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Analysing the impact of bottom trawls on sedimentary seabeds with sediment profile imagery

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Abstract

Sediment profile imagery (SPI) was evaluated for the assessment of otter trawling impacts on the seabed. This technique allows the imaging of the topmost sediment layers in profile, including the sediment–water interface. Two areas in the Aegean Sea were investigated in time series, each with control and impact areas: a commercial fishing lane with soft sediments at approximately 200 m depth and an experimentally trawled lane with harder maerly sediments at approximately 80 m depth. In total, 158 images were taken at the deep ground and 124 at the shallow ground. A number of measurements were taken from each image, leading to estimates of comparative penetration and small-scale seabed surface roughness. In addition, a large number of surface and subsurface attributes were noted in the images to form the basis of a multivariate analysis. Results indicated that penetration and roughness by themselves were not very good indicators, although roughness was a better indicator particularly in coarse sediments. The major reason for this is that the measurements alone (in particular roughness) do not distinguish between biological and anthropogenic disturbance. The multivariate analysis combining the measurements with the attributes was a good indicator in investigating trawling impacts in coarse sediments, where the lack of good penetration can be compensated by the view over the sediment surface, where more attribute-type data can be gathered. The SPI sampling window gives a relatively small imaged sample in comparison to other imaging techniques (side scan sonar, video, etc.) and in a heterogeneous environment, the more the replicates, the more reliable the method will be. A tiered imaging approach is recommended where more than one methodology is used.

Keywords: Sediment profile imagery; Trawling impacts; Imaging; Aegean Sea; Mediterranean Sea

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1. Introduction

In the last 10 years, there have been a large number of studies involving the investigation of bottom trawl impacts on sedimentary environments. Hall (1999) and Kaiser and de Groot (2000) have recently reviewed a wide range of aspects concerning trawling impacts, including recovery, studies on various fractions of fauna, physicochemical effects, resuspension of fine sediments and nutrients, damage and survival of target and non-target fauna. Experimental and field studies have shown that the abundance of epifauna and infauna (macro- and megafauna) is generally reduced with corresponding changes in community and trophic structure (Dayton et al., 1995; Jennings and Kaiser, 1998; Lindeboom and de Groot, 1998; Collie et al., 2000a; Gislason et al., 2000; Smith et al., 2000). However, smaller body-sized fauna, for example, the meiofauna, may be more resistant to trawling (Schratzberger et al., 2002).

Trawling typically reduces the surface roughness of the seabed, i.e. the microtopographic relief of the seabed (Auster et al., 1996; Jennings et al., 2001) related to the presence of sessile fauna, biogenic features, shell fragments, etc. Acoustic data from trawled sites (Kaiser and Spencer, 1996; Schwinghamer et al., 1996) have shown that trawling marks were detectable to a depth of 4.5 cm within the sediment (Schwinghamer et al., 1996). Although sedimentary grain size may not change in an area due to trawling (Smith et al., 2000), a number of differential physical impacts can be found over short distances, with heavy plough furrows with associated spoil heaps (door impacts), lightly scraped sediment surfaces (wire impacts), completely flattened and scraped surfaces (ground rope and net impacts), and small patches of relatively untouched sediments (Caddy, 1973; Krost et al., 1990; Smith et al., 2000). The marks can be seen with different spatial resolutions and scales by different techniques. Sediment surface impacts can be imaged by side scan sonar over wide areas (e.g. 200 m strips over kilometres) with a resolution of 15–20 cm, allowing only the imaging of door marks (Service and Magorrian, 1997; Schwinghamer et al., 1998; Friedlander et al., 1999; DeAlteris et al., 1999). Video is able to image smaller areas (1–2 m strips over sub-kilometres) with a resolution of approximately 2 cm, allowing the imaging of the majority of trawl marks (Service and Magorrian, 1997; Schwinghamer et al., 1998; Smith et al., 2000). Smaller scale imaging has rarely been used in trawling impact studies and this is normally limited to larger features on the sediment surface (Collie et al., 2000b).

Sediment profile imagery (SPI) utilises an imaging device in an inverted periscope (optical prism) to view the upper sediment layers (approximately 15×20 cm in area) allowing fine scale analysis of physical, chemical and biological features (Rhoads and Young, 1970; Rhoads and Cande, 1971; Rhoads and Germano, 1982, 1986). Direct measurements can be made from the images (e.g. prism penetration, roughness, depth of layers) and variety of surface and subsurface features noted (e.g. sediment structure, fauna, bioturbation traces, feeding voids). SPI data have been presented in combination with macrofaunal and/or geochemical data (Rhoads and Germano, 1982, 1986; O'Connor et al., 1989; Grehan et al., 1992; Rosenberg and Diaz, 1993; Rosenberg et al., 2000; Rumohr, 1993; Rumohr and Schomann, 1992; Rumohr and Karakassis, 1999; Bonsdorff et al., 1996; Nilsson and Rosenberg, 1997, 2000; Karakassis et al., 2002). The coupling between these sources of data has been based on indices compiled for the SPI images (e.g. organism–

sediment index of Rhoads and Germano, 1986, or benthic habitat quality of Nilsson and Rosenberg, 1997, 2000). Latterly, Rumohr and Karakassis (1999) and Karakassis et al. (2002) have used an approach where multiple variables were recorded from SPI images allowing comparisons among sampling stations through standard multivariate techniques.

