April and in Ithaki also during November. However, the ABC results were inconsistent with the common expectations from the impact of disturbance caused by organic enrichment. In particular it is worth noting that even the sites close to the cages dominated by capitellids cannot be classified as disturbed by this technique.

MDS results (Fig. 5) indicate that spatio-temporal patterns in change of macrofaunal species composition were similar in the three areas. Samples taken at 0, 5, and 10 m from the cages clustered at one side of the graph forming distinct sub-clusters with respect to sampling season (autumn, spring). The samples taken at the control site formed a separate cluster, and those taken at 25 m distance clustered close to the samples from control site. The patterns obtained for each farm

Table 2. Pairwise Spearman rank correlations between similarity matrices, derived from macrofauna species abundance data for the three study areas (all values significant at $p<0.05$).

	Cephalonia	Ithaki
Ithaki	0.51	—
Sounion	0.62	0.67

through MDS ordination were compared by means of the Spearman rank correlation coefficient among similarity matrices, according to the method introduced by Somerfield and Clarke (1995). Results (Table 2) indicate that, despite the differences in macrofaunal composition (Table 1) and total abundance, similarities among the spatial patterns observed at the three farms were significant ($p<0.05$).

Discussion

Alterations in the sediment chemistry occurred at sites in proximity of the three fish farms investigated, although they varied in extent. The redox at the silty seabed in Cephalonia dropped to negative values, whereas redox in the coarse sediments of Ithaki and Sounion remained positive. Cephalonia and Ithaki showed an increase in organic carbon and nitrogen content of the sediment by a factor of two. In Sounion (combining strong currents and coarse sediment), the increase was less pronounced. A decrease in redox was also observed in the vicinity of fish farms above silty bottoms in Scotland (Brown *et al.*, 1987) and at the east coast of Canada (Hargrave *et al.*, 1993) as well as above a sandy bottom in Puget Bay in N.E. Pacific (Weston, 1990). Brown *et al.* (1987) reported redox values as low as −186 mV during May at 3–11 m distance from the farm while Hargrave *et al.* (1993) reported negative values under the cages during the summer period. In contrast, Weston (1990) recorded values of 120 mV near the cages, increasing to 350 mV at 150 m distance. Increases in sediment concentration of organic material similar to those found in Cephalonia and Ithaki (by a factor of two) were reported for silty seabed by Brown *et al.* (1987) and Hargrave *et al.* (1993) as well as by Holmer and Kristensen (1992) in a non-specified sediment type. Weston (1990) reported considerably higher increases (factor four) for a sandy seabed. Microbial biomass in the sediment (determined through ATP) near the cages showed an increase by an order of magnitude in Cephalonia and Ithaki, and only by a factor of two in Sounion. The observation of proportionally larger increases in microbial biomass compared with organic material is consistent with the findings of Holmer and Kristensen (1992), who reported a ten-fold increase in sediment metabolism under trout cages in shallow Danish waters, while POC and PON increased by a factor less than two. The relatively low ATP content directly under the cages in Cephalonia can be attributed to inhibition of microbial activity owing to anoxic conditions.

Sediment anoxia, patches of Beggiatoa and absence of macrofauna have been reported in relation to salmon farming in the North Atlantic (Rosenthal and Rangeley, 1988; Kupka-Hansen *et al.*, 1991) and the Baltic Sea (Holmer and Kristensen, 1992). Because of the microtidal regime of the Mediterranean, the dispersion mechanism of particulate wastes might be less effective than in the Atlantic and, therefore, accumulation of organic material under and near the cages could be expected to result in highly anoxic zones. However, even under the cages there was no azoic zone, as defined by Pearson and Rosenberg (1978). Previously, Papoutsoglou *et al.* (1996) reported that visual inspection by divers failed to detect any effects on the seabed under fish cages at two sites in Greek coastal waters. In Ithaki and Sounion, visual inspections by means of divers and Remote Operated Vehicle revealed hardly any difference between areas under the cages and control sites. However, closer investigation of the seabed did reveal marked differences, both with respect to chemical variables and macrofaunal community composition, indicating that visual inspection is not a reliable method for assessing environmental impacts at sites with coarse sediments. In contrast, information obtained through visual inspection at Cephalonia was largely consistent with sampling results.

Brown *et al.* (1987) and Weston (1990) reported a clear dominance of the macrofaunal community by *Capitella* cf. *capitata* in the zone near the cages (in the latter study up to 150 m distance). Brown *et al.* (1987) could show little effect beyond the station located at 15 m distance, but their next station was at 120 m distance, and therefore the impact zone is not well defined. Weston (1990) observed a slight increase in abundance and a decrease in biomass, whereas both abundance and biomass increased at the farms that we investigated, particularly those above coarse sediments. The identical patterns of spatial change (Fig. 5) in the three areas indicate that the benthic community approaches its normal characteristics at 25 m distance. The ecotone point may lie in this region because diversity was at maximum and the assemblage included species from both the polluted region and from the original community. *T. heterochaeta* was consistently present at all control stations and also dominates the upper shelf in other areas of the Aegean characterized by highly oligotrophic conditions (Karakassis and Eleftheriou, 1997). This species was also consistently absent in the vicinity of the farms, even in Sounion where the effects were subtle. Therefore, *T. heterochaeta* might be considered a candidate indicator species for detection of organic enrichment. However, cirratulids (reported as *Chaetozone/Tharyx* spp) were found by Brown *et al.* (1987) at 3 m from cages in the zone dominated by capitellids in a Scottish sea loch. *Capitella* dominated the macrofaunal community at the heavily impacted site in Cephalonia and Ithaki whereas *P. kefersteini* was the dominant species at Sounion (and partly in Ithaki).

At all three farms, the benthic assemblages in the immediate vicinity showed symptoms of disturbance. In Cephalonia there was only a change in faunal composition, but in the coarse sediment areas there were also pronounced changes in abundance and biomass. The coarse substratum in Ithaki and Sounion apparently allows for oxic sediment conditions and, therefore, the microbial processes related to the decomposition of sedimenting material do not result in severe chemical stress for the macrofauna. However, the additional food resource is likely to be exploited by opportunistic species, i.e., "species whose reproductive and growth characteristics fit them to take immediate advantage of a sudden environmental change providing them with a favourable unexploited niche" (Pearson and Rosenberg, 1978). The abundance-biomass comparison technique did not indicate typical disturbance at any of the stations (even those clearly dominated by Capitella), whereas only in a few cases were there signs of moderate disturbance. In this respect the results obtained through ABC were inconsistent with the other sources of information (Weston, 1990).

Seasonal variability in geochemical and macrofaunal variables was always more pronounced at stations close to the farm (0–10 m) than at the control site or the stations at 25 m. This may be attributed to large differences in food supply to the farmed fish between warm and cold seasons, to increased oxygen supply to the sediments during winter or to H_2S toxicity, which is also affected by seasonal processes (Hargrave *et al.*, 1993).

The impacts of the three farms on the seabed varied both in terms of geochemistry and macrofauna. The silty sediment site showed typical characteristics of the effects of organic enrichment, comparable to those observed in the vicinity of salmon cage farms. In coarse sediments, the effects on geochemical properties varied greatly, but in neither of the two cases decreased the macrofauna quantitively. In all cases diversity in the immediate vicinity of the farms decreased, but the spatial extent of this effect was quite limited.

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