

Invited Review Paper

Commercial bottom trawling as a driver of sediment dynamics and deep seascape evolution in the Anthropocene



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ABSTRACT

Fishing gear and techniques have evolved through the centuries, and particularly after the Second World War, towards a mass production industry in such a scale that it has placed many commercial stocks in a delicate or depleted status. Furthermore, certain fishing methods have other undesirable side effects on ecosystems and habitats. In this work, the known impacts of bottom-dragged gear on the seafloor are reviewed. Some of the least known issues are emphasized, namely, impacts on the physical properties of deep-sea sediments, resuspension, erosion, near-bottom turbidity and seabed morphology. Due to its recurrence, mobility and wide geographical extent, bottom trawling has become an effective driver on shaping the physical basis of benthic habitats: its composition, texture and morphology at scales from micro to the entire continental margin. It is concluded that trawling is comparable in its transforming power over seascapes to the effects of agriculture or deforestation on land.

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Introduction

Bottom trawling is the main method of capture of demersal resources, accounting for 22% of the global fish production (Kelleher, 2005) and up to 80% if only the high seas fisheries for benthic resources are taken into account (Gianni, 2004). The widespread and intensive use of towed bottom-fishing gear on the continental margins of the world has raised concerns about the sustainability of this practice and its impacts on ecosystems and habitats (Jones, 1992; Watling and Norse, 1998; Dayton et al., 1995; Dorsey and Pederson, 1998; Puig et al., 2012). Compilations of the literature on impacts by bottom trawling and dredging have been carried out by Rester (1999) or Johnson (2002). The impacts of bottom trawling on the health and sustainability of living resources and in the broader ecosystem accounts for the largest contributions to the volume of literature published so far on trawling impacts. This work focuses on the review of the impacts of bottom trawling with a particular emphasis on water column turbidity, sedimentary budgets and seafloor morphology on the deep sea.

Of particular concern is the fact that demersal fisheries have been continuously shifting from shallower to deeper areas in recent decades (Haedrich et al., 2001; Morato et al., 2006). Several offshore human activities such as waste dumping, mining, cable laying or warfare can produce acute impacts in localized sites of the deep seafloor. However, comparative assessments conducted by Eastwood et al. (2007) and Benn et al. (2010) have concluded that the contribution of bottom trawling to the disturbance of the deep-sea floor is notably higher than all other anthropogenic pressures combined, given the intensity, recurrence and wide geographical presence of commercial trawling. For reviews of anthropogenic impacts on the seafloor other than fishing activities, the reader is redirected to Glover and Smith (2003), Halpern et al. (2008) or Tyrrell (2011).

Since different trawling devices may produce different impacts, this work starts with a technical description of the main bottom trawling gear and its primary effects upon contacting the seafloor. Next, some hints on the history of trawling activities and its expansion to the deep-sea in recent decades are given, followed by a discussion on some implications of this offshore shift. The relevance of trawling effects on sediment dynamics of continental margins is reviewed in the following sections, starting with “Trawling-induced sediment resuspension”. The resettlement of sediments thus mobilized open issues about its fate and the consequences for regional budgets of sediment and key elements such as carbon, next section deals with these aspects as well as the alterations of the physical properties of bottom sediments subject to chronic trawling. The last three sections address the modifications of the seafloor morphology at large scales or in its intrinsic relief, that is, the transformation of submarine landscapes under human pressure. Section “Biogenic habitats” focus on the threats posed to biogenic underwater habitats while the next section reviews the effects on soft muddy bottoms. In the last section, the previous two are integrated and put in relation with human-modified landscapes.