SPI data are normally used from a number of replicate images in sampling sites, although it has also been deployed in time-lapse mode for behavioural studies (Solan and Kennedy, 2002). Samples can be collected and processed quickly and, although it has been proposed as an alternative for traditional benthic sampling, the technique is primarily used either in pre-surveys for quick identification of hot spots or in conjunction with other traditional analytical techniques (e.g. Valente et al., 1999). The technique works well in soft sediments where deep prism penetration can be achieved, but has been of less use in coarser sediment with low penetration. SPI has been used extensively along enrichment and disturbance gradients and, more recently, in the monitoring of fish farm impacts (Karakassis et al., 2002).

SPI has been applied to the study of fishing gear impacts in the southern North Sea and the Irish Sea but has only been reported in a very limited way (Lindeboom and de Groot, 1998). Lindeboom and de Groot (1998) reported that physical differences from otter trawling could be seen in the North Sea between trawled and non-trawled sites in respect to penetration and roughness, whilst in the Irish Sea, recently settled resuspended sediments were seen as well as possible changes to sedimentary redox conditions. The presence of broken sediments on the Honk Kong shelf, observed in SPI images (Valente et al., 1993), has been attributed to beam trawling.

In the present study, we have used SPI to investigate the effects of bottom trawls in two different types of habitat, on soft muddy and harder maerl substrates (sand with coralligenous algal fragments) in a typical Mediterranean ecosystem of the South Aegean (Cretan Sea). Both habitats were sampled repeatedly during different seasons and reference (undisturbed) areas were used to monitor changes not related to trawling impacts, using a BACI (before after control impact) experimental design.

2. Materials and methods

2.1. Study areas

Bottom trawling impacts were investigated at two study areas in Iraklion Bay on the north coast of Crete in the southern Aegean (see Fig. 1). Both areas have been selected on the basis of previous studies relating to sedimentary impacts of trawling (Smith and Papadopoulou, 1999), with additional verification with side scan sonar and video imaging. The first area consisted of a commercial trawling lane with a narrow constriction that allowed for easy identification of the trawling lane and adjacent non-trawled control areas. This trawling lane more or less followed the 200-m contour and narrows with the contours behind Dia Island, where the trawlers often haul their nets. The trawl lane is well defined and control areas were easily identifiable in close proximity on either side of the trawl lane. Sediments have been described (Smith et al., 2000) as relatively soft silty clays (median grain size 0.016–0.019 mm, with sand, silt and clay at approximately 9%, 88% and 3%,

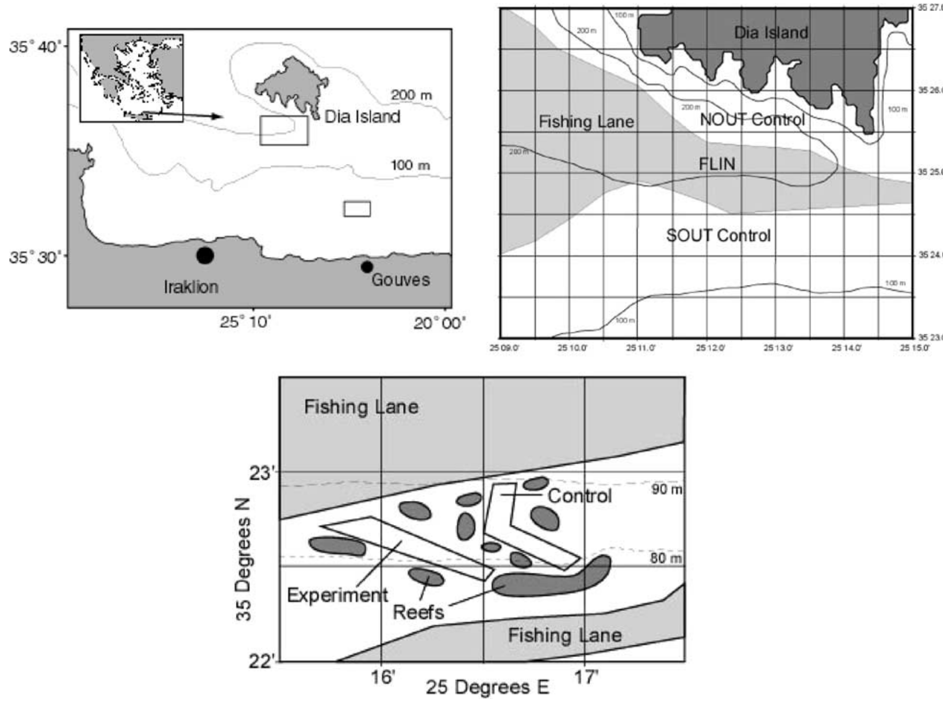

Fig. 1. Sampling grounds in the southern Aegean showing the two experimental areas, Dia Island and Gouves, with individual control and fishing (or experiment) areas.

respectively) with no significant differences in granulometry between the control areas and the trawl lane. Sampling areas included an area approximately 5 km long, along the trawling lane (FLIN) and two control areas, one 2 km long to the north of the lane (NOUT) and the other 3.5 km long to the south of the trawling lane (SOUT). Towed underwater sledge and side scan sonar were used during each sampling period for monitoring purposes and to ensure that the control areas were free of trawling impacts.

The second sampling area off Gouves was typical of shallower water trawling grounds (at approximately 80–90 m depth). The area was sited adjacent to other commercial trawling lanes within a protected area marked by rocky and calcareous algal reefs. An impact experiment was set-up with an experimentally trawled area (EXP) and an adjacent protected control area (EXPC). Both areas were approximately 1000 m long by 100 m wide (see Fig. 1). The experimental area was consecutively trawled 13 times over a 2-day period. Sediment composition was mixed, but was generally coarse sand with some mud and in localised areas, with calcareous sand/rock fragments (maerl) on the sediment surface (median grain size 0.10–0.13 mm, with sand, silt and clay at approximately 68%, 30.5% and 2.5%, respectively). Samples were taken along the length of the two areas.

