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Seasonal variability in sediment profiles beneath fish farm cages in the Mediterranean

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ABSTRACT: The chemical and physical (water content) changes in sediment profiles beneath and around fish farm cages were investigated on a seasonal basis in Cephalonia Bay, Greece, a relatively enclosed marine area with weak currents and silty substrate. The surface concentrations and the vertical distribution of the sedimentary variables studied (organic matter, organic carbon/nitrogen, chlorophyll, phaeopigments, water content and total phosphorus) varied substantially with distance from the cages and with season. The black-coloured top layer (farm sediment) showed high concentrations of organic matter, phaeopigments and total phosphorus as well as high water content while the compact subsurface layer had concentrations close to (or lower than) those at the control site. The thickness of the farm sediment layer under the cages varied with season, while in all seasons it decreased rapidly with increasing distance from the cages.

KEY WORDS: Fish farms · Sediment chemistry · Vertical profiles Mediterranean

INTRODUCTION

The proliferation of the aquaculture in the coastal zone during the last 20 yr has caused concern for impacts on critical environmental variables (GESAMP 1990) and therefore information on such impacts has been extensively studied and reviewed during the last 10 yr (Gowen & Bradbury 1987, Gowen 1991, Iwama 1991, Wu 1995), the common point being that most of the detectable effects on marine ecosystems are related to sediment beneath the fish farms. Several authors have reported the presence of a loose and flocculent black sediment under fish cages (Hall et al. 1990, Angel et al. 1995), commonly named 'fish farm sediment' (Holmer 1991). This sediment is characterized by low values of redox potential (Hargrave et al. 1993), high content of organic material (Hall et al. 1990, Holmer 1991) and accumulation of nitrogenous and phosphorous compounds (Holby & Hall 1991, Hall et al. 1992). These changes in the physical and chemical characteristics of the seabed induce conspicuous changes in the structure of the benthic communities (O'Connor et al. 1989, Weston 1990, Pocklington et al. 1994). Most of the above cited papers are related to the salmon industry in Northern Europe and North America, while very little is known about such impacts in the southern areas of the northern hemisphere including the Mediterranean (Munday et al. 1994), where a continuously expanding farming industry of sea bream and sea bass has been established in the coastal zone. However in warm, oligotrophic seas with a microtidal marine environment such as the Mediterranean, some deviations from the general patterns could be expected as a result of higher metabolic rates, different temporal patterns in water movement and differences in the structure of plankton and benthic communities.

Even less is known on the temporal variability of the environmental impacts that are directly related to the variance in food supply due to the different temperature of the ambient water (Goddard 1996). Seasonal variability in food supply determines the seasonal variability in environmental loss of carbon, nitrogen and phosphorus towards the seabed and the water column

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according to well-studied mass balance models (Gowen & Bradbury 1987, Hall et al. 1990, 1992, Holby & Hall 1991). However the resulting seasonal pattern in nutrient availability in the water column is anticipated to differ from the 'natural' seasonal pattern. In the case of non-impacted marine ecosystems, nutrients are abundant during winter and early spring and they are gradually depleted at the surface waters during the warm season, whereas in mariculture-impacted ecosystems most of the nutrient loss (and consequently most of the nutrient enrichment in the water column) occurs during the warm period (i.e. summer and early autumn). Among the nutrients, phosphorus is of prime importance for the Mediterranean, which is considered, unlike most of the world's ocean, as a P-limited sea (Krom et al. 1991). The understanding of seasonal dynamics of sedimentation of phosphorus from fish farms in the Mediterranean is an important element for the prediction of the long-term impacts of aquaculture on the coastal environment.

We examined the temporal variability in sedimentary variables at different distances from fish farm cages in Cephalonia Bay in the SE Ionian Sea through the analysis of vertical profiles. A simple numerical index (summarizing in 1 value patterns in vertical profiles) is proposed for the investigation of the impacts of the fish farms on the seabed.

MATERIALS AND METHODS

Study area. Cephalonia Bay is a rather enclosed area, which is connected with the open sea through a small opening at the southern end. The fish farm investigated was the first ever established in Greek waters (in 1981) and one of the largest in the Mediterranean, producing ca 1000 t of sea bream and sea bass per year.

The particular unit monitored was a group of 10 cages, each with dimensions of 15 m by 15 m by 12 m depth, arranged in 5 pairs in a north-south direction. The water depth at this site varied between 16 and 20 m, the mean current velocity being 3.6 cm s^{-1} with a maximal value of 18 cm s^{-1} recorded within a 2 yr deployment of current meters (P. G. Drakopoulos, Institute of Marine Biology of Crete, unpubl. data). According to these measurements, water moved southward more than 70% of the time. The particular unit had been in operation for 4 yr when our investigation started, producing ca 140 t of gilthead sea bream *Sparus aurata* per year.