Characterization of bottom fishing gear

Generically speaking, “trawling” is any fishing technique involving the towing of a collecting device to harvest living resources. Diverse methods exist to keep the net/collector horizontally and vertically open as the gear is pulled by a moving vessel. Fishing boats can pull the nets at midwaters (pelagic trawling) or along the bottom (bottom trawling). Within bottom trawling, still two subdivisions are to be made in terms of distance to the seafloor. In “demersal trawling”, the net is towed at a distance from the seafloor. However, most usual configurations involve a close contact of the trawling gear with the bottom, which is known as benthic or bottom trawling, the term we will use hereafter. Three major categories of bottom towed gears can be drawn: dredges, beam trawls and otter trawls. Many sub-types and ad hoc configurations of these exist and, in fact, the exact designs are often shaped in every detail to meet the requirements imposed by substrate type and life traits of the targeted species. Other fishing techniques such as caging, gillnetting and some types of long-lining are also laid in contact with the seabed but in these cases, impacts on the seafloor are mainly restricted to deployment/retrieval operations, when the nets and anchoring systems can be briefly dragged along the bottom. More detailed information on bottom fishing techniques can be found in von Brandt (1984) or Sainsbury (1996).

Dredges

In its simplest form, a dredge consist of a horizontal metal bar or blade that digs or scraps the seafloor owing to its weight and the strain exerted by a towing wire. Fig. 1 offers an overview of several common dredge setups. Bottom-dwelling living resources are collected in a bag connected to the advancing dredge. Dredge designs are very variable and often species-specific but nonetheless two big clusters can be outlined: epifaunal dredges that harvest animals living on the seafloor by scraping or slightly digging bottom sediments, and infaunal dredges that penetrate the seabed to some depth to collect buried animals such as clams or burrowing crustaceans.

The blade can be supplemented by ‘teeth’, forming a rake that bulldozes soft sediments, unburying and collecting burrowing animals.

As an example, the dredges used in the Atlantic coast of the US to catch oysters and crabs are equipped with a blade 0.5–2.0 m wide with teeth 10 cm-long (Steele et al., 2002). More than one dredge can be dragged at a time by a single ship.

In general, dredges are towed at less than 2.5 knots, becoming inefficient at higher speeds (Caddy, 1973; Dare et al., 1993). Owing to its weight and the resistance offered by the bar/rake, the use of dredges is usually restricted to shallow depths. As an exception, it is worth mentioning the offshore fisheries for scallops at 100–200 m depth. Given the natatory skills of scallops, these dredges are towed at speeds up to 5 knots (Steele et al., 2002) and also the size and weight of the ensemble is larger than in shallow water setups. Width of this particular dredge in the eastern US coast is 3–4.5 m and weighs 500–1000 kg according to Steele et al.

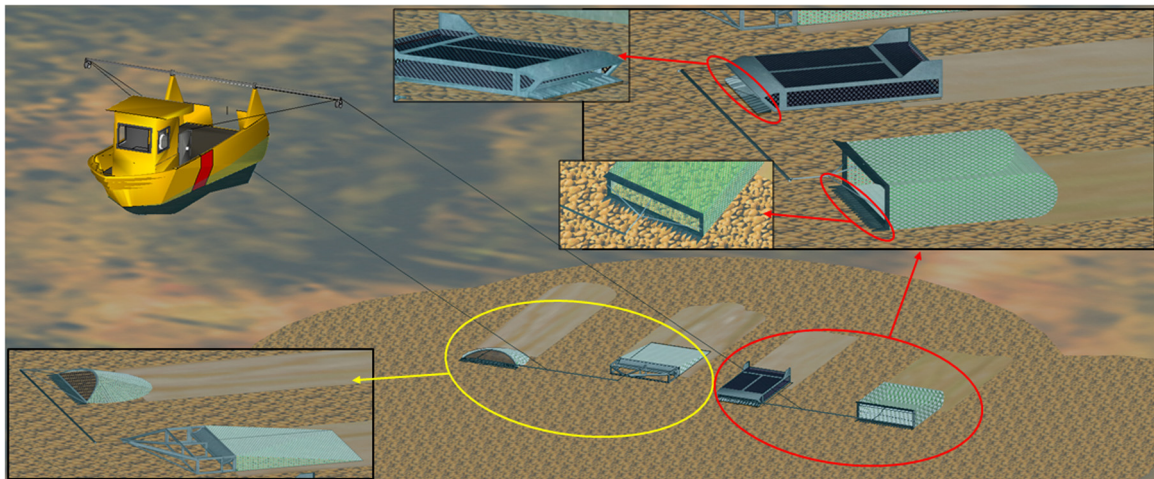


Fig. 1. Illustration of different designs of fishing dredges.

