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Bottom trawling

Bottom trawlers are commercial fishing vessels actively pulling nets along the seafloor with the aim of capturing fish and other marine species for human consumption or other industrial uses. Together with seiners, trawlers are the most common vessels in the World's fishing fleet[33]. Though a variety of trawling techniques exist, the one practiced in the study area is otter trawling, i.e. deploying nets over the stern that are kept open horizontally using otter boards. The otter boards weigh from 400-1,200 kg with the distance between them during trawling approximately 100 m. The mouth of the net is 40-50 m wide, and the total length of the net is about 80-150 m. The sweeplines that connect the otter boards to the net have a total length of 60-200 m. All components of the trawling gear are in direct contact with the seafloor during fishing operations. The otter boards can scour the seafloor, producing centimetre to decimetre scale scour tracks in the seabed depending on the nature of the sediment (see Supplementary Fig. 5). The most common fishing strategy is to follow the isobaths along the continental slope including submarine canyon flanks. In the study area, up to 180 large (i.e. >15 m overall length) bottom trawlers from eight fishing harbours (Fig. 2) operate over the same grounds year round on a daily basis, except for weekends, holidays, and during stormy periods. Multiple hauls are conducted each day.

The map in Fig. 1 illustrating the major known trawling grounds on the world continental slopes has been constructed after a systematic bibliography search but is not necessarily exhaustive. Taking into account that a very weak regulatory regime is applied on deep-sea bottoms, much illegal, unreported and unregulated fishing is deemed to make up a substantial part of the deep-sea trawling activity[2,34,35], and therefore, this chart must be viewed as a conservative assessment. Additionally, most bibliographic sources of deep-sea fisheries refer to trawling activities conducted in high-seas, but many local or regional trawling fleets also operate in continental slope regions, as in our study case. Isolated seamounts and seamount chains are also targets for deep-sea fisheries, but the map in Fig. 1 only refers to continental slope trawling grounds. The continental slope surface area compiled (red areas) accounts for a total of 4.4 million km^2, almost half the surface area of the United States of America or China, while the World's trawling grounds (including continental shelf regions and seamounts) have been roughly estimated at 20 million km^2 by the World Resources Institute[36].

The major regions identified on Fig. 1 are:

A: Mediterranean. Important fisheries are conducted in the upper and middle slope regions along a substantial part of the Western, Central and Eastern Mediterranean continental margins. The most important slope fisheries in the Mediterranean target aristeid deep-sea shrimps *Aristeus antennatus* and *Aristaeomorpha foliacea*. Other important fisheries are conducted in the upper and middle slope regions, e.g. hake *Merluccius merluccius*, monkfish *Lophius piscatorius* and Norwegian lobster *Nephrops norvegicus*. In the Spanish Mediterranean coast from the Alboran Sea[37] and Gulf of Alicante[38,39] to the Catalan[40] and Balearic Islands margins[41,42] the slope is intensely trawled down to 800 m depth, with *A. antennatus* as the most valuable species. Slope fisheries for aristeid shrimps *A. antennatus* and *A. foliacea* are also conducted in SE Italy, at depths between 300 and 700 m[43-45]. In the Sicily Channel, *A. foliacea* is intensively fished[46]. Slope fisheries for deep-sea shrimps are also very active in the entire Tyrrhenian Sea from the Gulf of Genoa down to the Sicily Strait including Corsican and Sardinian waters[34,43]. A growing deep slope fishery is under way in the Mediterranean coast off North African countries, mainly Morocco, Algeria and Tunisia[44,47]. Deep trawling is relatively less developed in the Eastern Mediterranean, but *N. norvegicus* is trawl-fished at least off northern Greece down to 400 m depth[48].

B: NE Atlantic (Iberian margin). Commercial trawling fisheries targeting a number of fish species and decapod crustaceans are reported down to at least 600 m depth in Portuguese[49] and Spanish[50] waters.

C: NE Atlantic (Central European margin). Deep water trawlers have been fishing on the continental slope west of the British Isles at depths >500 m for over two decades[51]. The USSR started exploratory trawling in the 1960s and the fishery experienced a very rapid development in the 1980s. At present, fleets from several countries heavily trawl extensive bank areas. Commercial deep water trawling occurs north and west of Scotland on the continental slopes of the Faeroe-Shetland Channel and the Rockall Trough[52]. Deep and persistent trawl marks in the Hebrides continental margin led *Roberts et al.*[53] to conclude that the margin was physically impacted by trawling to depths >1,000 m at least since the 1980s. Trawl marks and coral destruction at 200-1,400 m depth has been documented all along the Northeast Atlantic off Ireland, Scotland and Norway[53,54]. In the Porcupine Seabight, *Priede et al.*[55] estimated that bottom fishing impacted ~52,000 km^2, while *Benn et al.*[24] calculated a total trawled area in the deep-sea grounds of the Hatton and Rockall banks in the range of 1,482-74,320 km^2 for a single year (2005).

