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Impact of bottom trawling on water turbidity and muddy sediment of an unfished continental shelf

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Abstract

Two experiments were carried out to study the effects of trawling in the muddy prodeltaic deposit of the Llobregat River in the northwestern Mediterranean. Trawling was conducted in two experimental lines, and bottom morphology, sediment texture, and water turbidity were analyzed before trawling and at different time intervals afterward. The tracks of the trawl gears were still observed in sonographs of the bottom 1 yr after the first experiment. The vertical grain size distribution of bottom deposits indicated that the thickness of the sediment removed by the net between the gears was about 2–3 cm on average, though the erosion produced by the gears was deeper. Resuspended aggregates with a high silt content settled during the first hour after trawling, generating a temporary increase in the silt content of the surface sediment. One day after trawling, the surface sediment was mixed and already had a similar grain size distribution to that before trawling. After the beginning of trawling, water turbidity increased first near the bottom for a few hours and later also at shallower levels of the water column within a period of 2–5 d after trawling. At the end of the experiment, about 10% of the sediment affected by trawling was diffused in the water column and the remaining 90% had settled on the bottom. Average turbidity in the water column increased by a factor of up to three for 4–5 d after trawling. This experiment shows that intense and continued trawling on continental shelves has a noticeable effect on water turbidity, which must be considered in addition to natural processes.

Human activities in the coastal zone and on the continental shelf have a major impact on ecosystems. One of the most important human activities that has a significant effect on the seabed is bottom trawling. The direct effects of bottom trawling include scraping and ploughing of the seabed and sediment resuspension. Previous studies show that the degree of environmental perturbation produced by bottom trawling is related to the type of gear, the towing speed, the nature of the bottom sediment, and the currents in the study area (de Groot and Lindeboom 1994; Fonteyne 2000). The impact of trawling gears on benthic fauna has been studied in different parts of the world, such as the North Sea (de Groot 1984; BEON 1990; de Groot and Lindeboom 1994), the Irish Sea (Kaiser and Spencer 1995, 1996), Australia and New Zealand (Hutchings 1990), and North America (McAllister 1991; Auster et al. 1996). Some of these studies also include results concerning the physical impact of trawling on the seabed, such as the fact that scars caused by gears on sandy sediment of energetic areas are covered by ripples in a few hours (BEON 1990). However, trawling on muddy sediment can have longer term effects on the seabed and in the water column. Churchil (1989) revealed that large and highly turbid clouds of suspended sediment detected in the shelfbreak area of the Middle Atlantic Bight could be related to turbulence created in the wake of trawl doors. Tuck et al. (1998) observed that it took over 18 months before trawling tracks on muddy sediment became indistinguishable in side scan sonar records. Krost et al. (1990) observed that intensely fished areas have a high density of trawl tracks on the bottom depending on the type of sediment. Other authors such as Schwinghamer et al. (1996) and Gilkinson et al. (1998) have identified clear habitat alterations in the form of changes to the physical structures after trawling. However, an experimental study of the effect of trawling on water turbidity of a muddy area had never been carried out before.

Two experiments, consisting in creating a trawling disturbance by means of experimental fishing, were carried out in an unfished sheltered area of the northwestern Mediterranean Sea. The study area was on the inner Barcelona continental shelf, in a zone of the Llobregat River prodelta between 30 and 40 m water depth (Fig. 1). The average water discharge of this river is 715 Hm^3 yr^{-1}, and the prodeltaic deposit extends 165 km^2 onto the Barcelona continental shelf. The modern Llobregat prodelta forms a ''mud belt'' with a clay + silt content of over 80% (Fig. 1) and a mean grain size of about 7–8 phi, which extends northeast–southwest along the inner and middle shelf. Currents on the inner shelf are parallel to the coast 80–90% of the time, and the most persistent current direction is toward the southwest. During the remaining time, the currents are influenced by the action of the wind. The average current velocity is 5–10 cm s^{-1}, and the maximum current velocity is approximately 40 cm s^{-1} during high-energy events (Amengual et al. 1988). The study area has a low-period mean wave climate and a microtidal regime ($<$0.3 m). The average offshore significant wave height in this part of the Mediterranean is about 1 m, and the average wave period

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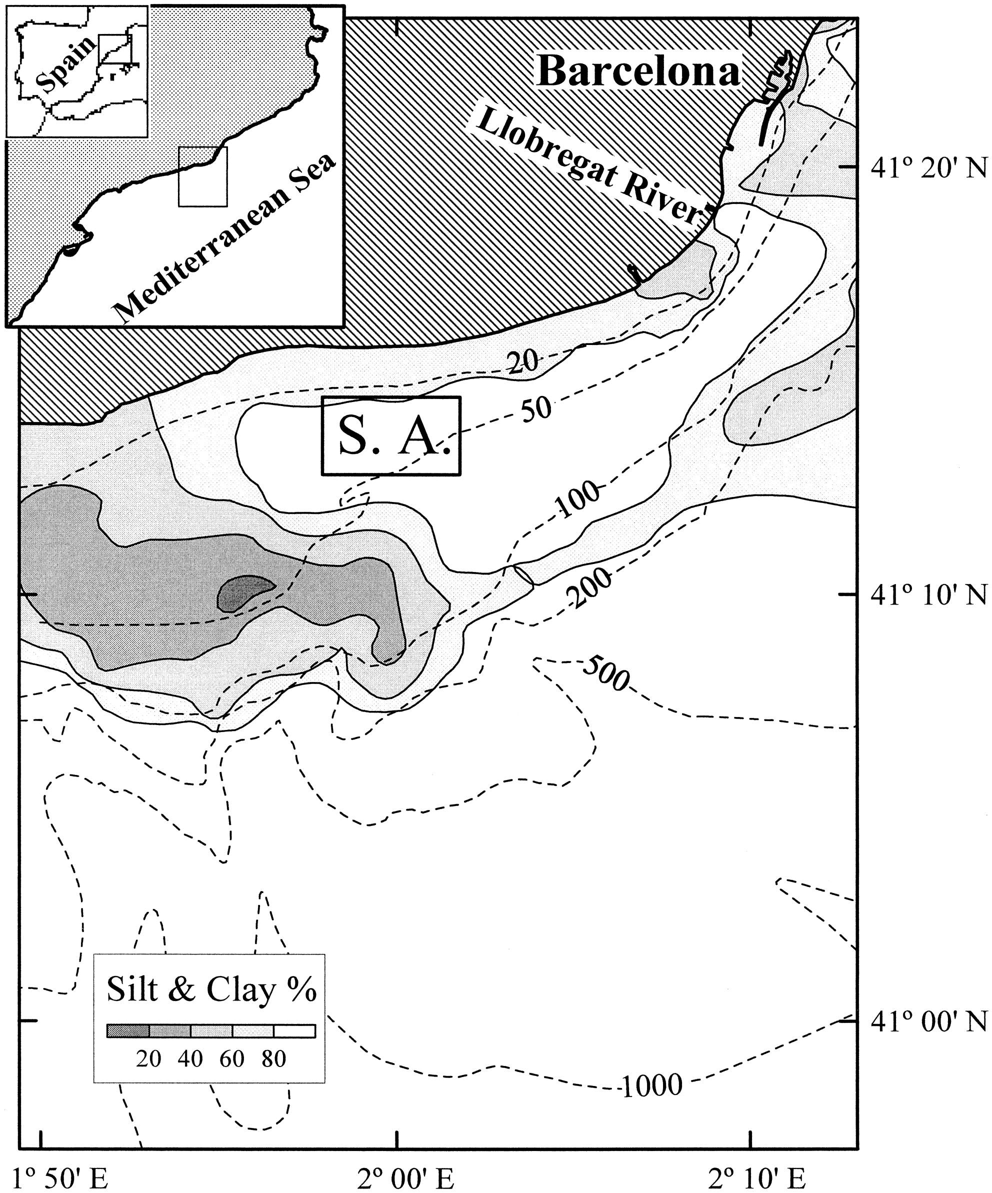