(2002). Dredging for scallops has been conducted on the Scotia Shelf and the Bay of Fundy since the second half of the XIX century (Messieh et al., 1991 and references therein) and has also been very active in recent decades along the Argentinian shelf-break (Lasta et al., 1998).

A particular kind of dredge that enhances fishing efficiency as well as sediment disturbance is represented by the hydraulic dredge. In this modality, bottom sediments are liquefied by high-pressure water jets directed in front of the sorting blade, thereby improving the penetration into the sediments and the extraction of buried mollusks. Hydraulic dredges are used close to the coast and also offshore to harvest clams. They are usually towed at low speeds (Steele et al., 2002).

Beam trawls

The beam trawl technique can be considered an extension of the dredge approach: In fact, the main element equilibrating the

ensemble of the fishing gear is still the rigid horizontal bar (hereafter “beam”) that keeps the net wide open. Fig. 2 illustrates a generic beam trawl gear. The bar is elevated from the ground while sweeps on the base of the net dig the seabed to collect benthic fauna. A pair of “shoes” (Fig. 2) connect the gear with the towing vessel and maintain the mouth of the net close to the bottom and vertically open. Rakes and other bulldozing devices typical of dredges are absent and instead the total length of the beam and subsequently the collecting area are enlarged. The robust collecting bag typical of dredges is substituted by a larger, slenderer, funnel-shaped net that terminates in a cylindrical collector called the codend, where the catch is concentrated. A lighter frame also permits higher towing speeds and, consequently, a larger area of seabed is disturbed per unit time (Jennings and Kaiser, 1998). In the North Sea, towing speed of beam trawlers ranges between 3.5 and 7 knots (Valdemarsen and Suuronen, 2003). Two beam trawls are often operated simultaneously by a single vessel, each one towed from one of the ship sides.