D: NE Atlantic (Norwegian margin). An important deep-sea fishery for *Nephrops norvegicus* exists in the Norwegian continental slope. The main trawling areas identified off Norway at depths >200 m come from *McAllister et al.*[56].

E: NE Atlantic (Icelandic margin). Commercial trawling on the continental slope of Iceland is widespread all around the perimeter of the island. *Ragnarsson and Steingrímsson*[57] estimated that, on average, 212,139 km^2 per year were swept with trawl gear during 1991-1997, when the fishing effort was most intensive at 100-500 m depth over most of the area. However, in some sectors the effort extended to deeper waters, down to 1,000 m. Off southwest Iceland, during the 1991-1997 period, the effort was highest in the 200-499 m depth range, comprising an annual swept area equivalent to 79% of the total area of that depth range[57]. Norwegian lobster *Nephrops norvegicus* and Greenland halibut *Reinhardtius hippoglossoides* are two of the most important deep slope fisheries in Icelandic waters[58].

F: NW Atlantic (East Greenland). Deep-sea trawling fisheries of Greenland halibut *Reinhardtius hippoglossoides* occur off southeastern Greenland involving large by-catches of roundnose grenadier *Coryphaenoides rupestris*[15]. The extent of the fishing area has been extracted from *McAllister et al.*[56].

G: NW Atlantic (Eastern Canada and U.S). The main fishing grounds for deep-sea demersal species in the NW Atlantic are on the slopes of the Grand Banks of Newfoundland and the Flemish Cap, mainly targeting the Northern shrimp *Pandalus borealis*, the Greenland halibut *Reinhardtius hippoglossoides* and the starry ray *Raja* *radiata*[34]. *Kulka and Pitcher*[59] documented trawling along the shelf break and upper slope of the Grand Banks and Flemish Cap for the 1980-2000 period, noting a displacement from relatively shallow to deeper grounds from the 1980s to the 1990s.

H: SW Atlantic (U.S. and Gulf of Mexico). Since the 1960s and particularly during the 1970s deep-sea shrimp fisheries developed off Florida targeting the royal red shrimp *Hymenopenaeus robustus*[60].

I: SW Atlantic (Brazilian margin). Bottom trawling on the deep Brazilian margin has greatly increased during the last decades, notably along its SE segment, where deep-water aristeid shrimps *Aristaeopsis edwardsiana*, *Aristaeomorpha foliacea* and *Aristeus antillensis* are exploited at depths between 500 and 1,000 m[61,62]. Trawling for deep-sea shrimps has also extended to French Guiana[63].

J: SW Atlantic (Argentinean margin). There is a persistent and extensive trawling fishery for Argentine hake *Merluccius hubbsi* and Argentine short-fin squid *Illex argentinus* all along the Argentinean shelf and upper slope down to 500 m depth and on the Rio-Grande Rise[34,64].

K: SE Atlantic (Namibian and South African margins). The Namibian demersal fishery for hake species *Merluccius paradoxus* and *Merluccius capensis* and the deep-sea red crabs *Chaceon maritae* and *Geryon quinquedens* started in the 1950s[65] and is nowadays the most economically relevant fishery in this country. Since the nineties, a deep-sea trawling fishery for orange roughy *Hoplostethus atlanticus* and alfonsino *Beryx* spp. is conducted by a limited number of vessels at 600-900 m depth off Namibia[34,66]. Demersal trawl fisheries have been active in the southern Benguela upwelling region, off South Africa, for over a century at depths between 200 and 800 m. Recent technological improvements have allowed this fishery to move at depths down to 1,000 m (*Atkinson et al.*[67] and references therein).

L: Eastern Central Atlantic (Mauritanian margin). A trawling fleet indistinctly exploits shelf and slope stocks of crustaceans[68]. Among the most valuable species, the deep-water rose shrimp *Parapenaeus longirostris* is fished from 200 to 400 m and the striped red shrimp *Aristeus varidens* from 400 to 800 m. Hake *Merluccius senegalensis* is also fished off Mauritania between 300 and 600 m depth[68].

M: NE Pacific (Canadian margin). Deep-sea trawling takes place off British Columbia from Vancouver Island to Queen Charlotte Island to depths down to 1500 m. *Kulka and Pitcher*[59] estimated the extension of the trawling area in 406,300 km^2, with 12,000 km^2 of persistent and high intensity trawling during 1994-2000.

N: NE Pacific (U.S. margin). An important demersal bottom trawling fishery targeting Dover sole *Microstomus pacificus*, sablefish *Anoplopoma fimbria*, thornyheads *Sebastolobus* spp. and several rockfish *Sebastes* spp. is active in northern California[69,70]. A sidescan sonar survey conducted in the outer shelf and slope of the Eureka region, northern California observed the greatest density of trawl marks at ~400 m depth, also noticing that the fishery extends to depths below 900 m depth[70]. A bottom trawling fishery for the northern prawn *Pandalus jordani* is also active down to 360 m depth in Morro Bay and from Eureka to the Oregon border[71].