Sampling strategy. In order to determine the seasonal change in the thickness of the farm sediment layer as well as the variability in vertical profiles of chemical variables, sampling stations were established under the cages (0 m) as well as at 5, 10 and 25 m distances from the edge of the cages downstream in the main current direction. A control site with similar depth (21 m) and substrate type was established 1 km upstream. Samples were collected during 4 sampling trips (October 1996, February, May and July 1997) by SCUBA divers using 20 cm long core tubes of 5 cm internal diameter. When arriving at the surface, cores were immediately deep frozen (at -20°C) until subsequent analysis. Stations at distances of 5 and 10 m from the cages were sampled only during the last 2 trips. Replicate samples were also collected at the 0, 25 m and control stations in order to determine variability within samples. In order to minimize effects of pseudoreplication, cores at stations located in the vicinity of the farm were taken at least 1 m (perpendicular to the main current direction) apart from each other, while those at the control station were taken randomly at least 5 m apart from each other. In the laboratory the cores were sliced into horizontal (1 cm thick) layers.

Redox potential (Eh) profiles at 2 cm intervals were also determined in larger core samples by means of an electrode standardized with Zobell's solution (Zobell 1946).

Chemical analyses. The water content of the sediment (SWC) was determined as the weight loss after drying at 80°C until constant weight (approximately 20 to 30 h). Total phosphorus was determined in the dried samples, which were homogenized by grinding and digested with a mixture of perchloric and nitric acid (Burton & Riley 1956, Sturgeon et al. 1982). The concentration of P was determined colorimetrically as molybdate reactive phosphorus (Strickland & Parsons 1972). Total organic carbon and nitrogen were determined in part of the samples using a Perkin Elmer 2400 CHN Elemental Analyzer according to the procedure described by Hedges & Stern (1984). Organic material (loss on ignition, LOI) was determined as the weight loss of the dried sample after combustion for 6 h at 500°C (Kristensen & Andersen 1987). Sediment contents in chlorophyll (chl) and phaeopigments were determined according to the method described by Yentsch & Menzel (1963) using a Turner fluorometer (model 112) and 90% acetone as diluter.

Data analysis. In order to obtain a measure of the vertical variability for each sedimentary environmental variable, the coefficient of variation [CV(*k*)] was calculated as the ratio of standard deviation over the mean of a variable (*k*) at all depths of the core cast, i.e.:

$$\mathrm{CV}(k) = \frac{\mathrm{SD}(k)}{\bar{k}}$$

The concept behind this calculation is that non-impacted sediments are expected to show relatively