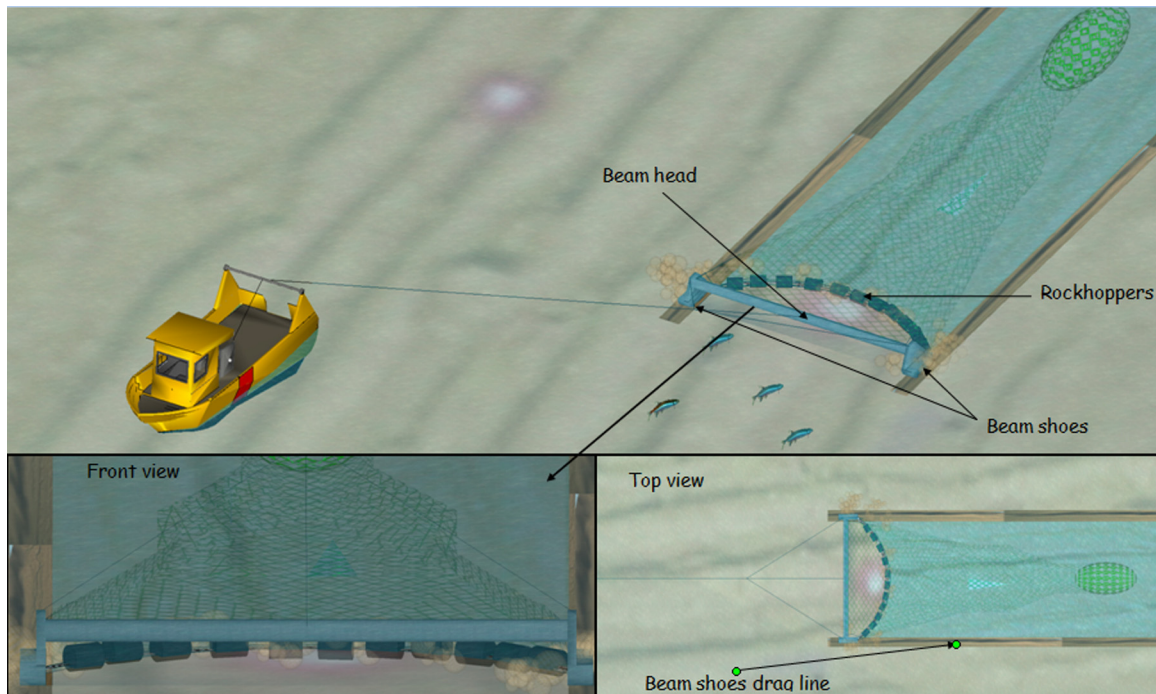


Fig. 2. General view and elements of a generic beam trawl gear.

Beam trawls are used on flat areas at depths from a few to several hundred meters, but most often less than 100 m to harvest species of flatfish and crustaceans that live in contact or within the upper surface sediments. In muddy bottoms, a series of “tickler chains” can be attached to the frame with the aim of stirring and resuspending sediments ahead of the advancing gear, which improves catchability.

Most of the information about beam trawl characteristics (and associated impacts) comes from its emblematic area of use, i.e., the countries bordering the North Sea, where beam trawling has been active since the Middle Ages. After the industrial revolution, the beam technique spread to other European seas and further overseas. At present, it is practiced worldwide in fisheries spanning from artisanal fisheries such as in coastal Nigeria (Ambrose et al., 2005) to heavily industrialized as in the China Sea (Yu et al., 2007). In the North Sea, beams measure between 4 and 12 m horizontally and are equipped with up to 15 tickler chains (Polet and Depestele, 2010). The weight of the entire beam trawl asset ranges from several hundred kg for a shrimp trawl to several metric tons in flatfish trawls, which are supplemented with multiple tickler chains. The average weight of North Sea Beam trawls was up to 3.5 tons in the late 1970s but increased to more than 10 tons by the early 1980s (de Groot, 1984; van Beek et al., 1990).

Otter trawling

In the pursuit of bigger catches and profits – which generally equates to larger areas swept per haul and fishing day – otter trawls represented a leap forward in the evolution of trawling technologies. The otter trawl permitted wider net openings by sacrificing the horizontal bar. Instead, the net is horizontally spread by means of two boards (also called doors) at its extremes, each one pulled from a line. The sum of the hydrodynamic force acting upon the doors and the tension from the towing line keeps the ensemble spread. Fig. 3 illustrates the shape and main elements of a generic otter trawl gear. The removal of the rigid front frame also allows the gear to adapt to rougher and steeper terrain and, as a result, otter trawlers can venture into deeper and remote grounds not accessible to other bottom fishing techniques.

In early otter trawl setups, the doors were directly attached to the wings of the net, as is still today the case in certain shrimp fisheries (Steele et al., 2002). From the 1930s, cables known as bridles, sweeplines or warps have been introduced between the doors and the trawl net. As a consequence, the area effectively swept by the passing gear is not anymore dictated by the distance between the wings of the net but by the much larger distance between doors.

