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# Effects of demersal trawling on marine sedimentary habitats analysed by sediment profile imagery

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**Abstract**

Demersal trawling causes one of the most widespread physical and biological changes in marine shallow and shelf sedimentary habitats: trawl otter boards may create furrows in the sediment surface, while trawl nets and attached weights scrape the sediment surface. As a consequence, benthic animals are disturbed or killed, and resuspension of particles increase. The impact of trawling on benthic animals has traditionally been analysed by changes in species composition and abundance, whereas frequency and distribution of trawl tracks are frequently analysed by side-scan sonar. We have used sediment profile images (SPIs) (30 × 22 cm) and observed furrows and other physical disturbances on the sediment surface that we attribute to trawling. In a manipulative experimental trawl study in Sweden (BACI design), significant impacts were found in trawled benthic habitats (73–93 m deep) compared with pre-trawling conditions and with reference areas. In particular, furrows from trawl boards had a severe ecological impact. In the Gulf of Lions (northwest Mediterranean), similar patterns were observed in the vast majority of 76 images taken at random at depths between 35 and 88 m in four different areas. Epifauna and polychaete tubes were generally either rare or not observed at all on trawled sediment surfaces. Burrows and feeding voids were, however, frequently present in some trawled areas and seemed to be comparatively less affected. Such biogenic structures in the sediment were generally associated with rather deep (3–4 cm) mean apparent redox profile discontinuities (aRPDs), which were measured digitally as the visible division zone between oxidised (sub-oxic) and reduced sediments. Increased roughness caused by the trawl

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boards acting on the sediment surface, e.g. depressions and protrusions, could have effects on sediment solute fluxes.


*Keywords:* SPI; Benthos; RPD; BHQ; Gullmarsfjord; Gulf of Lions

## 1. Introduction

Fishing is the most widespread anthropogenic activity in the marine environment (Jennings and Kaiser, 1998). It is, however, not until recently that a better knowledge of over-fishing on marine ecosystems has begun to emerge (Goñi, 1998; Jackson et al., 2001). Demersal trawling is causing widespread physical and biological effects on many shelf sea areas (Collie et al., 2000). For example, some areas in the North Sea are trawled several times annually with consequences for benthic animals. Jennings et al. (2001) reported dramatic reductions in the biomass of infauna and epifauna due to this chronic trawling disturbance, but could not detect any significant effects on trophic network structure. An otter trawl, which is the most widely used bottom trawling technique, has two rectangular otter boards to keep the mouth of the trawl net open and weights attached to the ground rope between the boards to keep the net close to the bottom. The boards may penetrate 15 cm or more into soft mud (Krost et al., 1990) and the tracks have been detected by side-scan sonar for more than a year after trawling in the western Mediterranean (Palanques et al., 2001). The impacts of the net are probably of shorter duration. Bergman and van Santbrink (2000) and Bergmann et al. (2001) have demonstrated the mechanical damage to epifaunal and infaunal invertebrates. For example, the disappearance of the reef-building tube worm *Sabellaria spinulosa* in the Wadden Sea has been attributed to trawling (Riesen and Reise, 1982). In a pioneering study, Arntz and Weber (1970) showed that trawl boards crush shells of the long-lived bivalve *Arctica islandica*, and later Witbaard and Klein (1994) found that events of trawl disturbance could be deduced from the occurrence of sand fragments and scars in the shell of this bivalve.

Impacts of demersal trawling on benthic habitats and fauna have been summarised by de Groot (1984), Jones (1992), Dayton et al. (1995), Jennings and Kaiser (1998), Watling and Norse (1998) and Collie et al. (2000). From these reviews it appears that epifauna and organisms living close to the sediment surface are particularly prone to damage. Bivalves with thick shells or with larger sizes seem to be less affected than smaller and thinner shelled bivalves that bury less deep (Rumohr and Krost, 1991; Gilkinson et al., 1998). Demersal trawling causes resupension of the superficial sediment. For example, Floderus and Pihl (1990) estimated that an otter trawl can sweep a bottom area of $\sim 0.6$ km$^2$, that some areas may be trawled 10 times per year, and that the mean recurrence of resuspension by trawling could be $\sim 30$ days year$^{-1}$. Relocation of particles could have both negative and positive effects on the benthic fauna depending on the frequency and magnitude of such events.