Time series sampling was carried out separately for the two experiments in 1999 and 2000. At Dia Island, this was spread across 2 years with samples being taken in the trawling lane and control areas during the trawling season (start of October to end of May)

Table 1
Sampling periods for the experiments at Dia Island and Gouves, including the number of images taken during each period

	Year	1999		2000			
	Month	April	September	April	June	September	November
Dia Island							
Period		0	1	3	4		6
Images		25	17	28	24	-	64
Gouves							
Period				2	3	4	5
Images				31	14	27	52

Closed trawling season sampling periods at Dia Island highlighted in gray.

Table 2
Attributes identified on the SPI images and used for multivariate analyses

Dia Island attributes	
Tube/Foram	Small tubes or Foraminifera (straight or branching) on the surface
Biot Mark	Bioturbation mark on the surface or subsurface
Clay Layer	Subsurface layering visible
Gradient	No subsurface layers visible
Clasts	Identifiable clasts on the surface or subsurface
Void	Subsurface burrow or feeding void
Refill Depr.	Refilled surface depression
BRS	Biologically reworked surface
Sulphide	Sulphide layers, streaks or marks present
Polychaete	Identifiable polychaete present subsurface
Biog. Mnd	Biogenic mound on the surface
Phys Dist.	Surface physically disturbed
Resettled	Presence of a resettlement layer on the surface
Gouves attributes	
Silty Fine Sand	Sediment appears as silty fine sand
Silty Medium Sand	Sediment appears as silty medium sand
Silty Coarse Sand	Sediment appears as silty coarse sand
Medium Sand	Sediment appears as medium sand
Coarse Sand	Sediment appears as coarse sand
Biological Sorting	Areas subsurface of biologically sorted sediment
Fragments	Shell or maerl fragments on the surface
Foraminifera	Foraminifera tubes apparent on the surface
Tube	Defined tube apparent on the surface
Tube Detritus	Broken tube fragments on the surface
Organic Detritus	Organic detritus on the sediment surface
Mound	Biological mound at the surface
Bioturb Mark	Bioturbation mark present subsurface
Branching Alga	Branching alga at the surface
Red Alga	Red alga at the surface
Maerl	Large maerl pieces on the sediment
Epifauna	Epifauna on the surface (e.g. sponge)
Scrape Mark	Physical disturbance on the surface
Flat	No microtopography or any other surface projecting feature

and the closed trawling season (start of June to end of September). The total number of images during each of the sampling periods is shown in Table 1. At the Gouves area, sampling started in the control and experimentally trawled lane immediately after the trawling impact, with a duration of 8 months. Additional samples were taken in the adjacent commercial trawling ground (EXPFL) during the last sampling period. Table 1 shows the number of images collected during each sampling period. Operational difficulties led to the collection of an uneven number of images and resulted in lost images during the September sampling at Dia Island.

2.2. Sediment profile imagery

Sediment profile images were taken using a custom-built SPI system (Hydrovision, Sweden). The system used standard SPI layout with a vertically mounted camera and flash

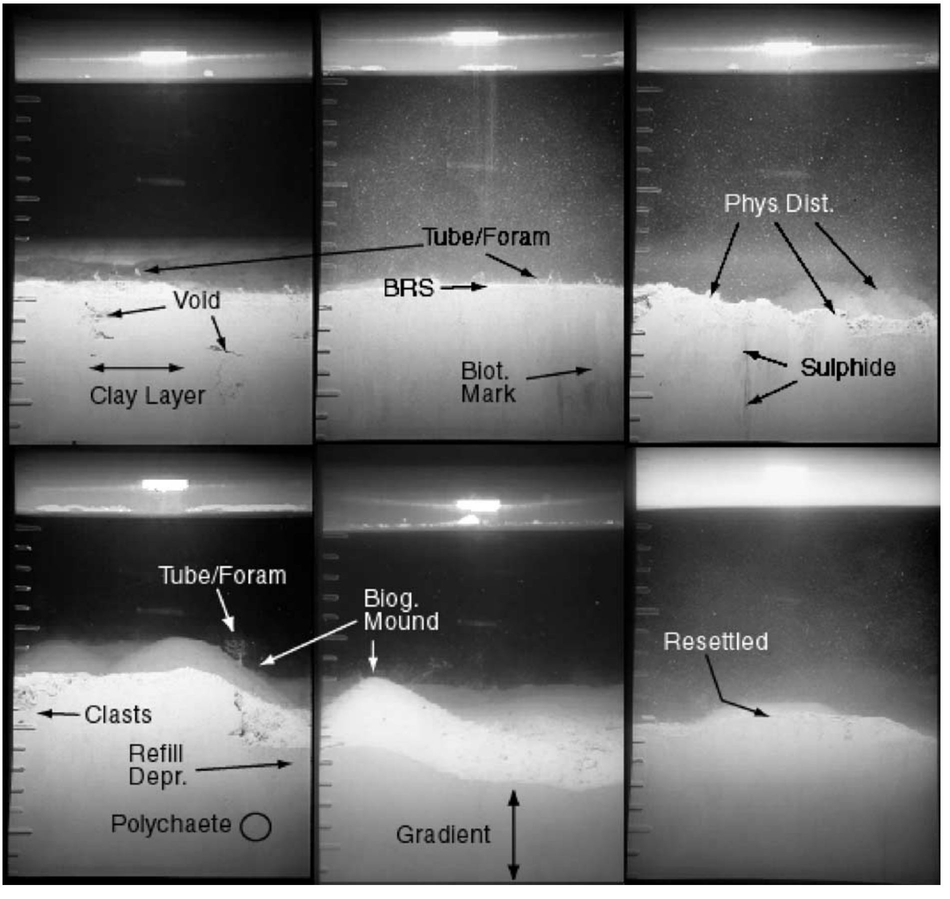

Fig. 2. Examples of SPI images from Dia Island indicating the primary attributes used in the multivariate analysis (see attributes, Table 2).