Fig. 1. General map showing the location of the study area (S.A.) and the content of mud (silt + clay) in the bottom sediment of this part of the Mediterranean Sea. Isobaths in meters.

is about 3 s (Gracia et al. 1989). Wave heights are lower than 4 m 98% of the time, and maximum wave heights are about 5–6 m. The wave regime has a seasonal evolution: (a) a low-energy period between June and September when the experiments were carried out; (b) a high-energy period between October and March with longer periods and higher wave heights; and (c) a transition period in April, May, and September with intermediate values (Jiménez 1996). The water column in this part of the Mediterranean Sea is vertically mixed during winter and stratified during the other seasons (Font 1986). To discriminate the effect of trawling better, the experiments were carried out in summer, when the wave energy was low and when river discharge was lower than 10 $m^3 s^{-1}$. In these conditions, salt water intrudes the Llobregat River and particulate matter is retained and accumulated in the riverbed (Puig et al. 1999). Thus, during the experiments the influence of river discharge and wave resuspension was low.

Widespread otter bottom trawling is potentially one of the most invasive forms of anthropogenic disturbance to benthic habitats in the Mediterranean. Many Mediterranean rivers develop muddy prodeltaic deposits that are affected by trawling. The results of these experiments should be representative of the trawling effects on Mediterranean mud prodeltas. One of the main objectives of this experiment was to study the role of otter trawling as an erosional/disturbing process on mud sediment and as a source of resuspended particulate matter in the water column. This paper shows the results of this research, focusing on the effects of trawling on the seabed micromorphology, water turbidity, and sediment texture.

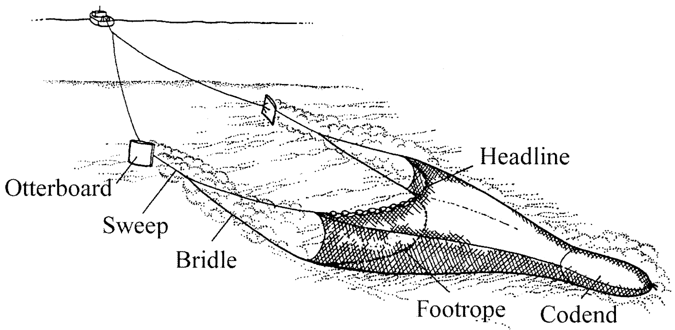

Fig. 2. Schematic diagram of an otter trawl.

Materials and methods

Two cruises were made, one in June 1996 and one in July 1997, in an area closed to trawl fisheries located on the inner part of the Barcelona continental shelf (Fig. 1). Trawl gear consists of a net, sweeplines, doors, and warps (Fig 2). The doors are oval or rectangular and made of iron. The footrope is at the front of the bottom part of the net and has lead weights that hold it against the bottom on the trawl path. At the end of the funnel of the net there is the codend. Two different vessels were used in these cruises. One was the R/V *Garcia del Cid* and the other a commercial trawler called *Monfi*, a typical commercial demersal otter trawler of the Mediterranean Sea. The doors of the *Monfi* weigh 750 kg, and during trawling the distance between these doors is 30 m and the width of the net mouth is about 4 m. The otter trawl was used to create a fishing disturbance on two experimental lines, one at 30 m depth (L.1) and another at 40 m depth (L.2) (Fig. 3). The first wayline was fished seven times and the second 14 times. The length of each haul was about 2,700 m and the fishing speed was about 3 knots. The R/V *Garcia del Cid* was used to collect water and sediment samples and to record hydrographic, sedimentological, and morphological data.

To study bottom morphology, side scan sonographs were recorded through a Hydroscan system. The Hydroscan was adjusted to observe the trawl tracks of the two experimental waylines of the study area imprinted on the sea floor (Fig. 3). A side scan sonar record of the seabed was taken prior to experimental trawling in the two cruises. In the 1996 experiment, trawling tracks were recorded in sonographs obtained immediately, 48, and 101 h after trawling in line 1 and immediately and 40 h after trawling in line 2. In the 1997 experiment, sonographs of trawling tracks were recorded immediately, 24, 102, and 150 h after trawling in line 1 and immediately, 24, and 72 h after trawling in line 2.

Time series of currents and water turbidity were recorded by one Aanderaa RCM-7 current meter coupled with a Sea Tech 25-cm transmissometer installed at 2 meters above the bottom (mab) during the 1996 experiment, and by two Aanderaa RCM 9 current meters with turbidity sensors installed at 2 and 7 mab during the 1997 experiment. These instruments were moored in the central part of the study area between the two trawling lines (Fig. 3). During the 1996 experiment, currents were recorded but the transmissometer was affected by an electronic malfunction and the record was too discontinuous to interpret the effect of trawling. During the 1997 experiment, the Aanderaa RCM 9 turbidity sensors worked properly during the complete recording period. These turbidity sensors measured backscattered infrared light at 1-min sampling intervals and provided Formazin Turbidity Units (FTU) units, which were converted to suspended sediment concentration (SSC) through the function $SSC = 1.74 \times FTU - 1.32$ using the calibration obtained by Guillén et al. (2000).

Bottom-sediment samples were taken with a 10-cm di-

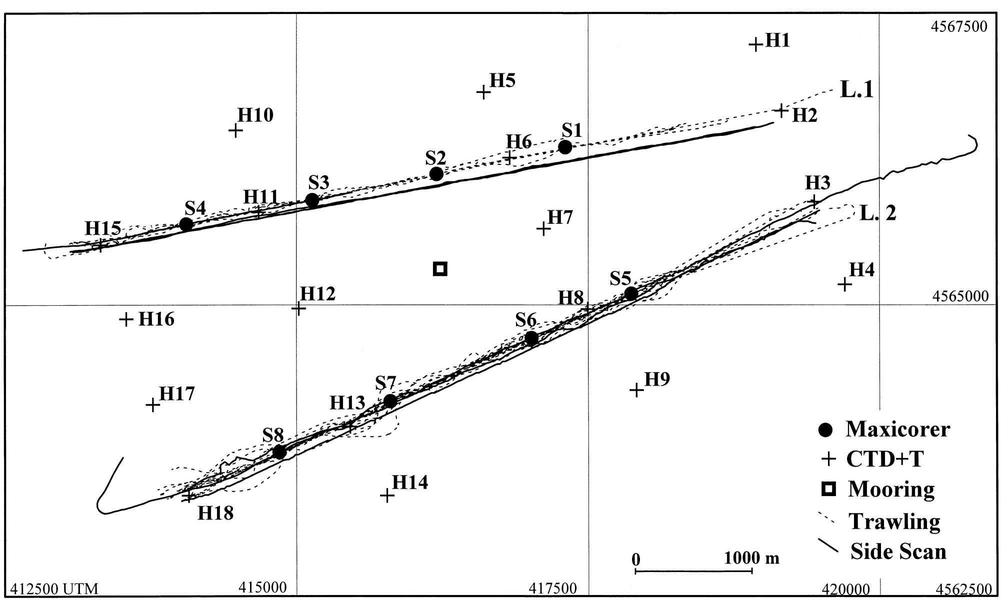

Fig. 3. Map showing the location of the sediment samples (S), hydrographic stations (H), side scan sonar records, trawling hauls, and mooring in the study area. L1: experimental line 1. L2: experimental line 2. Coordinates are in Universal Transverse Mercator (UTM).