O: Eastern Central Pacific (Panama and Ecuador margins). Deep-sea fishery on the upper slope down to 500 m depth off Panama[72] and Ecuador[73] targets several shrimp species such as *Heterocarpus vicarius* and *Solenocera agassizii*.

P: Eastern Central Pacific (Peruvian margin). Peruvian hake *Merluccius gayi peruanus* has been intensively bottom fished on the continental margin along the upper slope off Peru since year 1960[74].

Q: SE Pacific (Chilean margin). Several hake species are commercially exploited in Chilean waters since latitude 30ºS down to the southern tip of America. Hake species *Merluccius gayi gayi*, *Macruronus magallanicus* and *Merluccius australis* are caught down to 600-700 m depth[75].

R: SW Pacific (New Zealand margin). Commercial trawlers have intensively targeted the deep slope perimeter of the archipelago in the last decades[34,76]. The main fishery pursues the orange roughy *Hoplostethus atlanticus*. This fishery started in the late 1970s-early 1980s and although it initially occurred mainly on flat bottoms, over time it became more focused on seamounts (not shown in the map). The orange roughy fishery was first developed on the Chatham Rise, east of New Zealand, which consequently now constitutes one of the most heavily exploited grounds around the islands[77]. The fishery subsequently expanded to a much wider region around New Zealand and Australia, at depths of 700 to 1,200 m. A multi-species commercial fishery for scampi *Metanephrops challengeri* and several fish species is very active on the continental slope to the NE of the islands at 200-600 m depth. *Cryer et al.*[78] calculated for the Bay of Plenty fishery area off NE New Zealand that about 2,100 km^2 on average of the seafloor were swept each year by trawlers, which represents an estimated 20% of the area of the upper continental slope.

S: Western Central Pacific (Southeast Asian margin). A large bottom trawling area at depths in excess of 200 m is exploited along the continental slope of the Southern China Sea, as reported by *McAllister et al.*[56]. However, no more details on the type of fisheries conducted in this region or the depth of the fishing grounds have been identified.

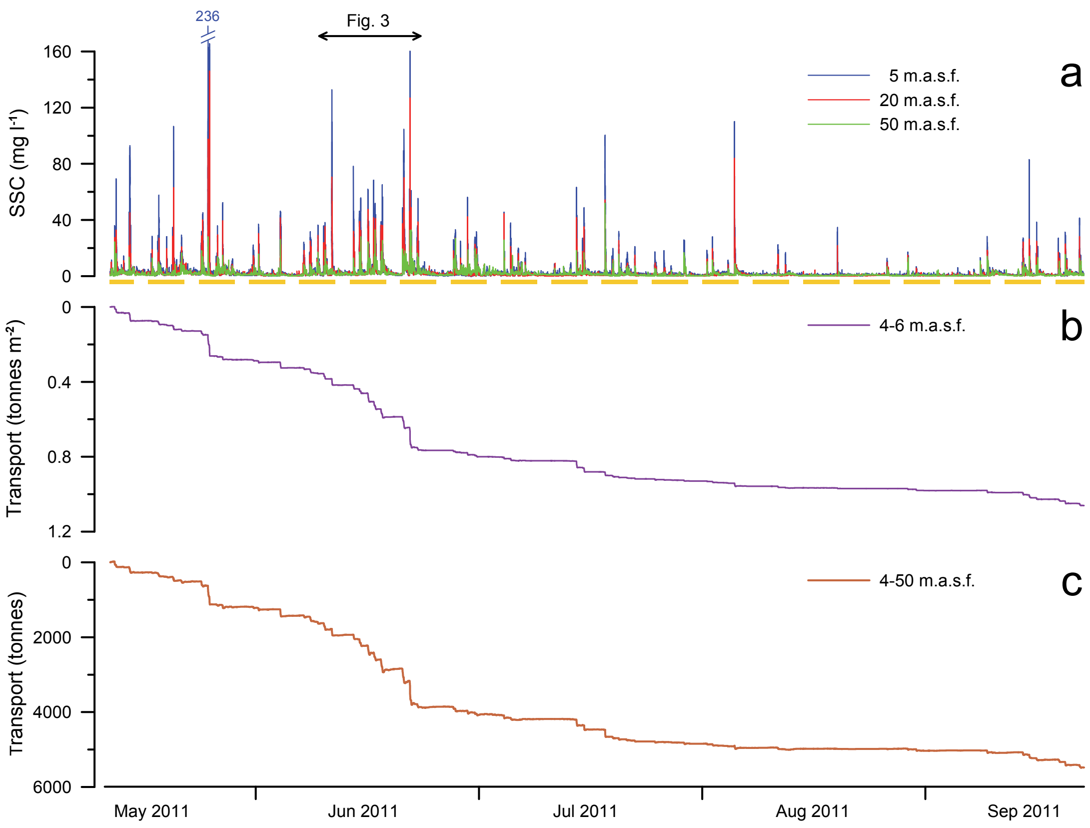
T: Eastern Indian Ocean (West Australian margin). The trawl fishery along the NW Australian margin relies on commercial stocks of deep-water crustaceans, mainly the scampi species *Metanephrops velutinus*, *M. australiensis* and *M. boschmai*, and the penaeid species *Aristaeomorpha foliacea*, *Haliporoides sibogae*, *Aristeus virilis* and *Plesiopenaeus edwardsianus*, all of them fished down to 500 m depth. In the western Australian mid-slope regions, deep-sea fishing for orange roughy *Hoplostethus atlanticus* and alfonsino *Beryx splendens* began in the latter half of the 1980s from 700 m depth down to 1,500 m[79]. The South Tasman Rise, south of the Australian EEZ, was heavily fished over the last decade[80].