photographing through a water-filled prism (the custom feature being that the prism can be dismounted for diver operations). The camera was a Nikon F90X taking standard photographic slide film (35 mm, 100 ASA). The SPI system was lowered to the seabed with slow speed for the last few metres. It was left on the seabed for 30 s (the camera is set for a 20-s delay after bottom contact to allow slow penetration of the piston dampened prism) with extra wire paid out if the supporting vessel was drifting in the wind. The system was then lifted 10 m above the seabed and dropped again, with repeats for the required number of replicates in a particular area. Position of each drop was noted along with water depth. After normal processing, the slides were digitised on a slide scanner (Epson Filmscan 200).

The digitised images were then imported into Adobe Photoshop for processing. Using the front plate scale bars and a software measuring function, maximum, minimum and visual mean penetration were noted. Bottom roughness was calculated for each image as a function of maximum minus minimum penetration. Major attributes for each image were noted (see Table 2 and Fig. 2 for Dia Island and Fig. 3 for Gouves) and then converted into a presence and absence matrix. The data were then analysed by firstly univariate comparison of measurements of penetration (nonparametric Wilcoxon or Kruskal–Wallis tests as appropriate) and secondly by multivariate analyses of the measurements and attributes utilising the software package PRIMER (Clarke and Warwick, 1994). The multivariate analysis of SPI data was carried out according to the method introduced by Rumohr and Karakassis (1999) and Karakassis et al. (2002). A large number of attributes

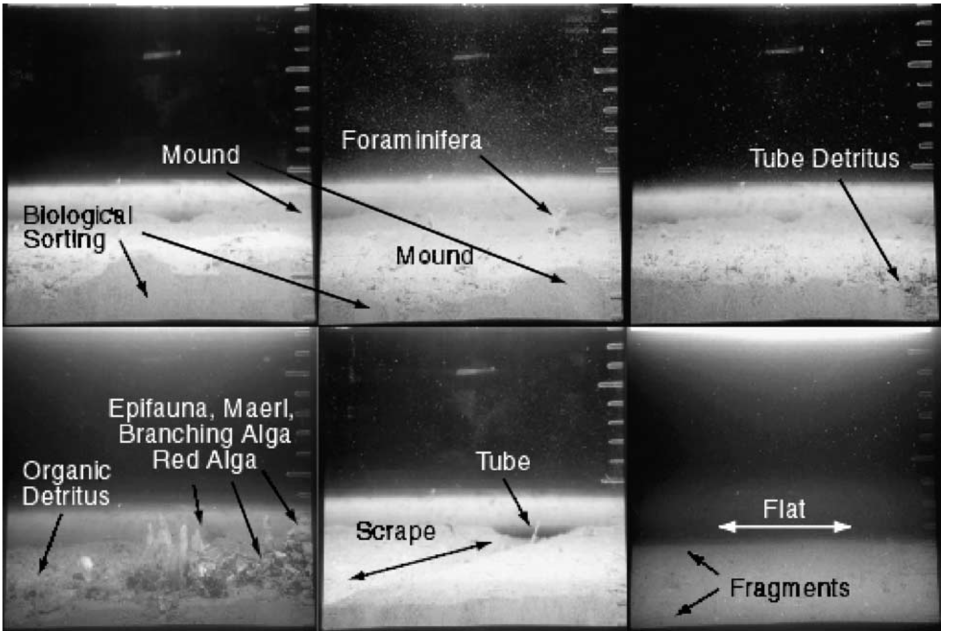

Fig. 3. Examples of SPI images from Gouves indicating the primary attributes used in the multivariate analysis (see attributes, Table 2).

identified in the SPI-obtained pictures were treated as quantitative data. The presence/absence (binary) data were quantified by calculating the frequency of occurrence of each attribute in the replicated photos obtained at each site in each sampling event. SPI data were *Z*-standardised to avoid the effect of differences in range and analysed by means of MDS, calculating similarities by means of Euclidean distance. The data for both the Dia and the Gouves areas were analysed using multivariate techniques twice. The first analysis included all the data ('All Data'), including measurements of penetration and roughness, and the attributes. The second analysis was confined to the attributes only ('Attributes Only') to see how the presence of the measurements may affect the analysis. The ANOSIM method (Clarke and Warwick, 1994) was used to detect statistically significant differences between the groups obtained by the cluster analysis.

3. Results

3.1. Univariate analyses

A total of 158 images were analysed from the Dia Island area. The mean data values for penetration and roughness are shown in Fig. 4 with values and significance levels in Table 3. Mean penetration in the soft sediments ranged between 7 and 10 cm. There was no clear trend in differences between the trawling lane and the control areas seen in Fig. 4. Significant differences were found between areas for penetration during the first and last two sampling periods, with opposing results concerning deeper penetration firstly in the southern control site and then latterly in the fishing lane. There were no clear results either, from the analysis of roughness with the only significant difference between areas during the first sampling period. Significant differences were found over time within each of the areas for penetration, but not for roughness.