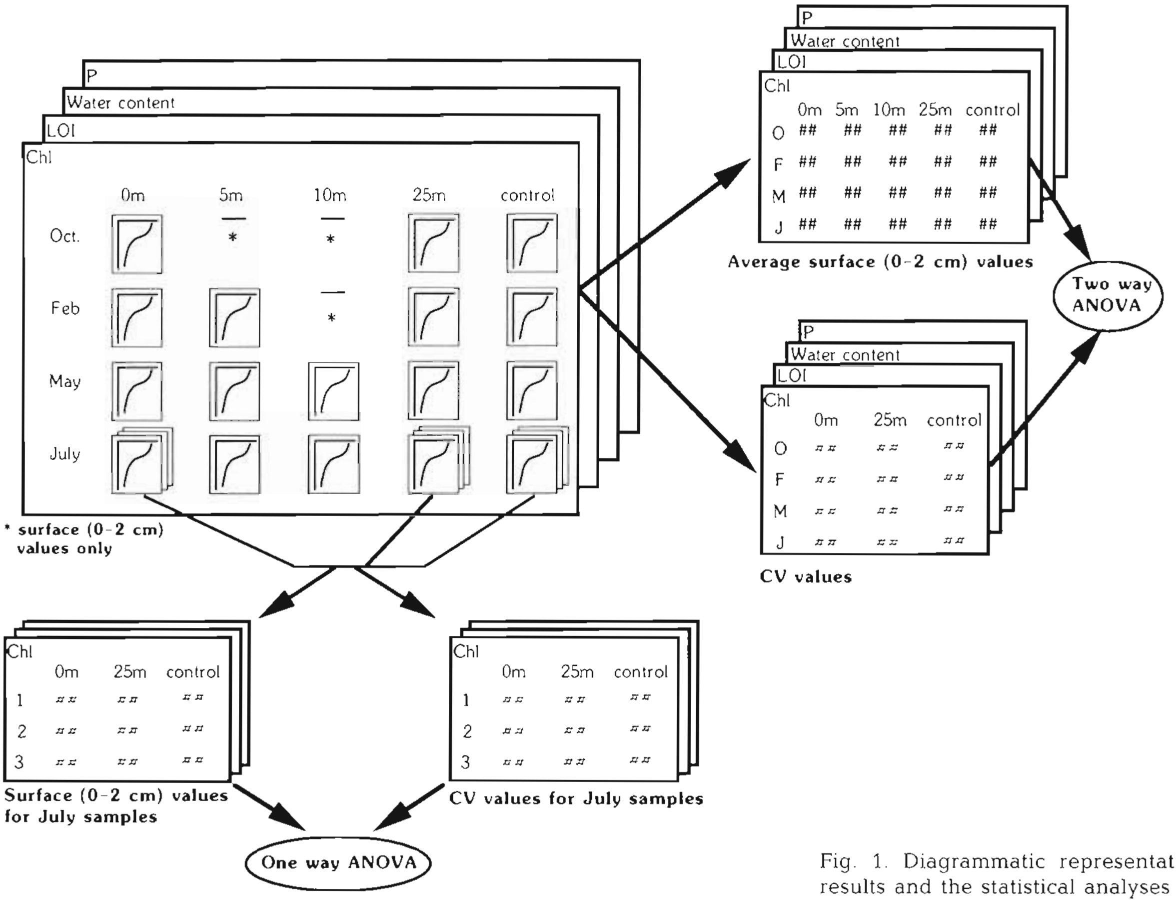

Fig. 1. Diagrammatic representation of the results and the statistical analyses performed

lower variability with depth due to low sedimentation rate and to the bioturbating activity of macrofauna. CV is a dimensionless value standardized by mean and therefore allows for comparison of variability across different variables.

A diagrammatic representation of the statistical analyses performed on the data obtained is presented in Fig. 1. Analysis of variance (ANOVA) was used to determine the overall significance of differences among samples and a post hoc Tukey test for multiple comparisons between groups of samples assembled according to the significant factors. One-way ANOVA was used to test for differences among stations sampled with replication in July. Two-way ANOVA (distance by season) was used to test for differences in the entire data set.

RESULTS

Redox potential showed similar patterns during all seasons (Fig. 2). At the control site positive values were recorded at least down to −4 cm from the sediment surface, while very low values were measured from the sediment surface at the station beneath the cages. The station located at 25 m from the edge of the farm presented intermediate values at all depths, with positive values at the surface except for July 1997 when negative values were recorded in the entire cast. In this particular season, Eh values at the 25 m station were closer to those at the station beneath the cages than to the respective ones at the control site.

Results on the vertical distribution of the SWC, LOI, chloroplastic pigments and phosphorus are presented in Fig. 3. The vertical distribution of all variables revealed conspicuous differences with depth, the higher concentrations being recorded at the surface layers of the station under the cages. At the 25 m station, the vertical pattern and the values measured were in most cases close to those at the control site.

The depth of the farm sediment was determined as the zone where maximal change in SWC was found between 2 sequential layers [d(SWC)]. The results (Fig. 4) showed differences among sampling seasons: the thickness of the surface layer was found to be 5 cm in October at the end of the warm season, it decreased to 2 cm in February (indicating a limited recovery process), it increased again to 4 cm in May and reached 5 to 6 cm in July. Neither the control site nor the 25 m station presented such peaks for the respec-

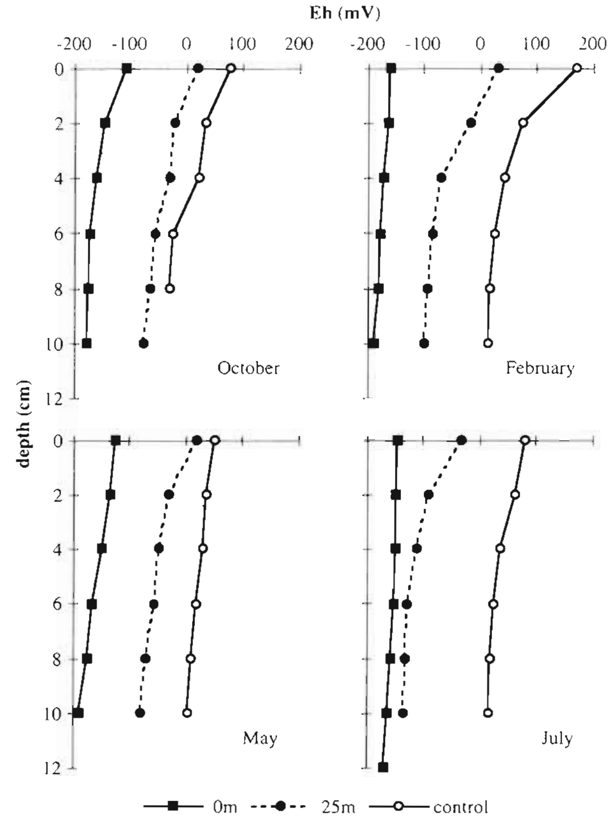

Fig. 2. Redox potential profiles at the stations beneath the cages, at 25 m distance and at the control site for the 4 sampling seasons

tive curves, both of these stations showed maximal values at the surface and subsequently decreased with small fluctuations. A similar pattern was evident for the change in organic material concentrations [d(LOI)], also presented in Fig. 4.

In order to assess the horizontal extent of the impact, surface values (0 to 2 cm) were used for stations under the cages, at 5, 10 and 25 m as well as at the control site (Fig. 5). The 2-way ANOVA (Table 1) revealed significant differences in concentrations of the measured environmental variables with distance but not with season. The subsequent post hoc test did not show any significant differences between the control and the intermediate stations (5, 10, 25 m), while there were significant differences between the station beneath the cages and the other (control and intermediate) stations for several variables.