Benthic infauna can be considered as ecological engineers (Coleman and Williams, 2002), i.e. the animals bioturbate the sediment, build burrows, create feeding voids and irrigate the sediment (Francois et al., 2001) with significant effects on redox conditions and solute transport between water and sediment (Aller and Aller, 1998). Little is known about the effects of trawling on biogenic structures and redox conditions in the superficial sediment, but see Nilsson and Rosenberg (2003) and Smith et al. (2003). In the present study, we investigate possible impacts of trawling using in situ sediment profile images (SPIs). The SPI technique was introduced by Rhoads and Cande (1971) and has, for example, been used for the analysis of physical disturbance by increased resuspension during underwater construction (Rumohr et al., 1992) and drilling operations (Rumohr and Schomann, 1992). SPIs have also proven useful to analyse benthic habitat changes in relation to changing oxygen concentrations (Nilsson and Rosenberg, 2000; Rosenberg et al., 2002) and organic enrichment (Karakassis et al., 2002). In these three studies analyses of SPIs also correlated with changes in the benthic fauna. The benefits of the SPI technique over conventional benthic faunal analysis is that it is relatively inexpensive and rapid.

In the present study, we used SPIs to assess the effects of demersal trawling on benthic habitats in the Gullmarsfjord in Sweden and the Gulf of Lions in the northwestern Mediterranean. The Swedish study was performed during experimental trawling in areas where trawling had been banned for 7 years. A statistically significant disturbance of the sedimentary habitat in trawled areas compared to in control areas has previously been shown by SPIs (Nilsson and Rosenberg, 2003). Hansson et al. (2000) found an overall declining trend in macrofaunal biomass and abundance in the same area. In the present study, a more detailed analysis of the SPI is made on the trawl effects on the sedimentary habitat. The study in the Gullmarsfjord was designed to characterise the effects of trawling from analysing the SPIs. The survey in the Gulf of Lions was based on random sampling in four different areas analysing SPIs, macrofauna and sediment characteristics (Rosenberg et al., in press). When analysing the SPIs, we noticed presence of mud clasts and furrows. The aim is to compare these patterns with those attributed to trawling in the Swedish survey. This would allow for a first assessment of trawling impact in the Gulf. To date, this presumably large-scale benthic disturbance of sedimentary habitats has not been investigated earlier in this part of the Mediterranean. There is, however, no information of the trawling intensity in the different areas of the Gulf. The SPI technique has, however, recently been used in a localized study in the Venice Lagoon to evaluate the impact of clam harvesting with different methods (Pranovi et al., 2002).

## 2. Material and methods

### 2.1. Swedish study

Effects of trawling were investigated in the Gullmarsfjord in 1996 and 1997 in a manipulative experiment (BACI; Before-After-Control-Impact; Hansson et al., 2000). In the present study, we focus on trawling impacts observed in SPIs obtained during the trawling phase in August to October 1997. Eight SPIs were analysed from each of three trawled areas and three control areas (each 0.8 nautical mile long; Fig. 1B; Table 1). The trawl used was a small shrimp-trawl for catching *Pandalus borealis* fitted with two 140-cm-long otter boards (weight 125 kg) and a distance of 30 m between the boards. The

Table 1
Data from sediment profile images in the Gullmarsfjord 1997, Sweden: control (C) and trawled (T) stations (with number of analysed SPI replicates), depth, week of sampling, total number of heart urchins (U) and mean number of polychaete tubes, maximum height of mud clast (MMC), mean and maximum sediment relief, depth of aRPD, BHQ index, penetration depth of prism and number of images where the sediment surface appeared disturbed (*D*) or furrows (*F*) were found