U: Northern Indian Ocean (West Indian margin). Though most of the perimeter of the Indian Peninsula was identified by *McAllister et al.*[56] as having >200 m depth fisheries, proper sources are hard to find or are contradictory. The SW margin off the Kerala region seems to be the margin segment most heavily exploited by trawlers. From 1999 onwards, trawlers operating off Kerala extended their operations offshore down to 400 m depth to exploit deep-sea resources[81], as related to the modernization of the trawling fleet[82]. The main deep-sea species caught are shrimps *Aristeus alcocki, Heterocarpus woodmasoni* and *H. gibbosus*.

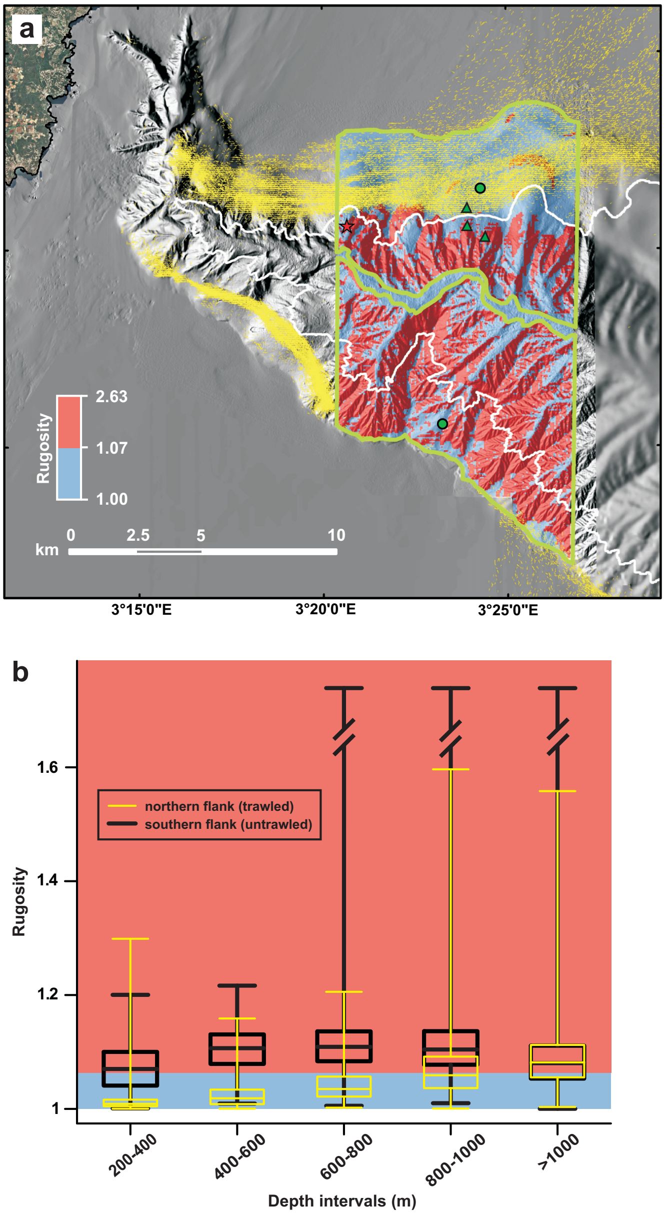
V: NW Indian Ocean (Arabian Peninsula margin). *McAllister et al.*[56] reports a region of deep-sea trawling to the southeast of the Arabian Peninsula off Yemen, while *FAO*[83] reports important fisheries along all countries of the Arabian Peninsula, although no location or depth maps of the fishing grounds or references on the type of demersal fisheries conducted in this region have been found.