ameter multiple corer (Bowers & Connelly). A first set of eight cores was taken on the experimental lines (four cores per line) before trawling (Fig. 3). After trawling, several sets of eight cores at the same locations as the first set were taken on the experimental trawling lines at different intervals of time. In the sediment cores, the vertical grain size distribution was analyzed to document potential changes created by the trawl. The grain size distribution was determined by a settling tube for the >50-μm fraction and by a Sedigraph for the <50-μm fraction following the method described by Giró and Maldonado (1985). Porosity was determined according to Bennett and Lambert (1971).

The spatial distribution of hydrographic properties was studied from grids of vertical data profiles. Vertical distributions of temperature and salinity were measured by a conductivity-temperature-depth (CTD) probe. Light transmission in the water column was recorded with a 25-cm pathlength Sea Tech transmissometer connected to the CTD. Light transmission data were transformed to beam attenuation coefficient (BAC). Water samples were taken during CTD casts with Niskin bottles mounted in a rosette. The SSC of these samples was measured by vacuum-filtering them into preweighed Nuclepore filters of 0.4 μ pore diameter. These data were used to calibrate a function to transform the BAC values into profiles of SSC in mg L^{-1} following the calibration formula SSC $= 1.59 \times$ BAC (Guillén et al. 2000). During the cruises, a grid of 18 hydrographic profiling stations was reoccupied five times in the 1996 experiment and four times in the 1997 experiment. The sampling strategy was to cover four across-shelf transects of 4–5 hydrographic stations: one grid before trawling, another grid during trawling, and the other two or three grids at different posttrawling time intervals on both experimental lines. The locations of the hydrographic stations are shown in Fig. 3. In addition, sets of eight profiles repeated every 5 min were recorded at one station on each experimental line, just behind the trawling ship between two hauls.

Results and discussion

Trawling tracks on the sea bed—Sonographs from the 1996 cruise recorded in the area of the shallower experimental line show a low reflectivity and a quite homogeneous pattern before trawling (Figs. 4A and 5A). This pattern corresponds to a relatively flat muddy seabed with some smooth roughness elements and high reflectivity spots possibly caused by the action of benthic fauna.

Sonographs after trawling show a 150-m wide strip of seafloor in which tracks of high reflectivity were impressed (Fig. 4B). These tracks corresponded to the prints of the doors trawled during the experiment. These prints have a high reflectivity, suggesting that they are sharp scars. Detailed observations of these scars show shadows that indicate sediment removal at both sides of the scars produced by lateral push from the doors. In the sonographs, there is no clear mark between the door prints. Thus, the effect of the bottom part of the net on the mud apparently did not generate any morphological change that could be observed in the side scan sonographs.

The sonar tracks recorded several hours after trawling within each experiment show very similar characteristics (Fig. 4C). This indicated that the morphology of the tracks made on this muddy seabed did not change on a time scale of days. This was due to the cohesive behavior of the bottom sediment in the study area and a lack of bottom currents that could have modified these morphologies.

After one year, the sonographs recorded in the 1997 cruise before the induced trawling disturbance showed a contrasted backscatter pattern due to recording proprieties. These sonographs also show lineations that corresponded to trawling tracks made during the 1996 experiment (Fig. 5B,C). This indicates that trawling tracks remained in the muddy sediment for more than 1 yr, although the recorded lineations showed a lower reflectivity after this time. This suggests that the muddy seabed of the study area was not affected by waves or currents strong enough to rework the surface sediment and erase the tracks quickly, and that sedimentation did not cover the scars during the study period. Wave action, near-bottom currents, river-flood events, and bioturbation could potentially contribute to smoothing or covering the tracks within a time scale of years. In addition, slopes at both sides of the scars were steep and probably unstable, and these scars may also be progressively smoothed up to reach a more stable morphology. Thus, natural processes in the study area did not eliminate the seabed trawling disturbances and only caused smoothing of the track morphology 1 yr after being produced

Hydrographic conditions—During the two experiments, the water column was well stratified, with temperatures that ranged from 22°C in surface water to 16°C in near-bottom water. During the 1996 and 1997 experiments, wave heights were lower than 1 m, wave periods lower than 5 s, and current intensities ranged from 2 to 10 cm s^{-1} with maximum peaks of about 20 cm s^{-1}. In these conditions, bottom wave and current shear stresses were lower than 0.005 N m^{-2}, which is not high enough to resuspend cohesive muddy sediment (Thomsen and Gust 2000). Thus, neither the currents nor the waves were energetic enough to resuspend appreciable amounts of sediment during the experiments, though they could maintain fine particles in suspension. This indicates that changes in water turbidity must be mainly caused by resuspension of bottom sediment induced by trawling during the experiment. In addition, the resultant net currents in the study area during the experiments were hardly 2 cm s^{-1}, due to the oscillations of the current direction. This low resultant net current suggests a small contribution of the sediment advected into or out of the study area.

Turbidity distribution in the water column—During the 1996 and 1997 experiments, the SSC ranged from 0.05 to 5 mg L^{-1}, and the highest values were near the seabed, where a bottom nepheloid layer (BNL) was well developed (Fig. 6). SSC was integrated over the water column, calculating the suspended sediment (SS) inventory at each hydrographic station (Fig. 7). The total amount of SS during each grid of hydrographic stations (Fig. 8) was calculated to qualitatively assess the effect of the trawling-induced resuspension.