| Sampled areas (no. of analysed SPI) | Depth (m) | Sampling week | No. of heart urchins | Mean no. tubes | MMC (mm) | Mean relief | Max. relief (mm) | aRPD (cm) | BHQ index | Penetration (cm) | *D* | *F* |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| C1 (8) | 89–96 | 33 | 0 | 6.8 (3.3) | 0 | 9.7 (4.0) | 15 | 4.6 (1.1) | 10.9 (1.6) | 15.0 (1.4) | 1 | 0 |
| C1 (8) | 89–96 | 35 | 1 | 7.6 (3.0) | 0 | 9.6 (7.1) | 26 | 4.6 (0.9) | 12.0 (2.4) | 16.8 (1.4) | 2 | 0 |
| C1 (8) | 89–96 | 39 | 2 | 10.3 (4.9) | 7 | 9.5 (6.0) | 16 | 4.5 (1.2) | 11.1 (1.5) | 16.5 (1.8) | 2 | 0 |
| C2 (8) | 80–90 | 33 | 0 | 9.8 (4.7) | 0 | 10.1 (4.9) | 16 | 4.7 (0.3) | 11.8 (1.0) | 14.9 (1.7) | 0 | 0 |
| C2 (8) | 80–90 | 35 | 1 | 11.1 (4.4) | 0 | 8.2 (1.7) | 10 | 4.8 (0.7) | 11.5 (1.3) | 15.1 (2.1) | 2 | 0 |
| C2 (8) | 80–90 | 39 | 0 | 11.3 (4.5) | 0 | 8.8 (6.2) | 21 | 5.2 (1.1) | 11.4 (1.8) | 15.6 (1.3) | 1 | 0 |
| C3 (8) | 73–79 | 33 | 2 | 4.6 (1.6) | 0 | 7.6 (2.4) | 11 | 3.4 (0.3) | 10.6 (2.1) | 14.1 (0.6) | 0 | 0 |
| C3 (8) | 73–79 | 35 | 2 | 7.1 (3.5) | 0 | 8.5 (3.9) | 15 | 3.3 (0.4) | 10.9 (1.0) | 13.1 (0.8) | 0 | 0 |
| C3 (8) | 73–79 | 39 | 1 | 7.5 (3.3) | 0 | 8.3 (1.5) | 10 | 3.6 (0.5) | 10.9 (1.1) | 14.1 (1.5) | 1 | 0 |
| T1 (8) | 79–90 | 34 | 1 | 2.6 (4.0) | 4 | 17.4 (12.3) | 44 | 2.4 (1.5) | 8.0 (3.5) | 14.4 (3.1) | 5 | 4 |
| T1 (8) | 79–90 | 38 | 1 | 4.5 (3.2) | 7 | 17.5 (10.8) | 43 | 2.3 (1.0) | 8.5 (2.1) | 13.5 (1.7) | 3 | 1 |
| T1 (8) | 79–90 | 41 | 2 | 4.1 (6.0) | 42 | 29.3 (20.5) | 59 | 2.0 (1.2) | 7.5 (3.5) | 13.0 (1.7) | 6 | 4 |
| T2 (8) | 88–93 | 34 | 0 | 2.6 (2.4) | 16 | 14.5 (7.1) | 30 | 3.9 (1.3) | 9.6 (2.3) | 17.6 (1.7) | 3 | 0 |
| T2 (8) | 88–93 | 38 | 0 | 8.5 (4.3) | 10 | 22.3 (14.3) | 46 | 3.2 (1.7) | 8.1 (2.5) | 15.1 (0.9) | 3 | 1 |
| T2 (8) | 88–93 | 41 | 0 | 5.0 (4.6) | 15 | 18.9 (10.8) | 43 | 3.3 (1.9) | 8.8 (4.0) | 12.9 (1.1) | 5 | 2 |
| T3 (8) | 76–81 | 34 | 1 | 6.2 (5.0) | 7 | 19.4 (15.6) | 50 | 2.9 (1.2) | 9.1 (3.3) | 14.6 (2.9) | 2 | 2 |
| T3 (8) | 76–81 | 38 | 1 | 9.1 (3.4) | 9 | 12.3 (4.8) | 19 | 3.1 (0.8) | 9.9 (1.4) | 12.6 (1.4) | 1 | 0 |
| T3 (8) | 76–81 | 41 | 0 | 7.5 (3.5) | 0 | 23.2 (26.8) | 91 | 2.6 (1.4) | 8.9 (2.8) | 12.8 (1.7) | 3 | 2 |

Numbers in brackets are standard deviations of the means.

ground rope was 14 m long with a total of ~ 20 kg of lead weights distributed evenly. Each area was trawled 80 times during December 1996 through October 1997. All stations in the Gullmarsfjord had a muddy sediment and the temperature varied between 4 and 8 °C and the salinity was ~ 34.5 psu.

### 2.2. French study

The trawl intensity in the Gulf of Lions is unknown and no control sites without trawl impact were available. Deployment of the sediment profiler was made in four different offshore areas in the Gulf of Lions in October 2001 (Fig. 1A). A total of 36 stations was sampled at random (4 replicates): 7 in area A, 7 in S (both off Banyuls-sur-Mer), 10 in F and 6 in R (in the Gulf of Fos and off the mouth of the Rhône River). Each of the sampled areas was 4 × 6 nautical miles. A total of 76 SPIs were successfully analysed from 26 stations with the number of analysed replicates given in Table 2. Images of poor quality were excluded from the analysis. Some stations had sandy sediment, but all trawl impacts were recorded on muddy sediments. The temperature at the bottom was ~ 16 °C and the salinity ~ 38 psu.