W: SW Indian Ocean (Somalia, Mozambique, Madagascar and East South African margins). The dominant bottom fishery in the high seas of this large region targets the fish species alfonsino *Beryx splendens* and the orange roughy *Hoplostethus atlanticus*[34,84]. Deep-water fishing vessels from several countries, e.g. Spain, Taiwan, Japan and France, operate in this region, which hosts one of the most productive deep-sea water fisheries of the world[84]. East of South Africa and southern Mozambique, a local fishery down to 500 m depth targets several species of crustaceans, such as the pink prawn *Haliporoides triarthrus* and *Aristaeomorpha foliacea*, two scampi species *Metanephrops mozambicus* and *Nephropsis stewarti* and the deep-sea crab *Chaceon macphersoni*[85]. Off Mozambique, two other valuable deep-water resources are the blue and red deep-sea shrimp *Aristeus antennatus* and the stout red shrimp *Aristeus virilis*, which are exploited down to 700 m depth[86].

X: Southern Ocean (Antarctic margins). Large-scale bottom trawl finfish fisheries began at the end of the 1960s around some sub-Antarctic islands, while fishing along the coasts of the Antarctic continent started in the early 1980s[34,84]. The main species targeted by bottom trawlers were the Patagonian toothfish *Dissostichus eleginoides* and the Antarctic toothfish *D. mawsoni*[34]. At present, bottom trawling is banned in the area regulated by the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR), except at Heard and McDonald islands. However, illegal, unregulated and unreported bottom trawling is known to occur in the CCAMLR area[87].

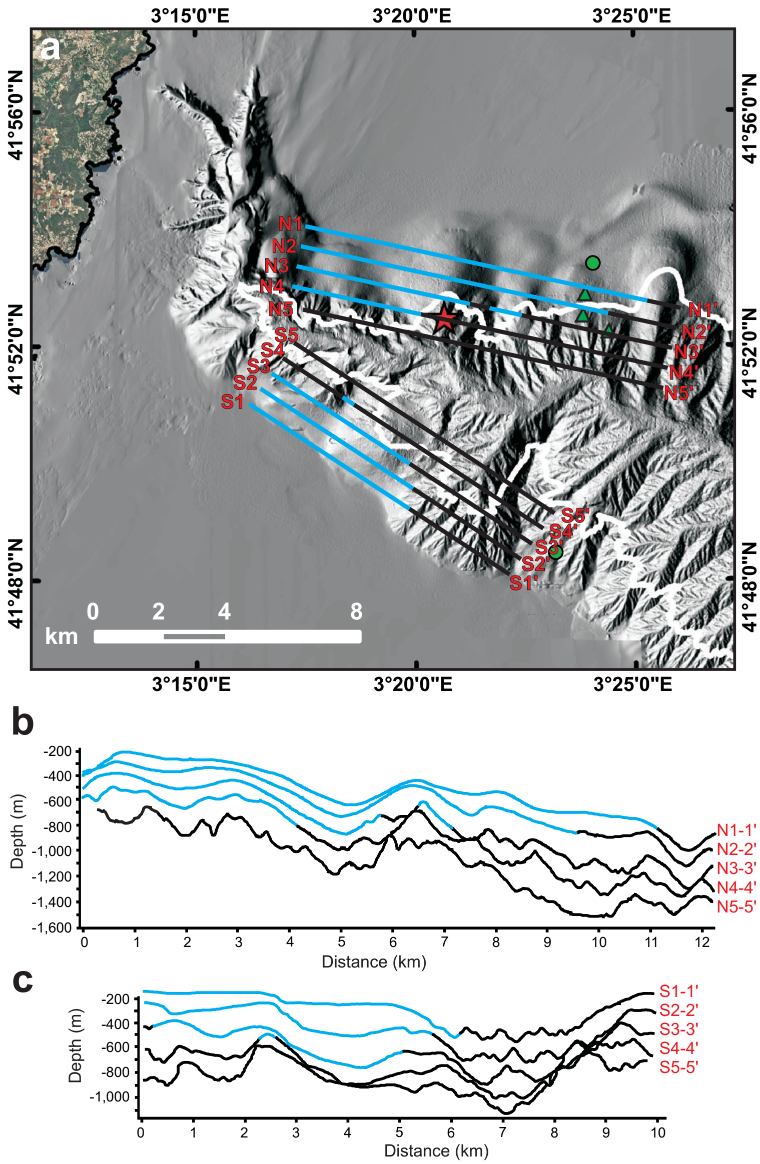


Supplementary Figure 1 | Suspended sediment concentration (SSC) records and cumulative transport during the observational period. a, Time series of near-bottom SSC at the three recording heights above the seafloor (m.a.s.f.: meters above sea floor) showing numerous trawl-induced sediment resuspension events. **b,** Downslope cumulative sediment transport at the closest level from the seafloor (4-6 m.a.s.f.). **c,** Downslope cumulative transport estimate between 4 and 50 m.a.s.f. across the width of the tributary valley monitored, accounting for a total of 5,378 tonnes of sediment during 136 days. The two week period illustrated in Fig. 3 is indicated. Orange bars at the base of SSC plots denote weekdays and the spaces stand for weekends. Mooring location is shown in Figs. 2 and 4 and Supplementary Figs. 2 and 3.