The CV (Fig. 6) was calculated for 3 stations (0 m, 25 m and control) during all the sampling seasons. Different patterns in the vertical distribution of each variable are reflected in the values of CV. The 2-way (season by distance) analysis of variance (Table 2) revealed again significant differences with distance only. The Tukey post hoc test (among distance categories) showed significant differences between the station under the cages and the other two for SWC and LOI, whereas in the case of phosphorus and phaeopigments no significant differences were found between the stations at 0 and 25 m from the cages. In all the variables examined, no significant difference was detected between the station at 25 m and the control. No post hoc analysis was performed for chl since no significant effect was found for either season or distance.

Analysis of vertical profiles by means of CV using 3 replicates at each station (0 m, 25 m and control) was performed for SWC, LOI and chl. Results (Table 3) showed that CV could detect significant differences

Table 1. Results of 2-way ANOVA for surface values for all the sampling seasons. *$p < 0.05$, **$p < 0.01$. ns: not significant

Variable	Source of variability	*F*	df	p		Tukey post hoc test			
						0 m	5 m	10 m	25 m
Water content	Season	0.66	3	ns	5 m	ns			
	Distance	5.96	4	0.013	10 m	*	ns		
					25 m	*	ns	ns	
					Control	*	ns	ns	ns
LOI	Season	0.32	3	ns	5 m	*			
	Distance	6.05	4	0.007	10 m	**	ns		
					25 m	*	ns	ns	
					Control	*	ns	ns	ns
Phosphorus	Season	0.81	3	ns	5 m	ns			
	Distance	5.43	4	0.010	10 m	ns	ns		
					25 m	*	ns	ns	
					Control	**	ns	ns	ns
Chl	Season	1.29	3	ns	5 m	ns			
	Distance	4.32	4	0.022	10 m	*	ns		
					25 m	ns	ns	ns	
					Control	*	ns	ns	ns