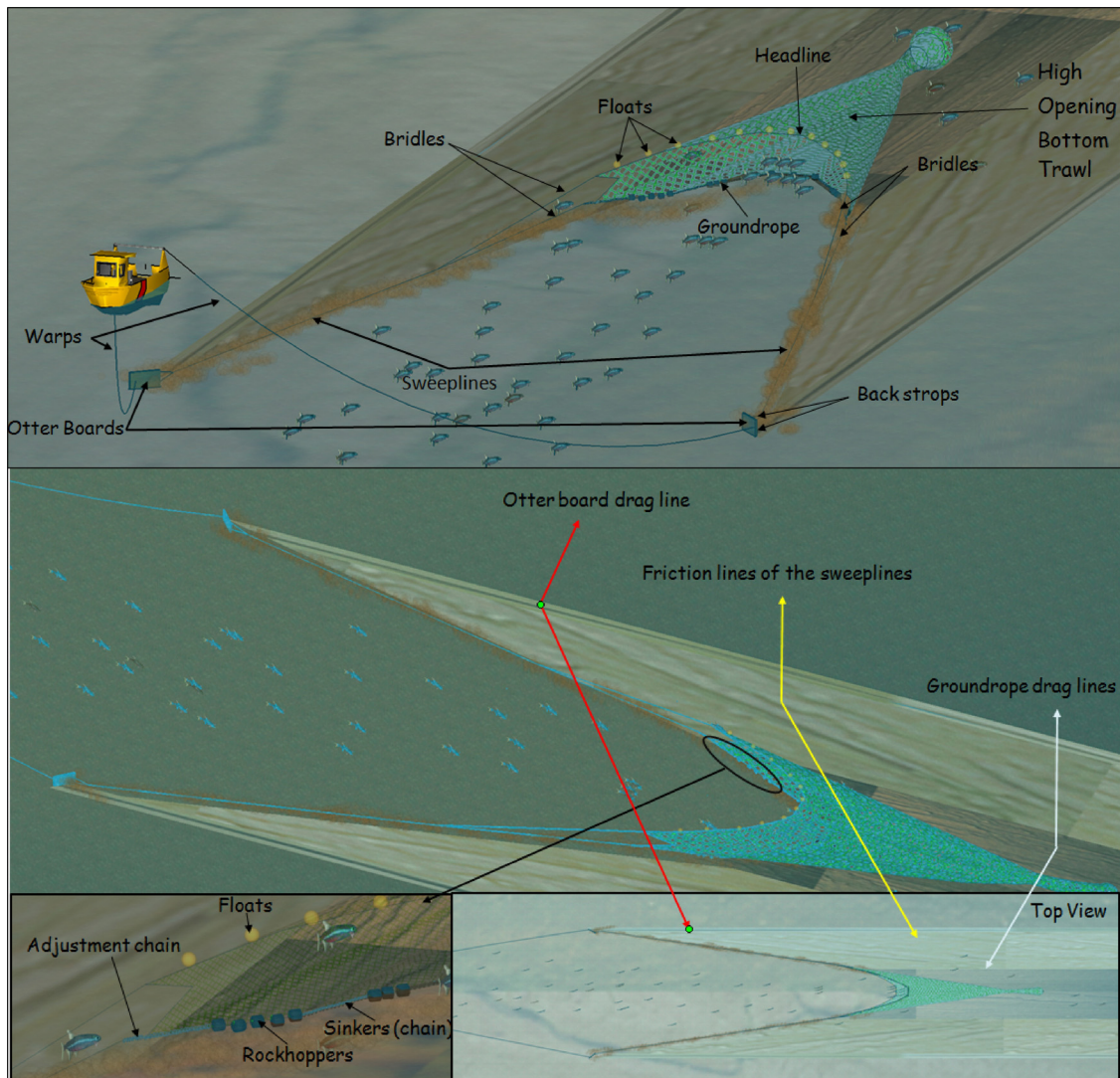


Fig. 3. Otter trawl gear showing its main elements and its effects on a soft-bottom seabed as it is dragged along it. The otter boards disturb the seabed creating deep furrows and resuspending clouds of sediment in their wake. The groundrope and sweeplines scarp the seafloor, flatten the microrelief and also produce sediment resuspension.

Floats in the upper section (or headrope) of the net mouth and weights on its lower side (footrope or groundrope) complete the scheme to keep the mouth of the net wide open while holding it in contact with the seafloor (Fig. 1). The footrope is usually complemented with heavy devices such as metal bobbins and rollers or rubber ‘rockhoppers’ that provide ballast and facilitate the advance of the gear through irregular terrain (He and Winger, 2010). Rockhoppers are large rubber discs measuring up to more than 1 m in diameter (Gunnarsson, 1995). Steele et al. (2002) reports a 40 m-long rockhopper section with an estimated weight of 4800 kg.