A total of 124 images were analysed from the Gouves experimental area. The mean data values are shown in the lower part of Fig. 4 with values and significance levels in Table 4. Mean penetration in the coarser sediments was much lower than at Dia Island and ranged from 0.01 to 1.6 cm. Lowest penetration and roughness by far (both significant) was found in the commercial fishing lane adjacent to the experimental area. Mean penetration at the control site was higher in every case than at the experimental fishing lane, but only significantly so during the first and last sampling periods (last sampling period EXP:EXPC Wilcoxon test, $p = 0.005$). Mean surface roughness was significantly higher at the control site than the experimentally fished lane during the first and the last sampling periods. Mean penetration was found to vary significantly over time in both areas, more significantly so in the experimentally trawled lane with very similar results for roughness with a increase in the experimental trawling lane, after impact.

3.2. Multivariate analysis

Fig. 5 shows the results from the Multi-Dimensional Scaling (MDS) and the dendrogram analysis from the soft sedimentary Dia Island area. For 'All Data' (attributes and

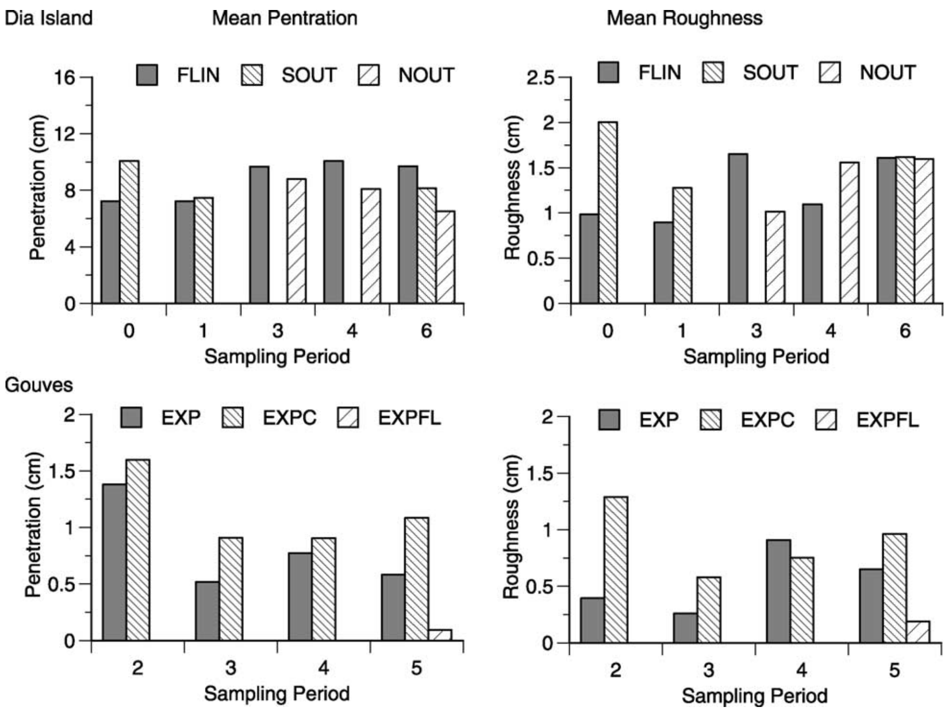

Fig. 4. Changes in mean penetration and roughness from the SPI images of Dia Island (FLIN, Fishing Lane; SOUT, south control; NOUT, north control) and the Gouves experiment (EXP, experimental fishing lane; EXPC, control; EXPFL, commercial fishing lane) for each sampling period. The levels of significance are shown in Tables 3 and 4.

Table 3
Mean penetration and roughness values (cm) for the Dia Island SPI images (FLIN, fishing lane; SOUT, south control; NOUT, north control) with P values for non-parametric Wilcoxon (2 cases) or Kruskal–Wallis test (>2 cases) within each sampling period and between periods for each sub-area

Period	FLIN	SOUT	NOUT	*P* value
Penetration				
0	7.232	10.072		0.005
1	7.220	7.469		0.263
3	9.672		8.783	0.279
4	10.070		8.101	0.046
6	9.699	8.156	6.514	<0.001
P value	<0.001	0.004	0.001	
Roughness				
0	0.983	2.002		0.002
1	0.898	1.276		0.093
3	1.650		1.016	0.363
4	1.095		1.557	0.917
6	1.610	1.619	1.595	0.451
P value	0.342	0.219	0.199	

Significant values highlighted in gray.

Table 4
Mean penetration and roughness values (cm) for the Gouves SPI images (EXP, experimental fishing lane; EXPC, control; EXPFL, commercial fishing lane) with *P* values for nonparametric Wilcoxon (2 cases) or Kruskal–Wallis test (>2 cases) within each sampling period and between periods for each subarea

Period	EXP	EXPC	EXPFL	*P* value
Penetration				
2	1.380	1.598		0.041
3	0.519	0.908		0.068
4	0.773	0.907		0.678
5	0.583	1.084	0.094	0.001
P value	0.001	0.042		
Roughness				
2	0.395	1.288		0.001
3	0.259	0.580		0.144
4	0.909	0.752		0.515
5	0.651	0.963	0.189	0.004
P value	0.003	0.041		

measurements), the stations were evenly scattered, but with the control samples more grouped in the centre (highlighted within the dashed line) with the trawling lane samples having greater variability. The dendrogram had a relatively low Euclidean distance with a grouping of the three latter trawl lane samples of the time series with the least distance. The other two trawl samples were mixed in with the control samples. The result of the ANOSIM test, however, showed no statistical significance for differences between the control area and the trawl area for ($p = 0.42$).

The MDS for the 'Attributes Only' showed more scattered stations, not as clear, but with several of the fishing lane stations (3, 4 and 6FLIN) grouped towards the lower part of the MDS. Stress factors were similar at 0.05, indicating an excellent representation (Clarke and Warwick, 1994). For the cluster analysis, the Euclidean distance was generally wider than with 'All Data'. There was again no significant difference with the ANOSIM test ($p = 0.21$) between areas.