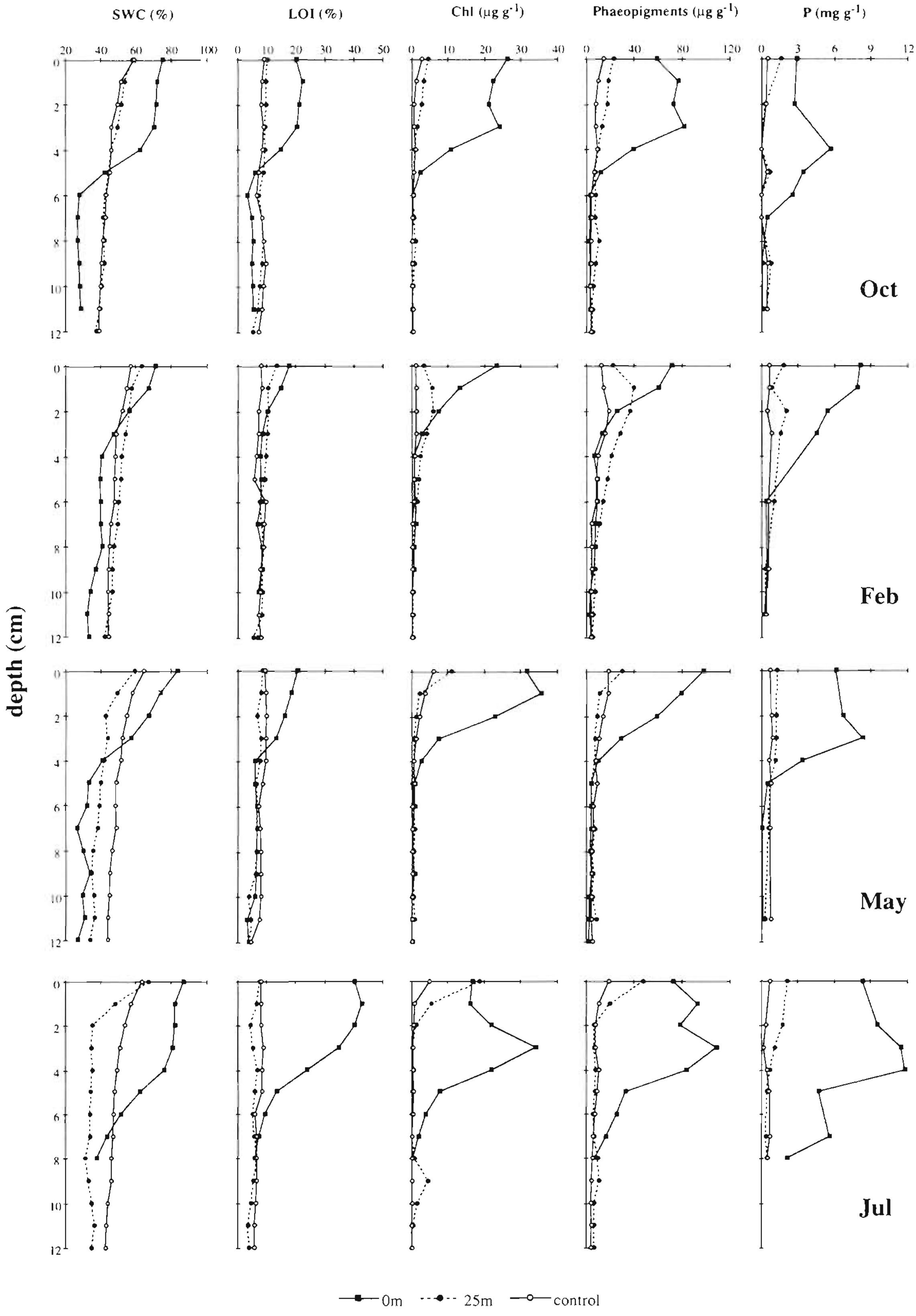

Fig. 3. Vertical distribution of sediment variables in core profiles beneath the cages, at 25 m distance and at the control site. SWC: sediment water content; LOI: organic material

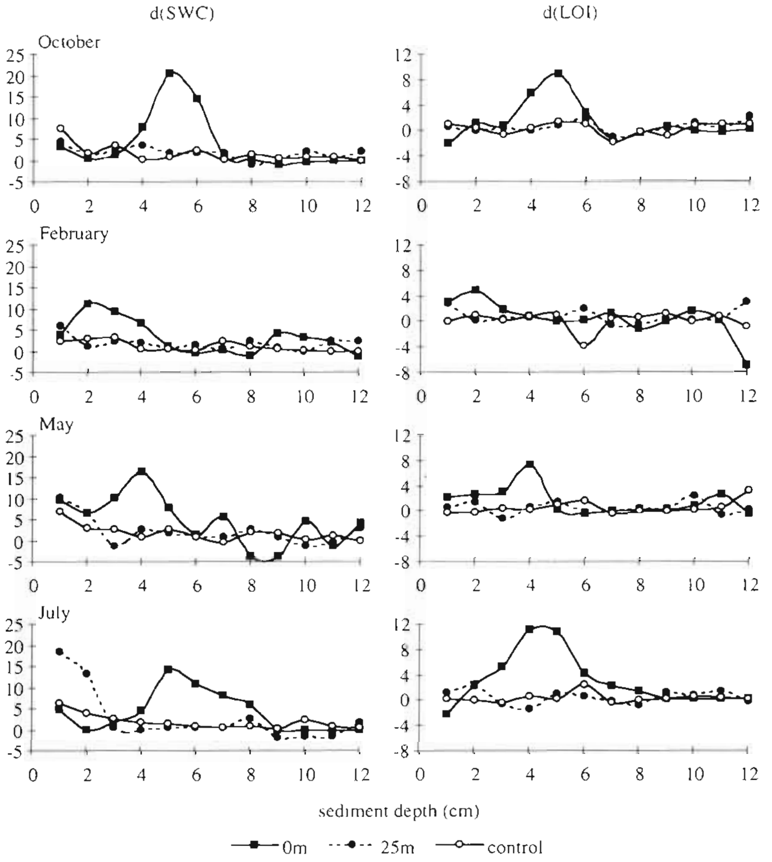

Fig. 4. Determination of farm sediment depth for each season as the depth corresponding to the maximum value of d(SWC) and d(LOI)

between the cages and the other stations for SWC and LOI, whereas in the case of chl only the station at 25 m was significantly different from the other two.

LOI provides a measure of the organic content of the sediment, however this value is a good estimator of the organic carbon in highly enriched sediments whereas it overestimates organic material in samples with low organic content due to pyrolysis of carbonates and other combustible inorganic compounds. The surface LOI values reported above (Fig. 5) for the station under the cages and at the 25 m station seem to be higher than those at the control station by a factor of 5 for samples taken in July. However results obtained for samples through CHN analysis (Fig. 7) showed that this factor is approximately 13 for organic carbon and 15 for organic nitrogen.

DISCUSSION

The results of the present study revealed a fluctuation of the farm sediment thickness throughout the year at the station beneath the cages which seems to be related to the food input which had a similar temporal fluctuation, the minimum (in January) being 50% of the period's maximum in June (D. Troyanos pers. comm.). The lower values measured during February indicate that a limited recovery process takes place during the winter period due to the coupling of low food input with increased efficiency in mineralization during winter (Gilbert et al. 1997). Strong wind-driven currents during this period of the year could also be responsible for sediment resuspension, removing part of the accumulated waste. However the investigation of change through ANOVA did not show any seasonal effect either for surface or for CV values. This discrepancy is probably due to the main characteristics of the 2-way ANOVA which is

Table 2. Results of 2-way ANOVA for CV values for all the sampling seasons. *$p < 0.05$, **$p < 0.01$ ns: not significant

Variable	Source of variability	*F*	df	p	Tukey post hoc test		
						0 m	25 m
Water content	Season	0.815	3	ns	25 m	*	
	Distance	13.696	2	0.006	Control	**	ns
LOI	Season	0.785	3	ns	25 m	**	
	Distance	28.054	2	0.001	Control	**	ns
Phosphorus	Season	0.102	3	ns	25 m	ns	
	Distance	9.299	2	0.015	Control	*	ns
Phaeopigments	Season	0.463	3	ns	25 m	ns	
	Distance	5.417	2	0.045	Control	*	ns
Chl	Season	0.463	3	ns	–	–	–
	Distance	5.417	2	ns	–	–	–