Different designs of otter boards exist (see Fig. 1.1. in Seafish et al., 1993). Traditional otter boards are flat and made in wood with steel reinforcements while more recent ones are made of solid iron or steel and weight from hundreds of kg to several tons. Gunnarsson (1995) reports, for the Icelandic trawl fleet, oval boards with surfaces of 8–11 m² and weights in the range 2400–4200 kg. At its base, the otter board contacts the seafloor with a “shoe”, generally a flat extension up to 30 cm wide that facilitates sliding over the bottom. During duty, the boards are tilted by hydrodynamic forces forming an angle with respect to the trawl’s forward motion, the so-called “angle of attack”. In this way, the area of ploughed seafloor is larger than it could be estimated from the shoe surface alone.

Trawling vessels (‘trawlers’) can range from small open boats with only 30 hp engines to factory trawlers with installed power >4,000 hp. Two otter trawl nets can be operated simultaneously by a single vessel in what is known as twin rig trawling (Galbraith and Rice, 2004). Towing speed depends on bottom type and targeted species but usually vary between 2 and 5 knots (He and Winger, 2010). As an example of a present day deep-sea otter trawl gear, the one commonly used in the blue and red shrimp fishery along the NW Mediterranean has the following dimensions: the otter boards weigh from 400 to 1200 kg and are spread apart approximately 100 m. The mouth of the net is 40–50 m wide, the total length of the net from mouth to cod end makes up to 150 m and the sweep-lines connecting the otter boards to the net measure 60–200 m (Palanques et al., 2006).

An alternative approach to the hydrodynamic opening of the net obtained with otter boards is represented by bottom pair trawling, where the net is towed from two boats, each one pulling one of the bridles. Although used more often in midwaters (pelagic trawling), pair bottom trawlers have also been used in continental margins off Europe, North America and the Far East (Thomson, 1978). Heavy footropes and rockhoppers and heavier nets than in otter trawling are reported for this fishing type by Galbraith and Rice (2004).

Direct physical impacts on the seafloor

In general, the penetration depth of fishing gear is higher in muddy bottoms but also depends on gear type, its dimensions and weight as well as the boat speed and the way the gear is operated (Black and Parry, 1999). With increasing towing speed the pressure exerted by the gear on the seabed tends to decrease (Fonteyne, 2000) while the swept area increases. The presence of add-ons such as rakes, groundropes, rockhoppers or tickler chains enhance the disturbance of bottom sediments.

Dredges

Resuspension and stirring of soft sediments (or scraping and eventually crushing of harder substrates) by dredges are caused primarily by the blade or toothed metal bar, although substantial damage can also derive from the collecting bag, which is usually steel-reinforced. Infaunal dredging is a particularly destructive

fishing practice since the seafloor is not merely scoured but actively bulldozed (Rose et al., 2010). The effect on soft bottoms has been described alternatively as a general flattening of the seabed relief and as wide furrows flanked by distinct ‘overflowing’ sediment ridges (Bradshaw et al., 2000). Beukema (1995) reports furrows 1 m wide and 40 cm deep. Hydraulic and suction dredges are probably the most penetrative of bottom fishing gear, up to 60 cm (Hall, 1999). A meta-analysis of fishing impacts by fishing gear conducted by Kaiser et al. (2006) signaled scallop-dredging over biogenic substrate as the most impacting of all fishing types. On the other hand, the relatively small size of dredging devices, slow towing speed and limited autonomy of most dredging fisheries, limits the spatial extension of its impacts. Bottom dredging for fish is a major transformer of the bottom sediments in coastal systems (Pilkaln et al., 1998; Black and Parry, 1994), but it becomes less important in deeper environments where other fishing methods (beam and otter trawlers) perform better.