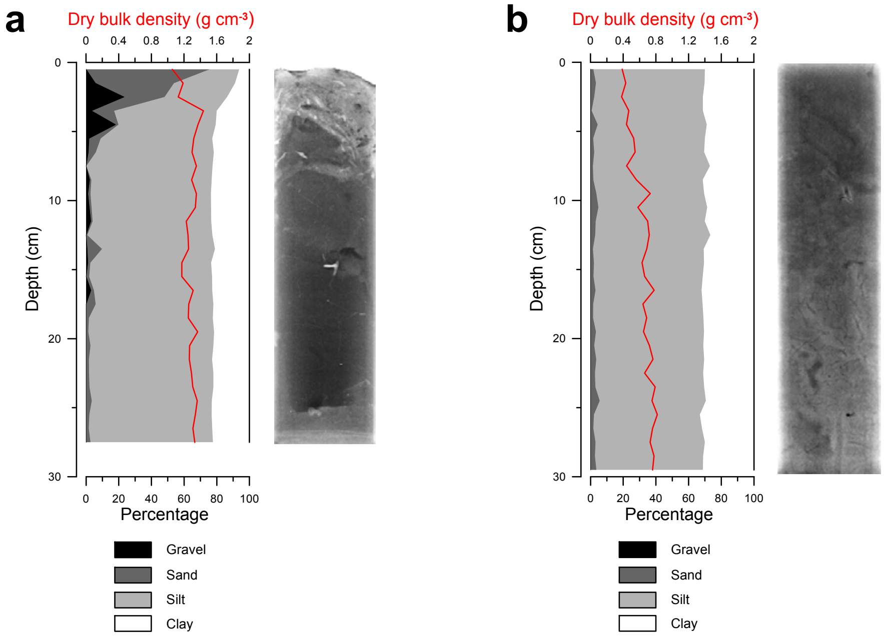


Supplementary Figure 2 | Rugosity analysis of La Fonera Canyon seafloor. **a,** The ArcGIS Benthic Terrain Modeler (BTM), developed as part of a cooperative agreement between the Oregon State University (OSU) Department of Geosciences and the National Oceanic and Atmospheric Administration (NOAA) Coastal Services Center[88], was used to calculate the rugosity-depth relation on a 50 m bathymetric grid subsample for a region of La Fonera Canyon (area bounded by green lines). Results of the analysis were plotted on the shaded relief image from the 15 m resolution bathymetric grid. The white line represents the 800 m isobath. Also shown are the locations of the mooring station (red star; see Fig. 3 and Supplementary Fig. 1), sediment cores (green dots; see Supplementary Fig. 4) and ROV images (green triangles; see Supplementary Fig. 5)