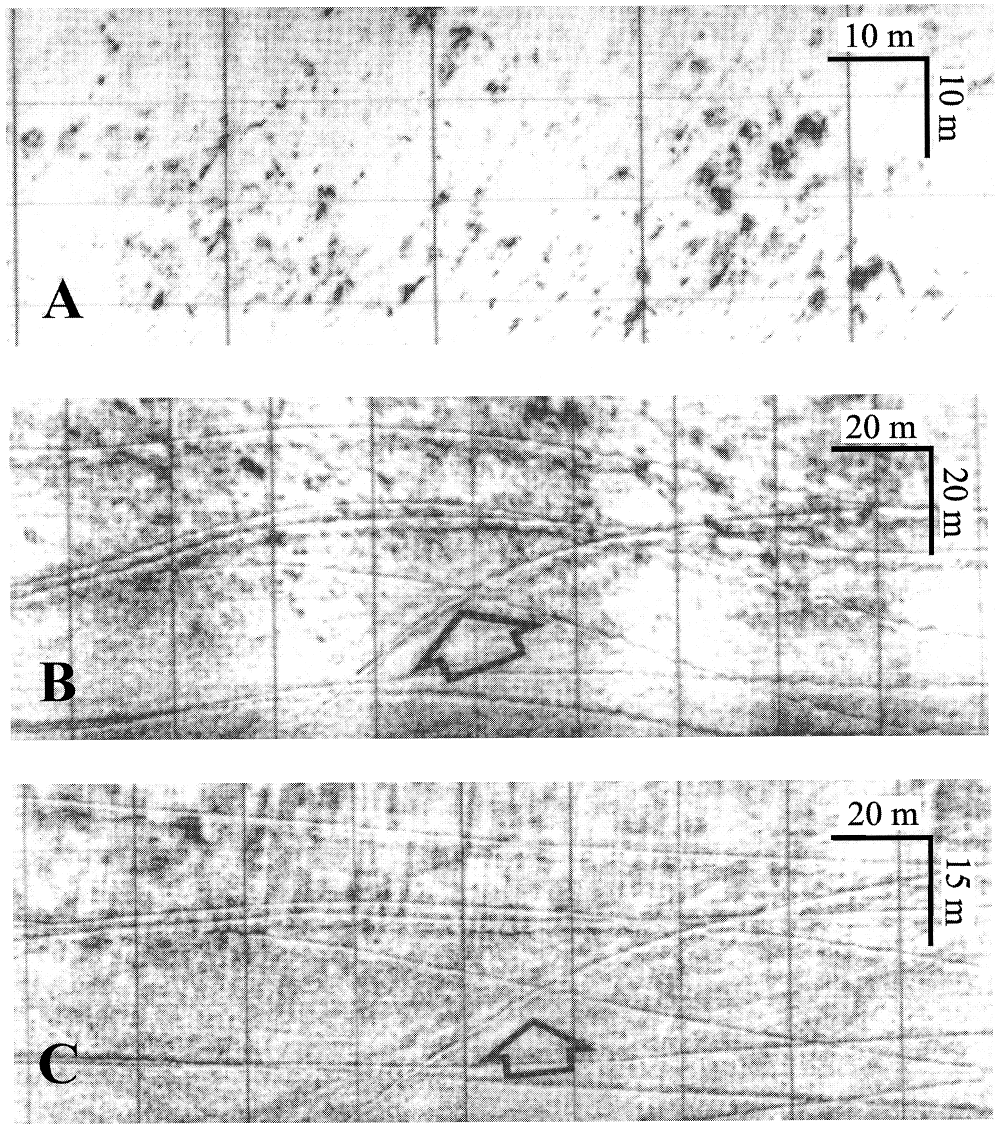

Fig. 4. Side scan sonograph showing details of the study area during the 1996 experiment: (A) flat muddy seabed with high reflectivity spots before trawling, (B) high reflectivity lineations corresponding to tracks of the trawled doors immediately after trawling, and (C) the same lineations 101 h after trawling. Arrow indicates a reference point of the same crossing of trawling lines.

Turbidity before trawling: Before trawling the mean SSC of the hydrographic stations during the two experiments ranged from 0.08 to 0.6 mg L^{-1}, and there was a 3–8-m thick BNL with maximum SSC values of 2–3 mg L^{-1} (Fig. 6A,A′). The SS inventory of the profiling stations ranged from about 0.13 mg cm^{-2} to about 2 mg cm^{-2} to maximum values of 1.8 mg cm^{-2} in 1996 and 2.6 mg cm^{-2} in 1997 (Fig. 7). In both the 1996 and the 1997 experiments, the mean SSC before trawling was 0.23 mg L^{-1} and the total amount of SS was about 120 tons (Fig. 8).

Turbidity during trawling: In the 1996 experiment, a grid of hydrographic stations was made during trawling between the fifth and the seventh hauls on the first line, 12 h after the beginning of trawling. At this time, the mean SSC of the hydrographic stations ranged from 0.05 to 0.5 mg L^{-1} and there was a 2–8-m thick nepheloid layer with a local maximum SSC of 2 mg L^{-1} (Fig. 6B). The SS inventory of the profiling station ranged from about 0.05 mg cm^{-2} to 2 mg cm^{-2} (Fig. 7). The mean SSC in the grid of the study area was 0.18 mg L^{-1}, and the total amount of SS was 85 tons, which is a factor of 0.78 compared with the value before trawling (Fig. 8). Thus, during trawling in the 1996 experiment, the SSC values were similar and even lower and the BNL was thinner and less developed than before trawling. This is probably due to the delay in advecting or diffusing the stirred up sediment the distance from the trawl track to the turbidity sensors during the experiment. Another test during trawling was made by recording eight consecutive turbidity profiles (one every 5 min) between the first and second haul on each trawling line. This test also failed to show any turbidity increase that could be associ-