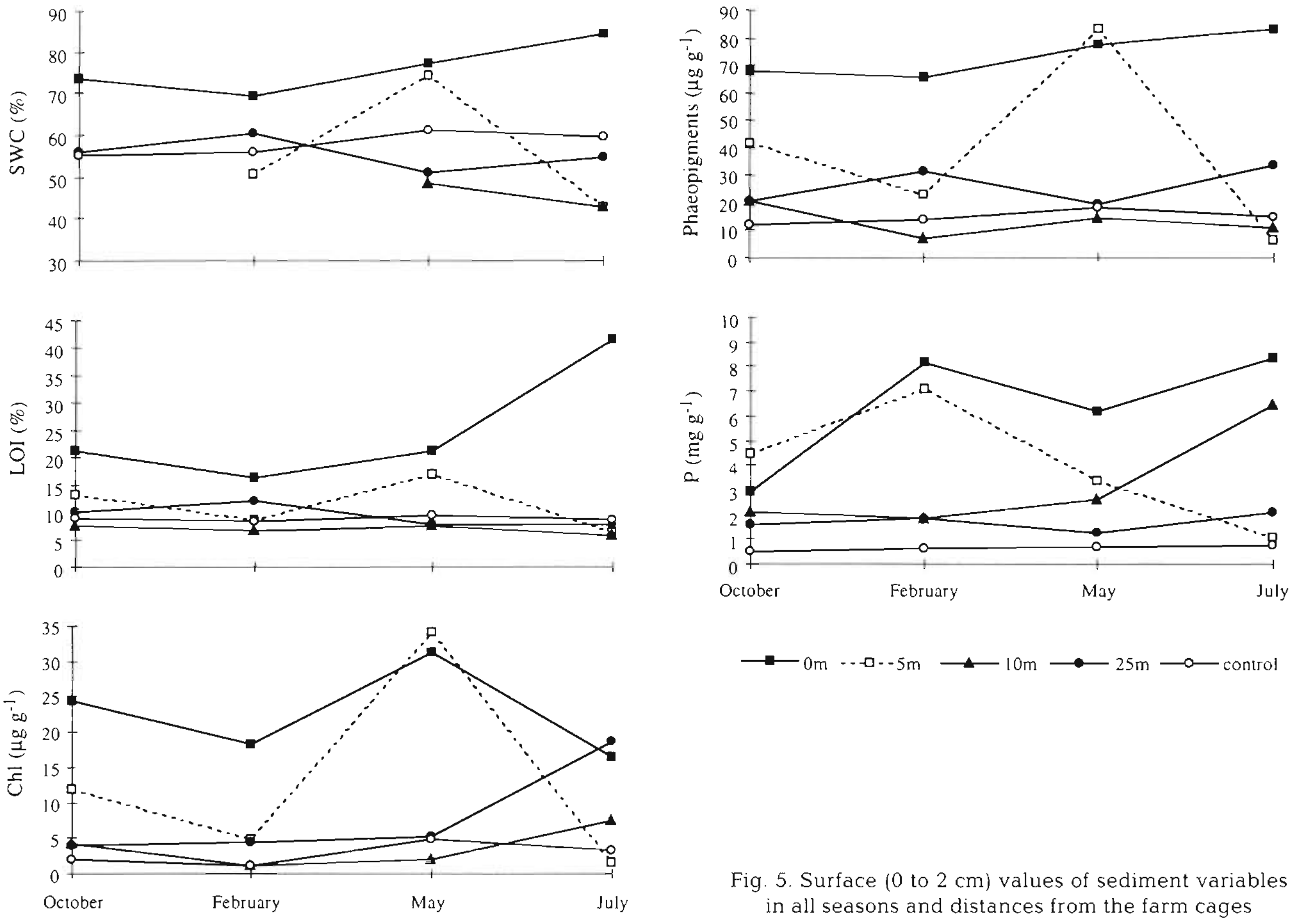

Fig. 5. Surface (0 to 2 cm) values of sediment variables in all seasons and distances from the farm cages

able to detect significant differences only when factor 1 induces similar response (increase or decrease) in all the values of all the levels of factor 2. However this is unlikely in the case of seasonal trends examined in our data and in particular for surface values. The values recorded here as concentrations (w:w) do not correspond to similarly deposited sediments since the sedimentation rate under the cages and even at the station at 25 m varies dramatically, the amount of settling material at the 25 m station, determined by means of sediment traps, being 5 to 10% that of the station under the cages (Tsapakis unpubl. data). Moreover the summer sedimentation of the (naturally deposited) organic material at the control station is expected to be (and it was found to be) minimal while for the same period the concentration of organic material under the

Table 3. Results of 1-way ANOVA for CV and surface values for the replicated sampling in July. $^{*}p < 0.05$, $^{**}p < 0.01$. ns: not significant