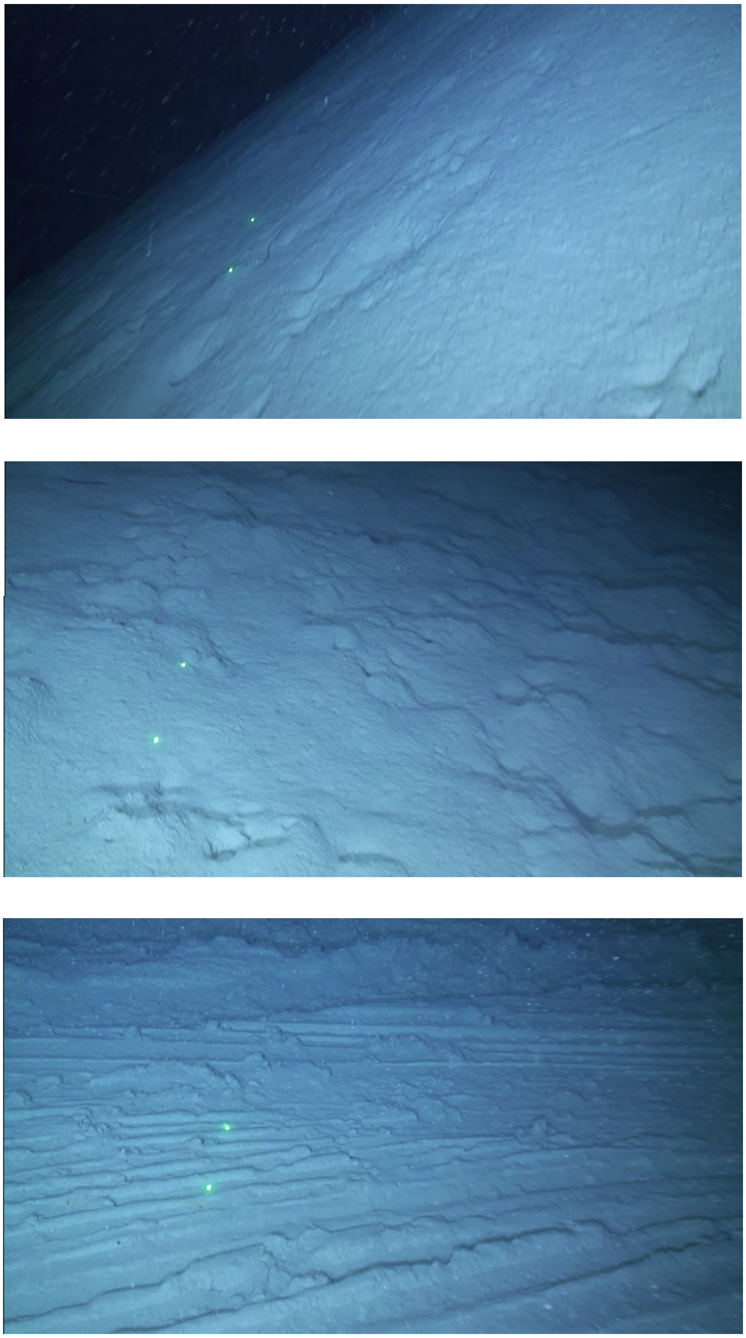
The positions of active trawlers for the years 2007 to 2010 are shown by small yellow arrows. Areas of high rugosity (red) correspond to the regions with little or no trawling whereas areas of low rugosity (blue) correspond to areas with the greatest amount of trawling. **b,** Box and whisker plots from the binary rugosity data in the northern canyon flank (yellow) and the southern canyon flank (black) at several depth intervals. Mean rugosity values in the trawled region of the northern flank (200-1,000 m depth) are significantly lower compared to the same depth intervals for the untrawled southern flank, while at depths >1,000 m the two plots overlap and both flanks show the same statistically significant rugosity (Kruskal-Wallis statistical test $p<0.0001$, DF 9, K-critical value 16.91; Multiple pairwise comparisons using the Dunn's procedure with a Bonferroni corrected significance level of 0.0011).



Supplementary Figure 3 | Bathymetric sections along La Fonera canyon flanks. a, Shaded relief image from the 15 m resolution bathymetric grid showing the position of the bathymetric sections. The blue line sectors represent the areas affected by bottom trawling. **b,** Sections along the northern canyon flank. **c**, Sections along the southern canyon flank. Note the change between rough areas in the untrawled region (black lines) and smoothed areas in the trawled region (blue lines) and the scale of relief that has been smoothed. The 800 m depth isobaths (white thick contour) and the positions of the mooring station (red star; see Fig. 3 and Supplementary Fig. 1), sediment cores (green dots; see Supplementary Fig. 4) and ROV images (green triangles; see Supplementary Fig. 5) are indicated.



Supplementary Figure 4 | Positive X-radiographs, grain size distribution and dry bulk density from two short sediment cores collected at similar water depths in trawled and untrawled areas of La Fonera Canyon flanks. **a**, Core collected at 484 m depth in a trawled area on the northern flank (41°53.45´N; 3°24.10´E). **b**, Core collected at 472 m water depth on an untrawled area from the southern flank (41°48.45´N; 3°23.23´E). Core **a** consisted of a featureless, over-consolidated (i.e. old) mud capped by a thin layer of coarser sediment with a high proportion of broken shell fragments. This is characteristic of an area where there is a sustained disturbance of sediment and a progressive winnowing of the finer sediment fraction through resuspension, in this case as a result of trawling. In contrast, core **b** consisted of low density, bioturbated soft mud. See core locations in Fig. 4 and Supplementary Figs. 2 and 3.



Supplementary Figure 5 | Seafloor pictures from the northern flank of La Fonera Canyon obtained during an up-slope ROV transect. **a**, Steep untrawled muddy seafloor with faint bioturbation structures at 1110 m depth (41º52.26´N; 3º24.48´E). **b**, Untrawled moderately steep muddy seafloor with numerous centimetre-high bioturbation mounds at 963 m depth (41º52.46´N; 3º23.94´E). **c**, Flattened muddy seafloor resulting from bottom trawling with fishing gear marks (sub-)parallel to the slope at 770 m depth (41º52.76´N; 3º23.92´E). Mean ROV altitude over the seafloor is 0.3 m. Depth of field of view is 1.2-2.5 m. Total imaged area per picture is 2-4.5 m^2. Distance between green laser points is 15 cm. White dots are marine snow aggregates. For locations see Fig. 4 and Supplementary Figs. 2 and 3.