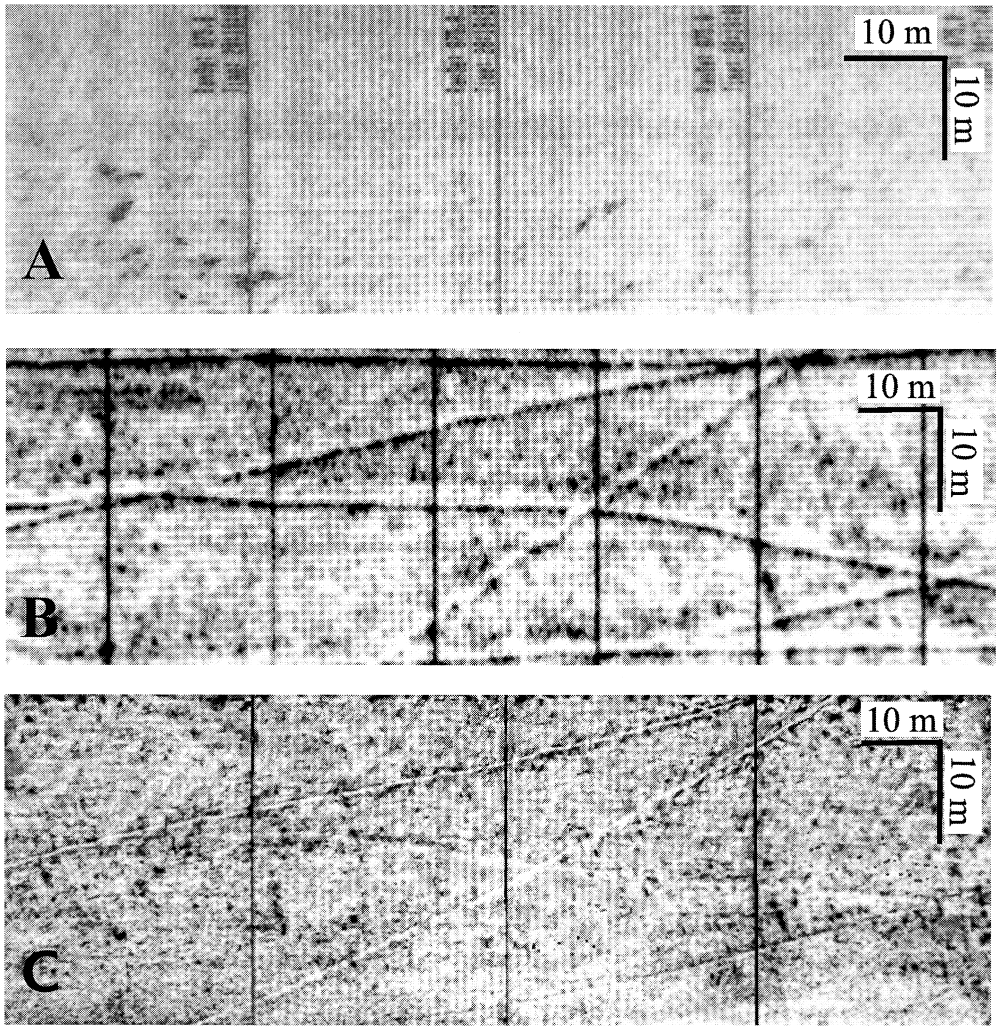

Fig. 5. Side scan sonograph showing details of the study area: (A) flat muddy seabed before trawling during the 1996 experiment, (B) high reflectivity lineations corresponding to tracks of the trawled doors 101 h after trawling during the 1996 experiment, and (C) low reflectivity lineations recorded before trawling during the 1997 experiment and corresponding to tracks of the doors trawled 1 yr before during the 1996 experiment.

ated with sediment resuspended during the induced trawling. All this indicates that, during the first hours after the beginning of trawling turbidity, disturbance was centered very near the bottom on the experimental line and could not be recorded with the methods used in this study because of the 2 m of safety distance left between the CTD and the seabed.

In the 1997 experiment, a grid of hydrographic stations was made during trawling, between the 10th and the 14th hauls on the second line, 20 h after the beginning of trawling on the second line. At this time, the mean SSC of the hydrographic stations ranged from 0.1 to 0.8 mg L^{-1}. In addition, the BNL was 2–10-m thick, and at some stations of the central area maximum near-bottom SSC values of 7.5 mg L^{-1} were observed (Fig. 6B′). The SS inventory of the profiling stations ranged from 0.2 mg cm^{-2} to 3 mg cm^{-2} (Fig. 7). The mean SSC in the study area was 0.37 mg L^{-1}, and the total amount of SS was 185 tons, which indicates that it increased by a factor of 1.7 compared with the total SS before trawling (Fig. 8). Thus, during trawling in the 1997 experiment SS inventories at each station and the total SS amount were significantly higher and there was a more developed BNL than before trawling. This indicates that during trawling on the second line there was already a noticeable turbidity increase in the water column, probably because of the previous disturbance from the first line.

Turbidity after trawling: 20 h after the end of trawling in the 1996 experiment, the mean SSC of the hydrographic stations ranged from 0.10 to 0.7 mg L^{-1}, indicating that the turbidity levels increased slightly in the water column of the study area. The BNL was 2–10-m thick, with a local maximum SSC of 2.5 mg L^{-1}. The SS inventory of the profiling stations ranged from 0.3 mg cm^{-2} to 2 mg cm^{-2} (Fig. 7). The mean SSC in the study area was 0.29 mg L^{-1}, and the total amount of SS was 150 tons, which represents a factor

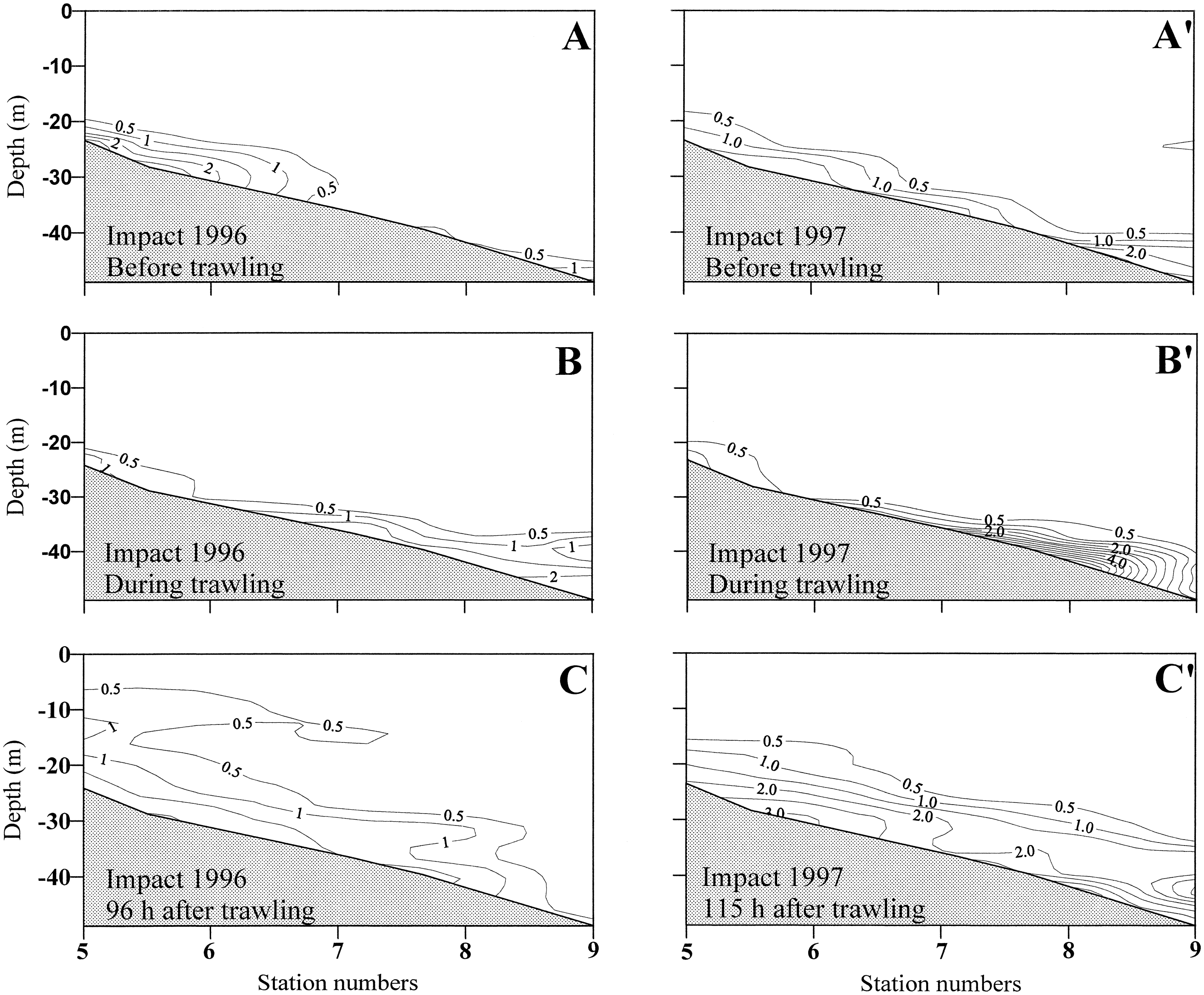

Fig. 6. Profiles of suspended sediment concentration (mg L^{-1}) across the trawling lines recorded (A and A′) before trawling, (B and B′) during trawling, and (C and C′) about 100 h after trawling during the 1996 and 1997 experiments. The location of the hydrographic stations is shown in Fig. 3.

increase of 1.26 compared with the SS before trawling (Fig. 8). These values were relatively maintained in the grid made 40 h after trawling.