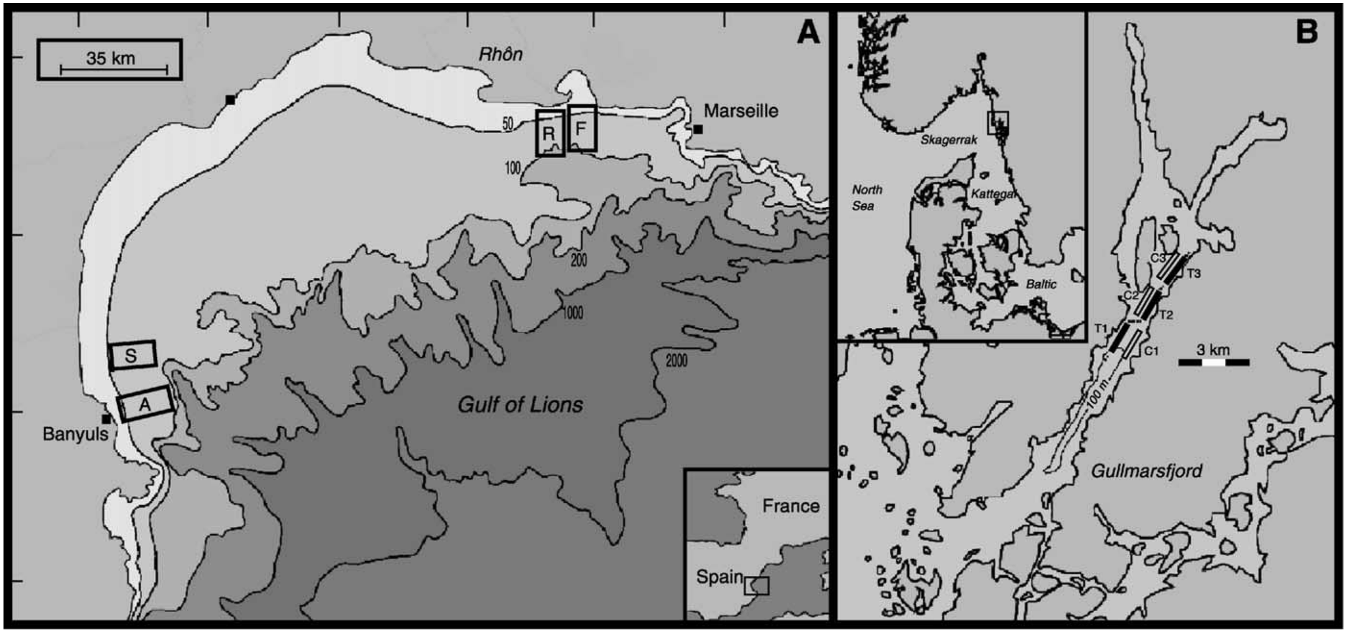


Fig. 1. (A) Location of the sampling areas (A, S, F and R) in the Gulf of Lions (west Mediterranean). (B) Location of the sampling areas in the trawl manipulative experiment in the Gullmarsfjord, Sweden, with control areas (C) and trawled (T) areas.