Process	Name	Location	Total area (km^2)	Source area (km^2)	Age *Time span*	Volume (km^3)	EAV (km^3yr^{-1})	Yield ($km^3yr^{-1}km^{-2}$)	Reference
Bottom trawling	La Fonera canyon tributary valley	NW Med margin	Unknown	$4.2\cdot10^{0}$	*136 days (2011)*	$9.0\cdot10^{-6}$	$2.4\cdot10^{-5}$	$5.8\cdot10^{-6}$	This study
	La Fonera canyon northern flank	NW Med margin	Unknown	$4.2\cdot10^{1}$	*1970-present*	$1.0\cdot10^{-2}$	$2.4\cdot10^{-4}$	$5.8\cdot10^{-6}$	This study
Canyon head failures	Nice slide	NW Med margin	$1.5\cdot10^{3}$	$6.3\cdot10^{-1}$	1979	$8.7\cdot10^{-3}$	$2.6\cdot10^{-4}$	$4.2\cdot10^{-4}$	89,90
	Astilla slide	W US margin	$2.3\cdot10^{-2}$	$1.2\cdot10^{-2}$	*24 mo (2003-05)*	$1.0\cdot10^{-4}$	$5.0\cdot10^{-5}$	$4.2\cdot10^{-3}$	91
	Monterey canyon head	W US margin	Unknown	$1.4\cdot10^{0}$	*29 mo (2002-05)*	$1.0\cdot10^{-3}$	$4.1\cdot10^{-4}$	$3.0\cdot10^{-4}$	91
	New Valley, Scripps Canyon	W US margin	Unknown	$3.6\cdot10^{-2}$	1975	$9.9\cdot10^{-4}$	$2.7\cdot10^{-5}$	$7.4\cdot10^{-4}$	92,93
Open slope failures	Eivissa Channel slides (total)	NW Med margin	$3.6\cdot10^{1}$	$1.8\cdot10^{1}$	~61,500 yr BP	$1.0\cdot10^{0}$	$1.6\cdot10^{-5}$	$9.0\cdot10^{-7}$	94,95
	BIG'95 debris flow	NW Med margin	$2.2\cdot10^{3}$	$2.0\cdot10^{2}$	11,647- 11,129 yr BP	$2.6\cdot10^{1}$	$2.2\cdot10^{-3}$ $2.3\cdot10^{-3}$	$1.1\cdot10^{-5}$ $1.2\cdot10^{-5}$	96,97
	Storegga slide	Norwegian margin	$9.5\cdot10^{4}$	$5.0\cdot10^{4}$	8,350- 7,850 yr BP	$>2.4\cdot10^{3}$ $<3.2\cdot10^{3}$	$2.9\cdot10^{-1}$ $4.0\cdot10^{-1}$	$5.7\cdot10^{-6}$ $8.1\cdot10^{-6}$	96,98,99
	Canary slide	NW African margin	$4.0\cdot10^{4}$	$6.0\cdot10^{3}$	17,000- 13,000 yr BP	$4.0\cdot10^{2}$	$2.3\cdot10^{-2}$ $3.1\cdot10^{-2}$	$3.9\cdot10^{-6}$ $5.1\cdot10^{-6}$	96,100
	Balearic abyssal plain megaturbidite	W Med abyssal plain	$6.0\cdot10^{4}$	$6.0\cdot10^{3}$	~22,000 yr BP	$5.0\cdot10^{2}$	$2.3\cdot10^{-2}$	$3.8\cdot10^{-6}$	101

Supplementary Table 1 | Comparison between sediment volumes remobilised by bottom trawling in the northern flank of La Fonera Canyon and those involved in naturally occurring submarine sediment failures. The table provides information on i) the total affected area, which includes the source area and the depositional area, "unknown" meaning that the latter is not constrained; ii) the source area from where the sediment was remobilised; iii) the best available age of failures or the time span of monitoring periods (in italics), with maximum and minimum ages given where known; iv) the volume mobilised during relevant time span (including monitoring periods where appropriate), or total volume of failure events, with maximum and minimum volumes given where known (Storegga slide); v) equivalent annual volume (EAV): volume mobilised per year of monitored period, or per year since occurrence for failure events; vi) sediment yield: sediment volume generated per unit surface of source area and per year of monitored period, or per year since occurrence for failure events; and vii) relevant bibliographic references. Values for the Eivissa Channel slides include four minor submarine slides (see relevant references). Source area and size of the Balearic megaturbidite is unknown, so it has been assumed that the source area was 10% of the total area covered by the deposit, which is a reasonable approximation for this type of mass gravity transport process. Note that the annual sediment volume remobilised by bottom trawling in the studied canyon flank is comparable to the volumes involved in canyon head failures occurring at similar time scales, whereas the total volume of sediment remobilized from the canyon flank since the industrialization of the bottom trawling fleet is from two to five orders of magnitude smaller than the volumes involved in open slope submarine failures that occur over geological periods of time. Nonetheless, both bottom trawling and open slope failures, when normalized over source area and time, can account for similar sediment yields. *Canals et al.*[96], *Huhnerbach & Masson*[102], *Locat & Lee*[103] and *Masson et al.*[104] provide further information on slope failures volumes and other relevant parameters.

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