The turbidity increased significantly 96 h after trawling in the 1996 experiment. The mean SSC of the hydrographic stations ranged from 0.10 to 1.18 mg L^{-1}, and the BNL was 5–13-m thick, with a local maximum SSC of 2.5 mg L^{-1} (Fig. 6C). There was also an intermediate nepheloid layer with a maximum SSC of 1 mg L^{-1}. The SS inventory of the profiling stations ranged from 0.5 mg cm^{-2} to 3.6 mg cm^{-2} (Fig. 7). The mean SSC in the study area increased to 0.54 mg L^{-1}, and the total amount of SS was 280 tons, which is a factor increase of 2.3 compared with the total amount of SS before trawling (Fig. 8).

Approximately 115 h after trawling in the 1997 experiment, the turbidity trend was similar to that observed in the 1996 experiment but with higher SSC values. The mean SSC of the hydrographic stations ranged from 0.38 to 1.18 mg L^{-1}, and the BNL was 7–15-m thick, with a local maximum SSC of 4 mg L^{-1} (Fig. 6C′). There were also some detachments of intermediate nepheloid layers with a maximum SSC of 1 mg L^{-1}. The SS inventory of the profiling stations ranged from 1.2 mg cm^{-2} to 3.9 mg cm^{-2} (Fig. 7). The mean SSC in the study area 115 h after trawling was 0.71 mg L^{-1}, and the total amount of SS was 355 tons, which represents a factor increase of 3.08 compared with the total amount of SS before trawling (Fig. 8). One hundred and fifteen hours after trawling, maximum SSC values were lower than during

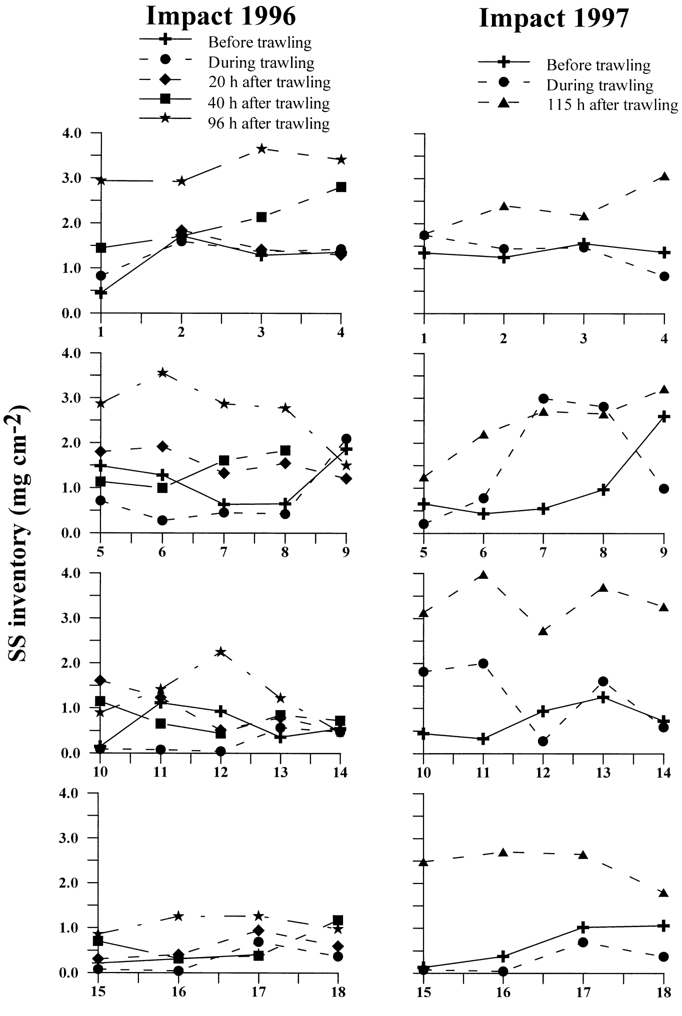

Fig. 7. Suspended sediment inventory at each hydrographic station recorded during both experiments before, during, and several hours after trawling. The location of the hydrographic stations is shown in Fig. 3.

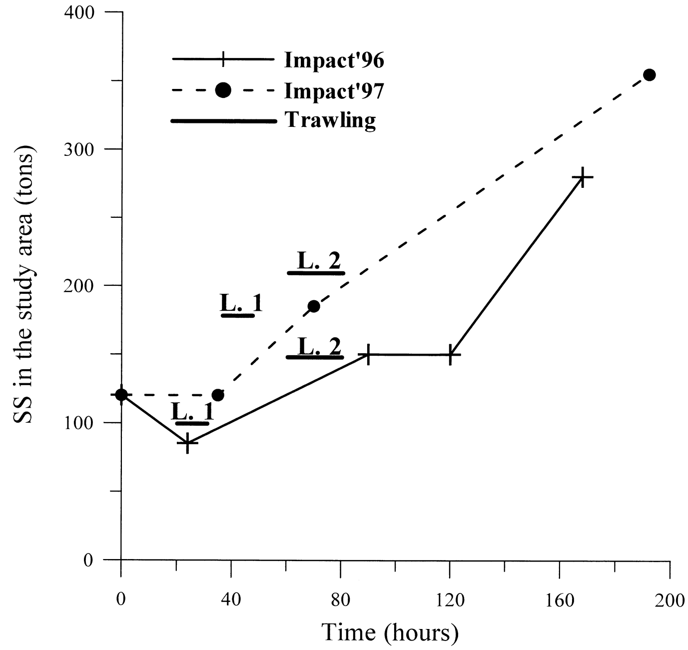

Fig. 8. Total amount of suspended sediment in each grid of hydrographic stations recorded before, during, and after trawling during the 1996 and 1997 experiments. Heavy lines indicate the time intervals of trawling on experimental lines 1 and 2.

trawling, but the BNL was thicker and the mean SSC was twice as high because the amount and the dispersion of SS increased with time in the study area.

Turbidity induced by trawling: In both experiments, turbidity distribution in the water column of the study area showed that trawling caused a gradual SSC increase during about 100 h after trawling. During the first hauls, this increase was not observed with the transmissometer installed in the CTD, which recorded from the surface to 2 mab. Therefore, the turbidity disturbance just after trawling must be very close to the bottom and probably located just above the trawled tracks. This increase was detectable 20–48 h after the beginning of trawling, when resuspended particles were already diffused some meters above the bottom by the prevailing currents. Turbidity in the water column down to 2 mab increased progressively because of the gradual diffusion of sediment resuspended by trawling, and SS in the water column increased from 120 to 355 tons 115 h after the end of trawling.