Table 2
Gulf of Lions

| Station (no. of analysed SPI) | Depth (m) | Percent < 63 μm | Epifauna (E) or tube (T) | Mud clast height (mm) | Surface relief (mm) | aRPD (cm) | BHQ index | Penetration (cm) | Trawled (T), Furrow (F) |
|---|---|---|---|---|---|---|---|---|---|
| A0 (2) | 35 | 70 | 1T | 0 | 9 (1) | 2.5 (0.9) | 7.0 (1.0) | 9.0 (0.1) | 0 |
| A1 (1) | 65 | 71 | 1T | 0 | 4 | 2.3 | 9 | 3.9 | 0 |
| A2 (1) | 82 | 46 | 1T | 0 | 7 | 2.1 | 9 | 9.5 | 0 |
| A4 (4) | 85 | 32 | 1T, 2E | 0 | 9 (9) | 1.9 (0.2) | 6.5 (0.5) | 3.2 (0.3) | 0 |
| A5 (4) | 86 | 46 | 3T, 4E | 0 | 7 (2) | 1.9 (0.4) | 7.8 (0.1) | 3.0 (0.5) | 0 |
| A6 (4) | 85 | 74 | 2T, 3E | 0 | 6 (1) | 1.8 (0.4) | 6.2 (0.2) | 3.6 (0.5) | 0 |
| F1 (1) | 38 | 85 | 0 | 14 | 14 | 0.8 | 5 | 14.0 | 1T |
| F3 (4) | 62 | 94 | 0 | 11 | 12 (3) | 3.0 (0.2) | 9.2 (0.8) | 11.2 (0.7) | 4T, 1F |
| F5 (3) | 68 | 96 | 1T | 12 | 20 (7) | 2.5 (0.2) | 8.3 (0.2) | 11.9 (1.0) | 3T, 2F |
| F6 (2) | 73 | 98 | 2T | 6 | 18 (1) | 5.5 (0.8) | 11.0 (0.0) | 11.5 (0.5) | 2T |
| F9 (3) | 82 | 99 | 0 | 5 | 13 (6) | 3.9 (0.4) | 9.3 (0.5) | 11.0 (0.2) | 3T |
| F10 (4) | 87 | 99 | 1T | 9 | 15 (5) | 3.0 (0.7) | 8.5 (0.8) | 10.9 (0.9) | 4T, 1F |
| F11 (1) | 30 | 66 | 0 | 6 | 36 | 0.2 | 1 | 10.4 | 1T, 1F |
| F12 (1) | 30 | 90 | 0 | 10 | 14 | 0.8 | 5 | 15.9 | 1T |
| R1 (1) | 67 | 96 | 0 | 6 | 54 | 0.4 | 7 | 12.8 | 1T, 1F |
| R2 (2) | 62 | 97 | 0 | 7 | 11 (3) | 1.7 (1.0) | 5.5 (0.5) | 11.4 (0.1) | 2T |
| R5 (4) | 86 | 98 | 1T | 9 | 25 (10) | 3.8 (0.4) | 10.5 (1.5) | 11.9 (1.0) | 4T, 3F |
| R6 (4) | 83 | 99 | 0 | 9 | 18 (7) | 3.4 (0.5) | 9.8 (1.1) | 13.4 (0.4) | 4T, 2F |
| R7 (4) | 88 | 100 | 2T | 5 | 21 (12) | 3.1 (0.3) | 9.2 (1.1) | 12.0 (0.5) | 4T, 1F |
| S1 (4) | 73 | 96 | 2T | 14 | 17 (6) | 2.8 (0.5) | 8.5 (0.9) | 12.0 (0.6) | 4T, 1F |
| S2 (4) | 64 | 95 | 1T | 11 | 11 (5) | 3.1 (0.3) | 8.7 (0.8) | 11.6 (0.6) | 4T |
| S3 (4) | 50 | 87 | 0 | 9 | 28 (7) | 3.1 (0.5) | 9.0 (1.0) | 11.3 (0.3) | 4T, 3F |
| S4 (2) | 48 | 86 | 1T | 10 | 8 (1) | 3.2 (1.0) | 9.5 (0.5) | 11.4 (0.4) | 2T |
| S5 (4) | 54 | 94 | 1T | 25 | 16 (6) | 3.7 (0.6) | 10.0 (1.4) | 11.4 (1.0) | 4T, 1F |
| S6 (4) | 62 | 95 | 0 | 19 | 18 (9) | 2.6 (0.5) | 8.5 (0.5) | 10.8 (0.5) | 4T |
| S7 (4) | 65 | 96 | 1T | 16 | 18 (8) | 2.4 (0.2) | 8.5 (0.5) | 10.9 (0.6) | 4T, 1F |

Stations (with number of images analysed), depth, percentage of fine particles (< 63 μm), number of images where epifauna (E) or tubes (T) were observed, maximum height of mud clasts (mm), mean surface relief (mm), mean apparent redox potential discontinuity (aRPD, cm), mean benthic habitat quality (BHQ) index, mean penetration of the prism, and number of images in which trawl marks (T) or furrows (F) were observed. Standard deviations of the means are given in brackets.

SPIs were taken in situ through a prism (30 × 22 cm; Rosenberg and Diaz, 1993) penetrating up to 20 cm into the sediment. The camera used in the Gullmarsfjord was a Nikon 801, and in the Gulf of Lions a digital CCD (Canon Power Shot Pro 70). Contrasts in the colours were digitally enhanced in Adobe Photoshop 6.0, which allowed accurate assessment of the depth of the apparent redox profile discontinuity (aRPD) measured as the shift between oxidised yellowish top sediment and reduced black sediment below (Rosenberg et al., 2001). Appearances of mud clasts and furrows on the sediment surface were considered to be caused by trawling. The sediment surface relief was measured as the difference between the highest and lowest sediment level observed close to the faceplate of the prism. It is a measure of small-scale bed roughness across the width of the prism window. The maximum height of mud clasts was measured as the vertical distance from the underlaying smoother sediment surface to the top of a mud clast. The benthic habitat quality (BHQ) index was calculated from each image. This index parameterises sediment surface structures, sub-surface structures, and the depth of the aRPD (Nilsson and Rosenberg, 1997, 2000). The BHQ index ranges from 0 (severely disturbed with no macrofauna) to 15 ("undisturbed" with mature benthic community) and is related to the successional stages (SS) of the benthic fauna according to the Pearson and Rosenberg (1978) model, where BHQ $<2$ relates to SS 0, BHQ 2–4 to SS I, BHQ 5–10 to SS II, and BHQ >10 to SS III (Nilsson and Rosenberg, 2000). Statistical tests were made by analysis of variance (one-factor ANOVA) and multiple comparisons were performed using the Student–Newman–Keuls post-hoc test. Correlations were made by simple linear regression.