	CV		0 m	25 m	Surface values		0 m	25 m
Chl	*F* = 20.052 df = 2,6 p = 0.002	25 m	**		*F* = 10.909 df = 2,6 p = 0.010	25 m	ns	
		Control	ns	*		Control	ns	**
LOI	*F* = 36.249 df = 2,6 p = 0.000	25 m	**		*F* = 80.801 df = 2,6 p = 0.000	25 m	**	
		Control	**	ns		Control	**	ns
Water content	*F* = 8.752 df = 2,6 p = 0.017	25 m	ns		*F* = 49.874 df = 2,6 p = 0.000	25 m	**	
		Control	*	ns		Control	**	ns

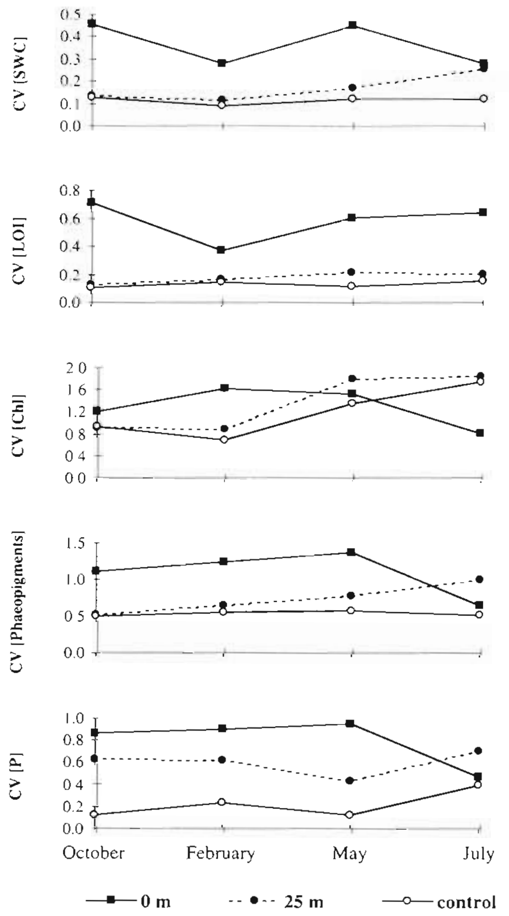

Fig. 6. Values of sediment vertical variability index (CV) for 3 sampling stations in all the sampling seasons

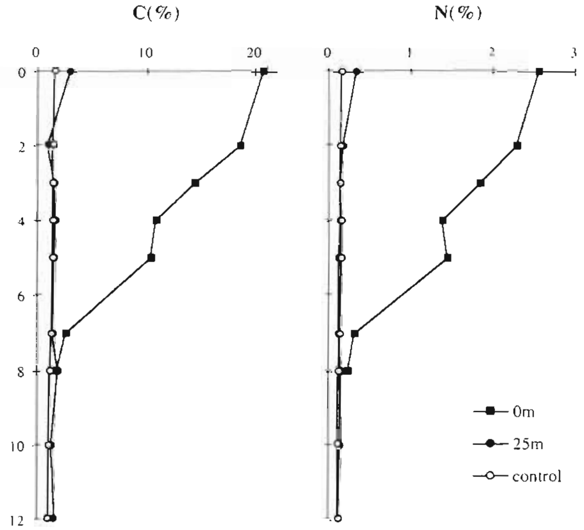

Fig. 7. Results of CHN analysis for organic carbon and nitrogen for samples collected during July 1997

cages is maximal due to the intensification of the temperature-dependent feeding process. A different seasonal pattern has been reported by Gilbert et al. (1997) for the impact of shellfish farming on the sedimentary variables in a Western Mediterranean lagoon. These differences are attributed to the different characteristics of the 2 farming practices, the shellfish farming depending on *in situ* plankton production whereas cage fish farming depends on exogenous organic input highly regulated by the ambient water temperature.

The extent of the seabed area impacted by fish farming activities varies in general with current velocity and depth according to the model proposed by Gowen & Bradbury (1987). Significant impacts have been reported at distances of 100 m from the cages but in general it seems that this impact is a highly localized phenomenon not exceeding 20 to 50 m (Beveridge 1996). Our results are in accordance with this view since only the station beneath the cages was consistently different from the control site for all the variables measured. However it seems that the intermediate stations were impacted up to a certain point since at least for some of the environmental variables they presented no significant difference from either the control or the impacted station. The detected impact on the intermediate stations could be due to either direct settling of small particles, carried longer distances by the current, or to resuspension and resettling by strong wind-driven currents.

There were conspicuous differences among environmental variables in terms of both enrichment factors and vertical distribution. This is no surprise since each of these variables is related to different processes impacted by the presence and the function of the farm.