Fig. 6 shows the multivariate results from the coarse sediment Gouves experimental area. Stress values for both MDS analyses indicated excellent to good representation (Clarke and Warwick, 1994). The MDS for 'All Data' clearly differentiated the first and second sampling periods of the experimental trawling lane from the rest of the trawling lane and control experimental samples. These latter samples are shown as one highlighted group in the centre, but were, in fact, all superimposed on one another. The adjacent commercial fishing lane (5EXPFL), sampled only during the last period was completely separated from all the other samples. The dendrogram analysis mirrored the MDS analyses with a much higher Euclidean distance than found between the Dia Island samples. The control samples were closely linked with Euclidean distance of 10–20 units followed by the first two trawling lane sites at a distance of approximately 30 units, with the commercial fishing lane separated at 40 units. The results of the ANOSIM test showed a statistically significant difference between the control area, the experimental trawl area and the commercial fishing area ($p = 0.016$). There was also a significant difference between the first two sampling periods of the experimental trawl area, the commercial fishing area, and the rest of the sampling areas and periods ($p = 0.004$).

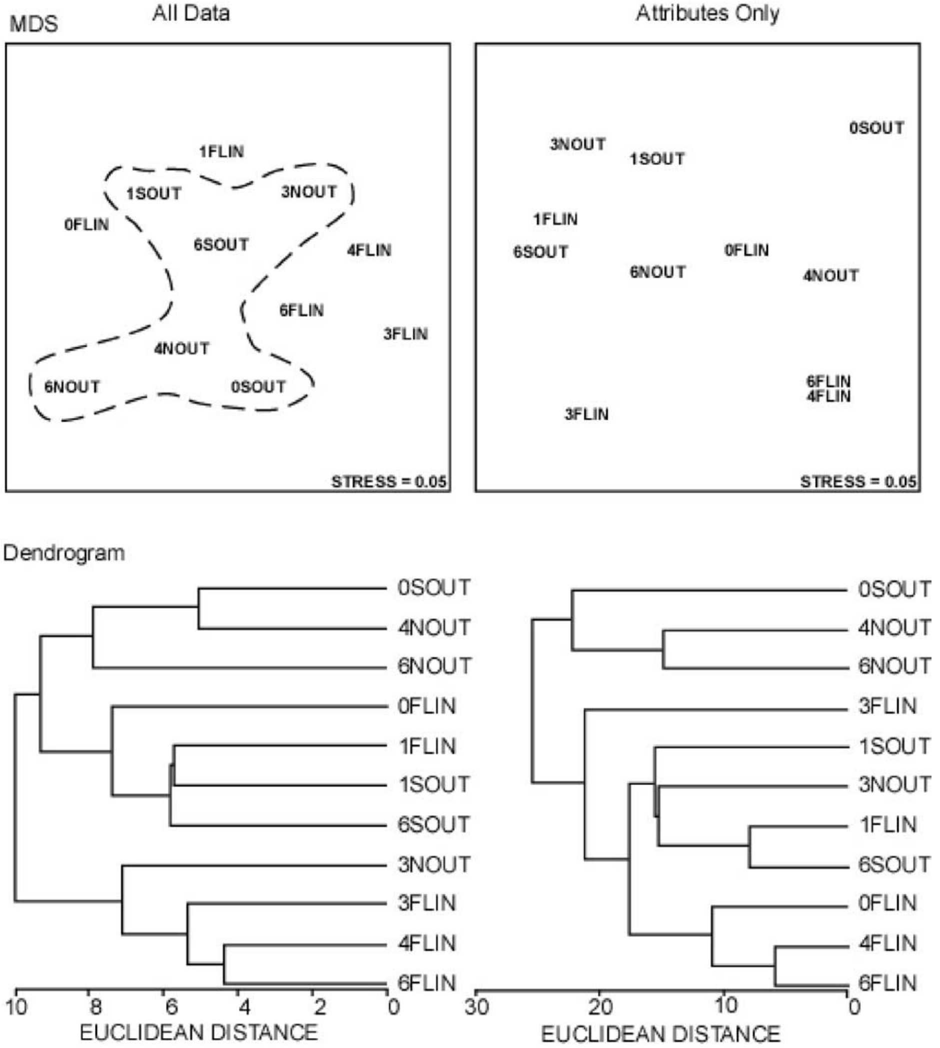

Fig. 5. Multivariate analyses (MDS and dendrogram) of the SPI images from the Dia Island area (trawling lane, FLIN; north control area, NOUT; south control area, SOUT; prefix number denotes sampling period given in Table 1). 'All Data' includes measurements of penetration and roughness as well as all attributes (Table 2). 'Attributes Only' repeats the analysis without the measurements.