## 3. Results

The areas investigated in the Gullmarsfjord were between 73 and 96 m (Table 1) and in the Gulf of Lions between 35 and 88 m deep (Table 2). In Fig. 2, three SPIs from trawled (T) areas and one control (C) area are shown from the Gullmarsfjord, and five SPIs are shown from the Gulf of Lions. In the image from the control area in the Gullmarsfjord (C2.40), four larger tubes that appear to belong to the polychaete *Melinna cristata* are visible in the centre of the sediment surface and several thinner tubes that appear to belong to the polychaete *Euchone papillosa*. The sediment in image T1.41:1 appears to be disturbed from scraping by the net with a mean aRPD of 17 mm and one tube (probably *E. papillosa*) extending into the water. The mud clasts on the sediment surface could be caused by the weights on the ground rope or by the net itself. In images T1.41:2 and T1.34, furrows and a disturbed sediment surface with a thin aRPD can be seen, but no polychaete tubes are visible. In these two images, part of the top sediment layer has been removed, probably by otter boards. Mud clasts were also evident in image S1 from the Gulf of Lions. Furrows appear in SPIs from stations R5 and R6a. Disturbance of the sediment surface was also found at some distance from the faceplate in image F5. It appears that the upper millimetres of the sediment had recently resettled in images from R6a and R6b, which was probably caused by resuspension from trawling. Despite disturbances on the surface, however, several voids and burrows were present in all images from the Gulf of Lions, and the mean aRPD was measured at several centimetres depth in the sediment.

In SPIs from the Gullmarsfjord, in total 15 heart urchins were observed at the sediment surface. Nine individuals were found in control areas and six in trawled areas (Table 1). The species appeared to be *Brissopsis lyrifera* and *Spatangus purpureus*. Maximum and mean relief measured in the SPIs was significantly ($F=21.076$, $df=1$, $p<0.05$ and $F=38.059$, $df=1$, $p<0.05$, respectively) greater in the trawled areas compared with control areas. The number of tubes at the sediment surface and the BHQ indices were significantly ($F=6.696$, $df=1$, $p<0.05$ and $F=36.093$, $df=1$, $p<0.05$) greater in control areas compared to trawled areas. Polychaete tubes were absent from two images from control areas and from six images where furrows were recorded. Furrows appeared in 22% of the SPIs in the muddy areas and were indicated by a great sediment relief. Mean relief