The vertical distribution of water content in the sediment followed the same pattern in all the sampling periods. The loose surface layer under the cages contained up to 95% water, exceeding that at the control station by at least 20%. Deeper in the sediment a rapid change with depth marks the limit of this recently deposited layer. In this deeper zone the sediment is more compact than at the control station, perhaps due to the absence of the bioturbating activity of the macrofauna since the accumulation of food and faeces during the warm season results in highly anoxic conditions under the cages which have been shown to reduce the available space for macrofaunal organisms (Hatziyanni et al. 1997). Kupka-Hansen et al. (1991) have reported a farm sediment thickness up to 30 cm (with 60 to 90% SWC) in Western Norway, indicating that no larger fauna (>5 mm) was found when thickness exceeded 20 cm.

The concentration of organic material (as estimated by means of LOI), as shown by CHN results, is a poor descriptor of the farm impact, at least as far as the comparison to the reference site is concerned. However this method allows comparisons between seasons and it has been used by many authors so far for the assessment of such impacts although the methodology used in the literature is anything but standard. Lower LOI values (15 to 20%) have been reported for shellfish farms in the Western Mediterranean (Gilbert et al. 1997), concentrations up to 10% were found under a sea bream farm in the Gulf of Aqaba (Angel et al. 1995) while levels similar to those in the present study have been reported for salmonids in Norway (15 to 47%) by Kupka-Hansen et al. (1991) and for rainbow trout in Denmark (18 to 24%) by Holmer & Kristensen (1992).

The concentration of chl in the sediment is related either to phytobenthos or to the sedimentation of phytoplankton cells from the water column. However in Cephalonia Bay and particularly around the farm cages, no filamentous algae or other benthic plants were found and the high turbidity reduces the amount of radiation reaching the seabed. Therefore it could be considered that the entire chlorophyll content is related to the sedimentation as also indicated by the low ratio of chl:phaeopigments. The pronounced increase in chl content beneath the cages could be attributed to higher phytoplankton production in the cages as a result of the increase in ammonium and phosphate coupled with increased sedimentation rates due to the significant decrease in current velocity within the cages (Inoue 1972 in Iwama 1991).

The pronounced sediment anoxia makes the sediment unsuitable for macrofaunal organisms and especially infaunal deposit feeders that could digest sedimenting phytoplankton cells, while the presence of mussels on the ropes and floating structures of the cages is likely to contribute to the increased sedimentation of undigested phytoplankton material through the production of pseudofaeces. Numerous studies have revealed such an increased production of pseudofaeces with increased concentration of phytoplankton in the water column (Bayne et al. 1976). The repackaging of phytoplankton cells in larger particles could produce a different pattern in the dispersion of particles under the cages than that predicted by Silvert (1994) since pseudofaeces tend to be larger in size than single phytoplankton cells, but smaller than unconsumed food pellets or sea bream faecal pellets. Therefore sinking rates of pseudofaeces are expected to be lower than the average particles sedimenting from the cages and consequently they could be transported further away by the water current. This could be the reason for the relatively high concentrations of pigments found in the sediments at the 25 m distance station.

Phosphorus concentrations at the 25 m distance stations showed consistently higher values (by a factor of 1.6 to 3.3) at the surface sediment layers than respective concentrations at the control station. This difference was even higher at the station below the cages, exceeding the respective concentrations at the control site by 6 to 13 times. In general total P concentrations showed a progressive increase in sediment loading with time, which is consistent with the information provided by the fish farmer concerning the intensification of feeding process in this unit. The vertical profiles of phosphorus concentrations under the cages in Cephalonia Bay showed a pattern similar to that found by Holby & Hall (1991) for a rainbow trout farm in Gullmar Fjord, Sweden, although the values reported by these authors for the surface layers were considerably higher (15 mg g^{-1}) despite the cessation of the feeding activity during the winter months (i.e. December to March) in this particular farm (Hall et al. 1990).

The results of the present paper support the observation by Holby & Hall (1991) for the accumulation of phosphorus in the farm sediment. Fig. 3 shows that unlike other variables, phosphorus load in the sediment constantly increases despite the smaller or larger fluctuations at the surface. Previously conducted measurements at the same sites (Karakassis et al. 1997) indicated that maximum loading occurs during late autumn and therefore it is expected that during October 1997 the accumulation of phosphorus would increase even more. The fact that a large amount of phosphorus tends to be buried in the sediment is an important issue since it implies that this part of the loss to the environment is not available for phytoplankton growth and therefore there is a lower risk of triggering algal blooms in P-limited marine environments such as the Mediterranean Sea. However in order to arrive at safe conclusions concerning phosphorus release in the warm Mediterranean sediments, specific experiments should be conducted for the measurement of phosphate fluxes.

The detection of change through the study of vertical profiles of the sediment water content was proved to be an efficient method in discriminating differences along the organic enrichment gradient. The CV index showed relatively low variability within replicates (standard deviation was less than 29% of the mean, as opposed to 36% for surface values).

The present study emphasizes the need for investigating patterns in vertical profiles as a means for the assessment of fish farming impacts. The measurement of surface values alone, although useful for the assessment of the size of the impact, may not provide adequate information on the dynamic processes related to the accumulation of waste material beneath the cages. Some of the environmental variables (and in particular concentrations) may be relatively constant in time while the depth of the farm sediment could vary considerably.

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