Near-bottom temporal series of turbidity—The temporal record of turbidity measured 2 and 7 mab during the 1997 experiment is shown in Fig. 9. The higher turbidity values were recorded at 2 mab, where they ranged from 0.1 to 8.8 mg L^{-1} during the experiment (Fig. 9B). Before trawling, turbidity at 2 mab was 0.1 to 2.2 mg L^{-1} and mean SSC was about 1 mg L^{-1}. During trawling in the shallower line minimum turbidity values were the same, 0.1 mg L^{-1}, but the maximum values increased to 4.5 mg L^{-1}. After trawling on the shallower line, and during trawling in the deeper line, the minimum turbidity values at 2 mab increased from 0.1 to 2 mg L^{-1}, whereas the maximum values were similar (about 4 mg L^{-1}). Just after trawling in the deeper line, the highest turbidity peak (about 6 mg L^{-1}) was observed and the mean SSC 2 mab was 3 mg L^{-1}. Subsequently, there was a period with a gradual decreasing trend, during which minimum turbidity values at 2 mab decreased from 2 to 0.1 mg L^{-1} and maximum values were about 3 mg L^{-1}.

Turbidity at 7 mab showed lower values ranging from 0.1 to 3.6 mg L^{-1} (Fig. 9A). Before trawling, turbidity at 7 mab ranged from 0.1 to 1.8 mg L^{-1}. During trawling on the shallower experimental line (L.1), minimum values increased to 0.2 mg L^{-1} but maximum values hardly reached 0.8 mg L^{-1}. After trawling on this line, minimum turbidity values at 7 mab were only 0.2 mg L^{-1}, whereas the highest peaks were between 1.7 and 2 mg L^{-1}. However, during trawling on the deeper line (L.2), turbidity decreased: minimum values were 0.1 mg L^{-1}, and maximum values were only around 0.6 mg L^{-1}. After trawling on the deeper line, turbidity at 7 mab

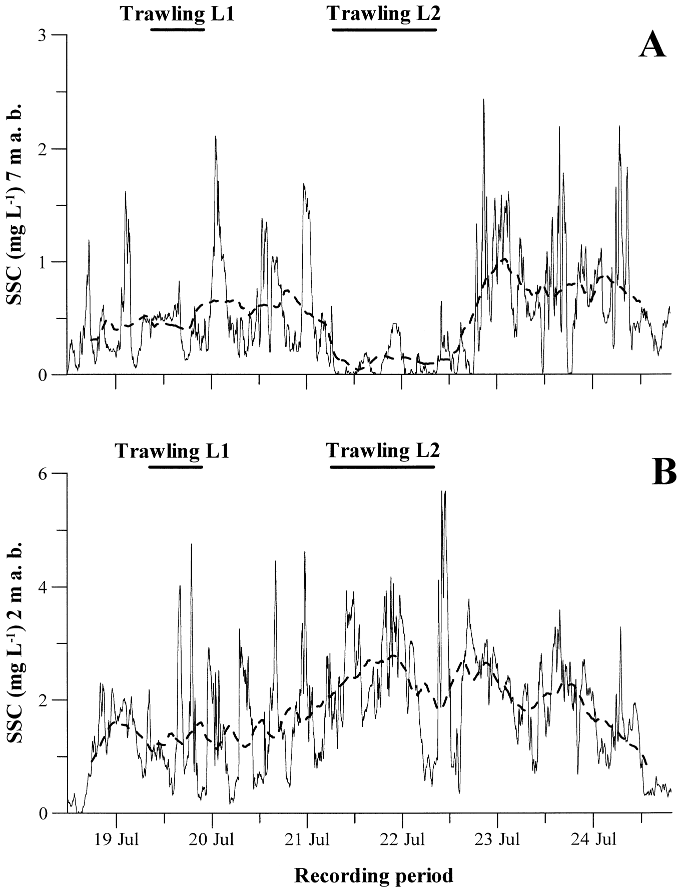

Fig. 9. Time series of suspended sediment concentration measured at the mooring (A) at 7 m above bottom and (B) at 2 m above bottom during the 1997 experiment. The discontinuous and heavy line corresponds to a 12-h average. The mooring location is shown in Fig. 3.

increased. Minimum values were about 0.5 mg L^{-1}, and maximum values were about 2 mg L^{-1}.

The turbidity record showed high variability, with main variations corresponding to tidal frequencies, although the effect of trawling was superposed on the natural variations (Fig. 9). During trawling, there was an increasing trend of turbidity at 2 mab. After trawling, turbidity decreased gradually at 2 mab, whereas it increased at 7 mab. This suggests that particles resuspended by trawling remained near the bottom (<7 mab) for some hours before being dispersed in the water column and that these particles helped to increase the background levels of water turbidity in the study area some hours after trawling. This was also observed in the last grid of hydrographic stations, when maximum SSC values decreased but the BNL was more developed and there were detachments of intermediate nepheloid layers.

Vertical grain size distribution of bottom sediment—Sediment cores were taken in order to evaluate the thickness of sediment removed by trawling. This estimation was carried out by analyzing the changes in the vertical grain size distribution of the sediment before and after trawling. Vertical grain size distribution of the cores taken at the same station showed spatial variability. However, the general trends and the main peaks could be identified before and after trawling and can be used to study changes induced by trawling.

The bottom sediment of the study area is mud with average porosity of 0.78 at surface sediment, decreasing with depth (at 10-cm sediment depth: about 0.65 in cores of line 1 and about 0.55 in cores of line 2). Grain size of the bottom sediment in the two experimental lines was similar: the clay content ranged from 20 to 40%, the silt content from 55 to 75% and the sand content from 2 to 8%. Among the different textural parameters, we observed that the most important one for studying the action of trawling in the study area was the silt content. Vertical silt distribution of the cores showed

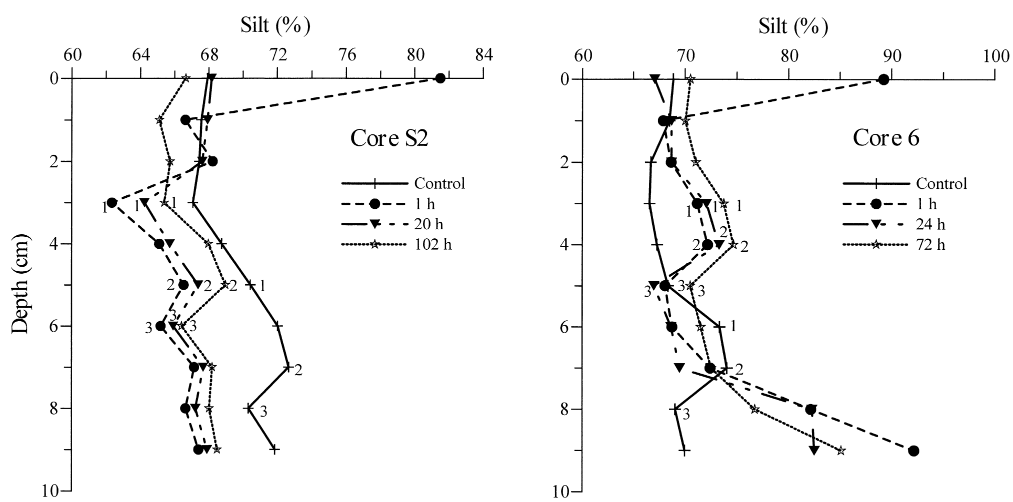

Fig. 10. Vertical distribution of silt content in cores taken at two selected core sites taken on the experimental lines before trawling (control) and after trawling. Numbers in the vertical profiles indicate inflexion points of the control distribution that also can be identified in the vertical distributions recorded after trawling. The same number identifies the same point, and the different depth at which it is located before and after trawling indicates the thickness of sediment eroded by the footrope. The location of the cores is shown in Fig. 3.