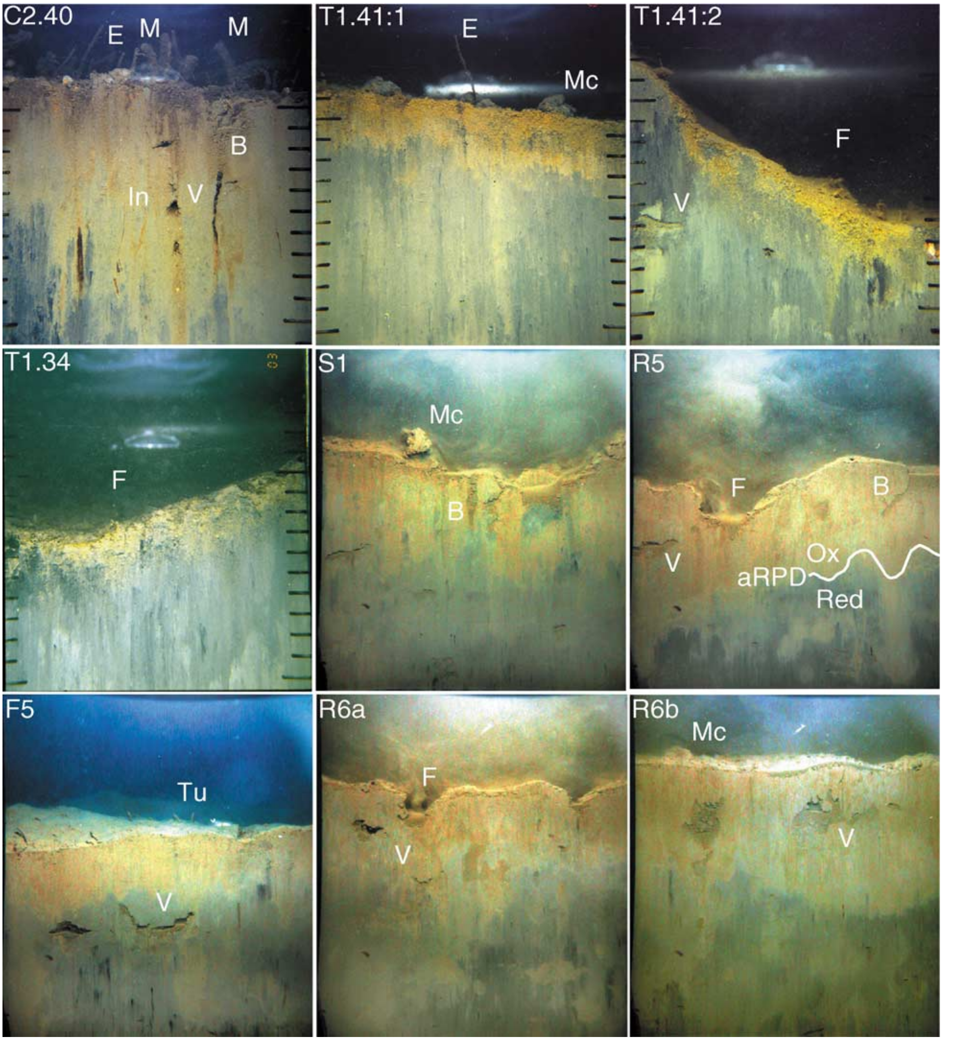


Fig. 2. Sediment profile images (SPIs) from the Gullmarsfjord in 1997: C2.40, T1.41:1, T1.41:2 and T1.34, where the two first digits refer to sample area (Fig. 1B) and the second two to sampling week; and from the Gulf of Lions in 2001: S1, R5, F5, R6a and R6b, where the letters refer to sample areas (Fig. 1A). Symbols in the images indicate the following: E = *E. papillosa*, M = *M. cristata*, B = burrow, V = void, In = infauna, F = furrow, Mc = mud clast, Tu = tube, Ox = oxidised, Red = reduced, and aRPD = apparent redox profile discontinuity. The vertical scale is in centimetre, the white halo is an artefact from the camera flash.

in trawled areas varied between 12 and 29 mm with a maximum of 91 mm, probably due to the impact of otter boards. The sediment surface appeared to be disturbed in 43% of the images of trawled areas that was probably at least partly due to the impact of the trawl net. The disturbance appeared in the images as part of the sediment surface had been scraped off.

In SPIs from the Gulf of Lions, epifauna (e.g. the crinoid *Leptometra phalangium*) and tubes were found on all sandy A-stations (Table 2). Epifauna was not found in SPIs from the other, muddy areas, and tubes occurred only in low numbers in 22% of the SPIs from these areas. Effects of trawling, visible as mud clasts, were not observed in images from A-stations, but in all SPIs from other stations. Furrows were observed in 30% of the images, excluding A-stations, and this could be attributed to disturbance by trawl boards. The maximum height of mud clasts on the sediment surface was 42 mm, and in 28 SPIs they were $\geq 10$ mm. Their numbers were significantly ($p < 0.05$) greater in SPIs from the S-stations than in those from the F- and R-stations. The maximum sediment relief in the SPIs was 54 mm, and a relief of $\geq 20$ mm was recorded in 20 images from the R-, F- and S-stations. Sediment relief was significantly ($p < 0.05$) greater at the R-, F-, and S-stations compared with the A-stations. The relief in SPIs with furrows was significantly ($F = 37.635$, $df = 1$, $p < 0.05$) greater than in images from trawled areas without furrows suggesting that trawl boards disturbed bottom evenness more than any other part of the trawl. Stations R1 and R2, which were close to the Rhône River mouth, had lower mean aRPD and BHQ indices than the other R-stations. A similar difference was found between the two shallow (30 m) stations F11 and F12 compared with the other F-stations. There was a highly significant ($p < 0.001$, $n = 25$) positive correlation between aRPD and BHQ indices.