When the MDS was applied to the 'Attributes Only', a very similar picture was found with the first two periods in the experimental trawling lane separated from the other trawling lane and control sites. This latter group was slightly more spread out than for the 'All Data' analysis. Again, the commercial trawling area was well separated from any of the other areas. The dendrogram was also similar, although with a slightly lower Euclidean distance. There was also a significant difference between the experimentally trawl area, the

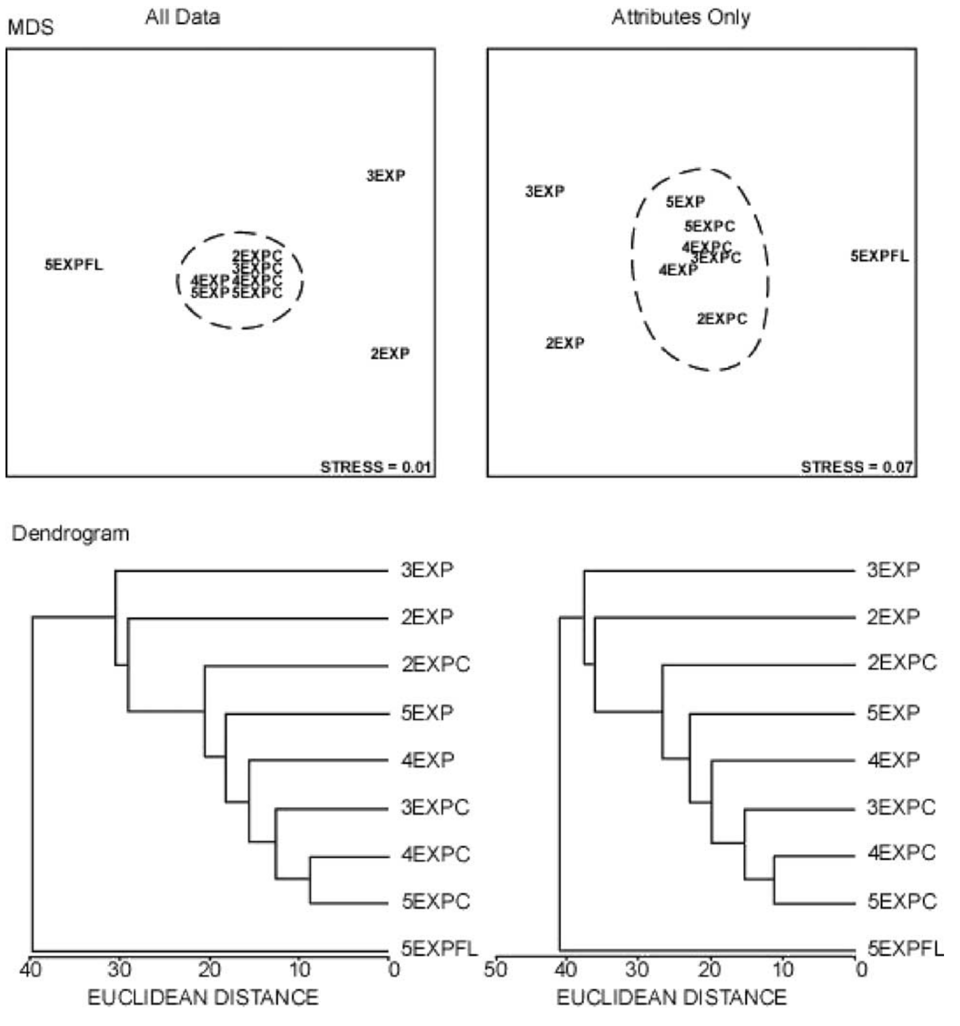

Fig. 6. Multivariate analyses (MDS and dendrogram) of the SPI images from the Gouves experimental trawling area (experimental trawling lane, EXP; control area, EXPC; adjacent commercial trawling lane, EXPFL; prefix number denotes sampling period given in Table 1). 'All Data' includes measurements of penetration and roughness as well as all attributes (Table 2). 'Attributes Only' repeats the analysis without the measurements.

commercial trawl area and the control area ($p = 0.025$), and a significant difference between the first two sampling periods in the experimental trawl area, the commercial fishing area, and the rest of the sampling areas and periods ($p = 0.004$).

The multivariate results at Gouves therefore indicated that at the start of the experiment, after the trawling impact, there were immediate differences between the trawling lane and the control area, but by the third sampling period (4EXP), there were no differences between the areas, 5 months after the trawling impact.

4. Discussion

Earlier studies using different methodologies have indicated that trawling decreases the roughness of the seabed and increases compaction. This has been noted using SPI and acoustic methods in the muddy sands of the southern North Sea by Lindeboom and de Groot (1998), and by acoustic methods on sandy sediments of the Grand Banks by Schwinghamer et al. (1996, 1998). Jennings et al. (2001) also reported on trawling reducing the complexity of both the surface and internal structure of soft-sediment habitats. At the beginning of the investigation of the commercial trawling lane at the soft sedimentary Dia Island, the first comparative results (0FLIN and SOUT) gave a clear indication that there was less prism penetration in the trawl lane (indicating more compact sediments) and a lesser degree of roughness, consistent with earlier published results. During the following sampling periods, however, the comparisons were either not significant or penetration was deeper in the trawled area. The results found here are indicative of the difficulty of using SPI penetration and roughness measures alone, for soft sedimentary impacts. It is concluded that the primary reason for this is the heterogeneous nature of trawling impacts. Other authors such as Lindegarth et al. (2000) have reported on the higher variability within soft-sedimentary trawl impacted sites in comparison to non-impacted sites. As noted in the introduction, various impacts can be found within a short distance within a trawling ground, with heavy plough furrows with associated spoil heaps (door impacts), lightly scraped sediment surfaces (wire impacts), completely flattened and scraped surfaces (ground rope and net impacts), and small patches of relatively untouched sediments. Scrape/plough marks and flattening are two opposing actions, and although flattening under the trawl may be more widespread than plough marks because of the relative size of the different parts of the gears, plough marks may still persist below the horizon of flattened areas. Mechanical breaking up of the sediment or settlement of resuspended material may decrease compaction (increasing penetration), or conversely, removal of soft surface layers or sediment compaction related to gear weight may decrease penetration. A mixture of these gear effects is consistent with SPI images from Dia Island. Fluidised or recently settled sediments were rarely observed, although this has been reported to be a dominant feature of trawl impacted sediments in Hong Kong: SPI images featured a unique "puzzle fabric" where the surface sediment layer was broken up into a thick fluidised layer with mud clasts above a more consolidated sediment (Valente et al., 1993; Binnie Consultants, 1996).