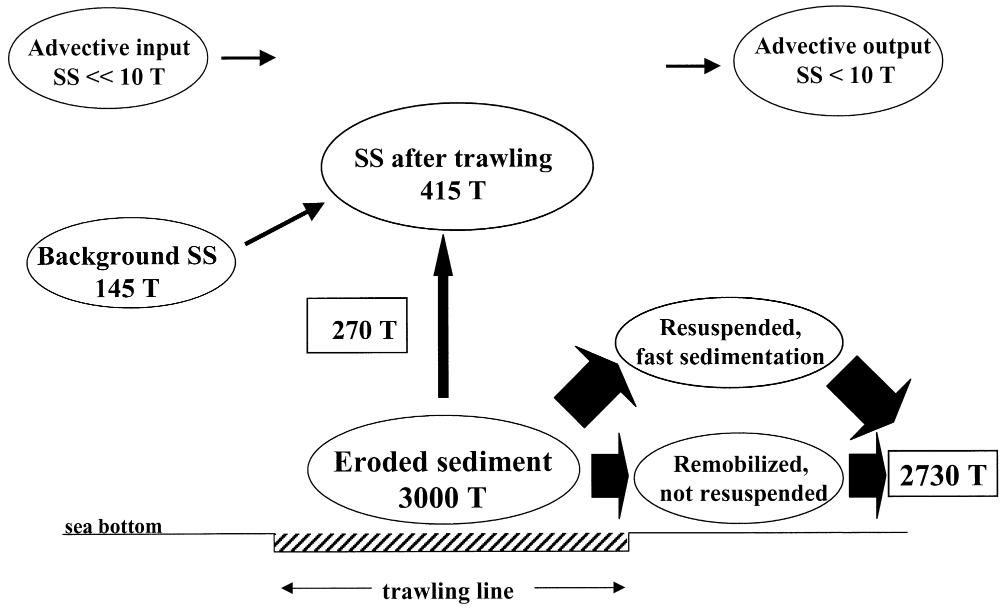

Fig. 11. Box model of the sediment budget to estimate the net effect of trawling on sediment of the study area during the experiment period.

peaks that could be used as reference levels to estimate the thickness of sediment eroded after trawling. In most of the sampling stations the silt peaks of the cores taken after trawling (from 1 to 102 h) were 2–3 cm higher than the silt peaks before trawling (Fig. 10), which indicates that the average erosion caused by trawling in the study area was 2–3 cm. This erosion is likely related to the effect of the footrope (Fig. 2), which is in the lower part of the net mouth and has lead weights that maintain it against the bottom on the trawl path. Sonographs suggest that the door tracks must be deeper. Thus, it is likely that none of the cores was taken in a door track.

In addition, most of the cores taken 1 h after trawling showed a silt enrichment in the surface sample (1 cm thick) that did not exist before trawling (Fig. 10). This is probably because after the trawling disturbance the resuspended particulate matter with a faster settling velocity should be aggregates with higher silt content. Thus, during the first hour after trawling, the aggregates with a higher silt content were deposited, increasing the percentage of this fraction in the surface sediment from 68–70% to 84–88%. This silt enrichment was not observed in the cores taken later, tens of hours after trawling. As there were no resuspension events after trawling, this silt enrichment was probably diluted on a time scale of hours/days by mixing and burial. The silt inventory of the cores taken at each sampling site before and after trawling was relatively constant (at a sediment depth of 10 cm, it was about 5.6 g cm^{-2} for cores taken on line 1 and about 6.6 g cm^{-2} for cores taken on line 2). Thus, surface sediment mixing by benthic organisms and sedimentation of clay-rich aggregates probably diluted the posttrawl silt layer.

Sediment budget—An approach to a sediment budget in the study area can be made in order to estimate the net effect of trawling on sediment distributions at the study site. Before trawling, the background amount of SS in the water column of the study area down to 2 mab was about 120 tons, and 115 h after trawling it was 355 tons. This amount increases if we add the suspended sediment from the $<$2-mab region where SSC can increase dramatically. Taking into account the average SSC recorded by the turbidity sensor installed 2 mab, we can estimate that this amount is at least 24 tons before trawling and 60 tons 115 h after trawling. This gives a minimum background of 145 tons of SS before trawling and a minimum of 415 tons of SS 115 h after trawling. This indicates an increase of at least 270 tons of SS 115 h after the disturbance induced by trawling (Fig. 11).

On the other hand, considering 2 cm as the mean thickness of the sediment eroded by trawling, the surface sediment porosity of 75%, the length of each trawled line (2,700 m), the width of the footrope (about 4 m), and the number of hauls (seven hauls in line 1 and 14 hauls in line 2), the amount of sediment eroded by the footrope is about 3,000 tons. This amount could be lower if the erosion of the footrope decreases in regions where the surface sediment already has been removed and the net goes over cohesive underlying sediments.

This approach suggests that at least 10% of the sediment disturbed by trawling was suspended in the water column 4–5 d after trawling, and this percentage was enough to triple the SS inventory in the water column of the study area. Additionally, the advective sediment transport out of the study area is very low (less than 10 tons) due to the low net resultant of the currents (hardly 2 cm s^{-1}), and the effect of the trawling during the experiment was mainly localized around the trawling tracks. The remaining sediment disturbed by trawling (up to 90%) probably accumulated on the bottom around the trawled lines either because it was only turned over by the net or because it settled during the 4–5 d after being resuspended. However, under the presence of strong bottom currents, the advection of sediment away from the trawled areas could contribute greatly to the sediment transport. Therefore, at the scale of the continental shelf, trawling could be one of the dominant processes controlling water turbidity and sediment fluxes in areas that are continuously and intensively exploited.

Conclusions

The morphology of the tracks generated by trawling in the cohesive sediment of the study area is not modified in a time scale of days. Bottom trawling in the study area left trawl marks on the seabed that remained for at least 1 yr after the trawls were conducted. Consequently, trawling must be considered as an important bottom micromorphology disturbing process in muddy and moderate-energy continental shelves.

Between the doors, the trawled net disturbed the muddy sediment to a depth of about 2–3 cm. One hour after trawling, the grain size of the surface sediment became siltier. After about 1 d, the surface silt enrichment was diluted by sediment mixing and grain size distribution of surface sediment returned to similar levels to those before and during trawling. Trawling activities produced a slow and gradual increase in the turbidity of the water column. During the first hours just after the beginning of trawling, the turbidity disturbance was very close to the seabed (below 2 mab). Progressively resuspended particles were diffused several meters above the bottom, and the average turbidity in the water column 2 mab began to increase significantly 24–28 h after the beginning of trawling. Approximately 4–5 d after trawling, turbidity in the study area had increased by a factor of three and the suspended sediment associated with the trawling effect represented about 10% of the total amount of sediment disturbed by trawling. In muddy areas with low-energy conditions, the effect of trawling on water turbidity is locally important and becomes a significant source of suspended particles around the trawled area for at least 4–5 d. Trawling could be a dominant process controlling water turbidity in muddy areas that are continuously and intensively exploited, where it should be considered in addition to natural processes.

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