## 4. Discussion

Our results have corroborated the view that demersal trawling causes significant changes to the sediment habitats. The present and an earlier study (Nilsson and Rosenberg, 2003) have shown that trawling reduces the BHQ index, which indicates combined impacts on surface structures, sub-surface structures and redox conditions. The significantly greater variability of the BHQ indices from trawled sites (Nilsson and Rosenberg, 2003) suggests that the effects are patchy; thus sometimes the image appear to have been taken on the trawl track and sometimes outside it or in a marginally affected area. Based on the visual information in the Swedish study, it was concluded that also the Gulf of Lions was impacted by trawling. The SPI documentation from the shelf of the Gulf suggests that wide areas were affected by demersal trawling, except from sandy areas such as area A. There is no quantitative statistics on trawling in the area, but the ares off the Rhône River and in the Gulf of Fos are trawled in particular for *Solea solea* (Harmelin-Vivien, pers. comm.). Trawling also occurs in the south part of the Gulf (Grémare, pers. obs.). Palanques et al. (2001) found that trawl marks could be recorded even after 1 year in muddy areas in the adjacent Catalan Sea. It has been found in other studies (Kaiser et al., 1998; Collie et al., 2000) that trawling impacts in sandy areas are less long-lived compared to in muddy areas. Thus, the sandy areas in the Gulf could also have been trawled, but the trawl marks could have disappeared, perhaps then as a result of stronger hydrodynamism than in the muddy areas. The sandy areas are often shallower and more subjected to resuspension due to winter storms (Grémare et al., in press). Although the investigation of this French part of the Mediterranean was made in only four sample areas that were wide apart, it is likely that a great part of the shelf is disturbed by more or less regular trawling down to a depth of between 100 and 200 m, i.e. at the slope of the shelf (Fig. 1A). It is, however, not known when the trawl marks were made in the different areas of the Gulf and how long they persist.

Two types of sediment surface disturbances can be separated in the images: furrows and scraping. The former are probably created by trawl boards and the latter may be a result of the net and weighted ground rope being towed on the sediment (Jones, 1992). In the Gullmarsfjord and the Gulf of Lions, furrows were found in 22% to 30% of the images indicating a significant impact of trawl boards, which will increase the habitat complexity. The sediment surface relief in the SPIs was greater in the Gullmarsfjord and the sediment surface seemed to have been ploughed away by trawl boards in some images. Such great changes were not observed in the Gulf of Lions, where possible trawl marks appeared as distinct but the furrows were comparatively smaller. The impact of trawl boards in the Gulf could be of older date (see above) or smoothed by trawl nets. In both areas, the number of epifaunal organisms including polychaete tubes, was low and seemed negatively affected by trawling. In an experimental study, Widdicombe and Austen (2001) showed that tube-building polychaetes were extremely sensitive to physical disturbance, whereas larger infaunal species such as *Lumbrineris fragilis* and *Goniada maculata* were not affected. Polychaetes of these genera were found in the sampled areas of the Gulf of Lions (Rosenberg et al., in press). Indications of trawl effects were found at all muddy stations in the Gulf, and most times visible as mud clasts on the sediment surface. The cause may be scraping of the sediment surface by trawl nets and the weighted ground rope.

What are the possible ecological consequences of physical disturbance of the sediment such as the creation of new mounds and furrows, and changed three-dimensional structures in the sediment with possible effects on diagenetic processes? Several images from the Gullmarsfjord showed that trawl boards may have adverse effects on deep-burrowing infaunal species and redox conditions in the sediment. Even though the sediment surface in the Gulf of Lions was disturbed, there were signs of infaunal activity: burrows and voids were common, and the aRPD was frequently found at 2 to 3 cm depth in the sediment. Although the time and intensity of trawling is not known, it is possible that some infaunal organisms survive trawling and perhaps particularly those living a few centimetres down in the sediment. The number of suspension feeders, however, was rare and among the five dominant species recorded in the four areas in the Gulf only *Amphiura filiformis* can be classified in this category (Rosenberg et al., in press). Thus, it seems likely that trawling has reduced the number of suspension feeders in the trawled parts of the shelf of the Gulf of Lions. If a disturbance by trawl is not too severe, it may be possible for some infaunal species to re-structure and maintain their burrows and activity in the sediment. As a result the redox conditions may not have changed significantly, but in the study in the Gulf no controls were available to verify this possibility. Physical disturbance may, on the other hand, increase the depth of oxygen penetration in enriched sediments and supply more oxygen for microbial decompositors (Widdicombe and Austen, 2001). For example, Hulthe et al. (1998) showed that old buried organic material can degrade >3 times faster in oxic conditions than in anoxic conditions. Some mobile megafaunal species may also benefit from increased habitat complexity caused by the physical disturbance (Auster et al., 1995).

Increased sediment relief and mud clasts that were created by trawls could have similar ecological consequences as increased bioroughness (biogenic microtopography). Thus, water currents moving along the sediment interface will accelerate and decelerate in response to small protrusions and depressions and this could have significant impacts on solute fluxes out of the sediment (Huettel and Gust, 1992). The removal of tubes at the sediment–water interface could also have effects on the water flow and change conditions for sediment erosion and accumulation. However, scientific evidence how to group animals and their biogenic structures into sediment stabilisers or destabilises are still lacking (Jumars and Nowell, 1984). We conclude that trawling has significant, variable and widespread ecological impacts on sedimentary marine benthic habitats, but further studies are needed to assess the consequences for biogeochemical processes.

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