The Gouves experiment was carried out on much coarser sediments with penetration significantly lower immediately after the impact in the experimentally trawled area, but lower by the end of the experiment. The mean penetration in the commercial trawling lane was by far the lowest of the three areas and highly significant in testing. A potential problem for this analysis was the very poor penetration of the system into coarse sediments and the potential for the prism to intersect a hard-bottom feature that is not seen in the image. Poor penetration leads to much closer values at the two experimental areas. With coarse sediments where there is already a high degree of compaction, it is also more likely that the primary impact of trawling is flattening and 'sweeping clean' when compared to softer sediments. Evidence is given for this in the significantly smoother surface after the trawling impact and gradual biological 'roughening' in the experimental area with time. Additional evidence comes from the adjacent commercial trawling lane viewed as a very flat, swept clean area.

A major difficulty in the use of surface roughness measurements stems from the complex nature of the interactions incorporated into this simple variable, which by itself does not differentiate between an impacted rough sediment (broken and scraped sediments) and a biologically roughened sediment (bioturbation features such as mounds, pits and burrows). In soft sediments, there can be a high degree of bioturbation as these are relatively low kinetic energy systems with fine-grained sediments that are more easily burrowed. An experienced viewer can, at a glance, classify a particular image making note of many features that characterise the image. An analytical problem with all imaging methods has been how to use such qualitative information (soft observations that cannot be easily quantified). The use of presence/absence attributes allow for the use of statistical methodologies. The multivariate methodologies used here could, for example, better take into account attributes that can be apportioned to biological or anthropogenic activities, and this methodology was found to better distinguish trawling impacts in coarse sediments. Incorporation of the sediment measurements with the attributes gave better results than just the attributes themselves. A number of authors have previously used SPI attributes, or combinations of attributes in indices (Diaz and Schaffner, 1988; Bonsdorff et al., 1996; Nilsson and Rosenberg, 1997, 2000; Rosenberg et al., 2000). Multivariate analysis of SPI data has been carried out by Grizzle and Penniman (1991), Bonsdorff et al. (1996), Rumohr and Karakassis (1999) and Karakassis et al. (2002), and we feel that this remains the best methodology of using SPI data for detecting disturbance in an experimental context.

The southern Aegean is considered to be an oligotrophic area and the soft sedimentary benthos is normally characterised by low abundance and biomass (Tselepides et al., 2000). The lack of fauna in soft sediment images has prevented the use of successional stages and is one of the main reasons for an attribute-based analysis. In contrast to Dia Island where there was relatively good penetration, the limited penetration at Gouves allowed an extended view over the sediment surface. This, coupled with a more diverse in-shore ecosystem, allowed for a much 'richer' set of attributes to be used, particularly marked by surface features. Choice of attributes may seem to be subjective, but this decreases with the increasing experience of the viewer in choosing attributes that are well definable and consistent. This may require viewing a set of images several times for the definition phase. It is noted that attributes may change depending on the environment and time and could be specific to the individual set of images being analysed. Attributes should therefore be chosen with care and the compilation of a standardised list would be of a high level of use. However, it should be noted that the analysis used allows the inclusion of attributes with no need of assumptions regarding their relevance to the problem studied, in the same way that the analysis of macrofaunal data needs no a priori decision as to what species are more sensitive to disturbance.

When viewed on side scan sonar images or video (Coggan et al., 2001), it was obvious that the trawled areas were qualitatively different from the control areas in both experimental areas. Another possibility for the lack of differentiation found in the Dia Island area may have been related to the number of replicate images taken in each area for each period. SPI applications largely been used along enrichment gradients (e.g.

O'Connor et al., 1989; Grizzle and Penniman, 1991; Valente et al., 1992; Karakassis et al., 2002) where replicate numbers as low as three images per stations have been used (Rumohr, 1993). The edge of a trawling area may have a gradient of intensity between highly trawled and no trawling action, but this is complicated by the heterogeneous nature of trawling impacts. Binnie Consultants (1996) have also noted the uncertainty in sampling trawl impacted areas where the SPI system may sample between individual trawl impacts within a larger trawled area. This may depend on the level of trawling intensity in a particular area or the longevity of trawl marks. The SPI system samples a relatively small area in high optical resolution in comparison to the other imaging techniques of video and side scan sonar, and consequently, the authors generally aimed for approximately 5–10 images in a set of replicates within a particular subarea. The authors now consider that, in contrast to eutrophication gradients, heterogeneous/physically disturbed environments require as high a number of replicates as possible (for example, 30 images per subarea). This may require some extra time in sampling, but would be well worth the effort in terms of statistical validation of results. The method should also be combined with another methodology that may give an indication of the level of heterogeneity, particularly utilising wider area imaging methods, i.e. a tiered approach, reconnaissance with side scan or video, then deployment of the SPI for high resolution imaging.

5. Conclusions

SPI is a very good and quick tool to investigate sedimentary environments. In physically impacted environments with high heterogeneity (e.g. trawl impacted areas), standardised measurements from SPI (penetration and roughness) need to be combined with other sources of data/information to better investigate fine differences between areas. The use of presence/absence attributes and multivariate analysis is one good method for this. This was clearly shown for coarse sediments but was not so deterministic in soft sediments. Because of the small sampling window of the SPI system and the high environmental heterogeneity caused by the impacts, a large number of replicates will make the method more reliable. The method will also benefit from the inclusion of some other sampling methodology (e.g. wider area imaging or benthic samples).

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