Beam trawling

The groundrope and shoes heavily disturb the seafloor and these disturbances are considerably enhanced when tickler chains are added to the ensemble. On soft bottoms, the typical penetration depths of the gear are 6–8 cm (Duplisea et al., 2001 and references therein). The passage of beam trawl gears tends to flatten seabed features such as sand waves or ripples (Fonteyne, 2000).

Otter trawls

The most readily noticeable effect of otter trawls on the seabed are the furrows left behind by the heavy boards, frequently observed through side scan sonar or multibeam surveys (e.g., Krost et al., 1990; De Alteris et al., 1999). Trawl doors penetrate more deeply in muddy than sandy sediments (Ball et al., 2000). A penetration of up to 15 cm was estimated by Krost et al. (1990) in soft bottoms of the Baltic Sea; other authors report otter tracks up to 30 cm deep and 0.2–2 m wide (Jones, 1992 and references therein). The persistence of these otter tracks depends on sediment grain size (Dellapenna et al., 2006) and the strength of biological and physical processes able to blur the otter track marks. Otter marks have been observed to remain visible for 12–18 months in muddy sediments of the Mediterranean (Palanques et al., 2001) and the North Sea (Lindeboom and de Groot, 1998). Schwinghamer et al. (1998) reported persistence times up to one year on sandy sediments off Grand Banks at 130 m depth.

Due to its relative visibility, the physical impact of the otter trawls on the seafloor is usually identified or mostly attributed to the otter boards (e.g., Hall, 1999). However, the disturbance capacity of the gear is not restricted to the area ploughed by the boards. During towing, most parts of the gear, such as sweep-lines, chains, ballast, footrope and its elements, and also the net and codend are also in contact (constantly or intermittently) with the seafloor (Rose et al., 2010). In fact, the sweep-lines (see Fig. 3) are intended to maximize sediment resuspension and in this way herd the fish toward the mouth of the net (Main and Sangster, 1981).

In comparison to other fishing techniques, the otter trawl can be considered as the main contributor to present-day trawling impacts at the global scale, at least in terms of spatial extent and particularly in the deep-sea (Benn et al., 2010). While beams and particularly dredges can produce more acute impacts, their use is mainly restricted to shelf and coastal seas and also the areas swept per unit time are lesser. Otter trawling on the other hand allows for bigger gears towed at higher speeds and, more important, it can access deeper, steeper and more rugged grounds not accessible by the other methods.

Technical measures to limit the impacts

With the increasing awareness of the impacts of trawling gear on the sea floor, certain measures have been taken to minimize its undesirable effects. Some of these measures aim to improve the selectivity of the fishing gear in terms of captured species and/or body sizes (e.g., [Catchpole and Revill, 2008](#); [Graham, 2010](#)). Other modifications have been introduced to limit seabed contact and the associated physical impacts. [Rose et al. \(2010\)](#) tested a modified otter trawl where sweeplines are raised over the seabed by means of disks, substantially decreasing the total area of contacted seafloor. Electric pulse devices coupled to beam trawls have been developed as an alternative to tickler chains to force targeted species out of the sediments and into the net while severely decreasing sediment churning and resuspension ([Yu et al., 2007](#)). [Sterling and Eayrs \(2006\)](#) developed a “Batwing” door to replace common otter boards. With this new door, the angle of attack is null and therefore the furrow and resuspension left behind by the doors is lesser. Other modifications introduced in bottom gear to minimize its impact on the seafloor are reviewed in [Linnane et al. \(2000\)](#), [Rose et al. \(2010\)](#) or [He and Winger \(2010\)](#).

A brief history of bottom trawling

The first reports of trawling fisheries date to the North Sea and Baltic beam trawlers used in the XIV Century ([Sahrhage and Lundbeck, 1992](#)). Until the XIX Century, bottom-dragged fishing gear as any other fishing activities were conducted by wind-propelled boats and hence their spatial range of action or the duration of fishing trips were very limited. Fishing industries underwent a quantum leap from the mid XIX century as a consequence of the Industrial Revolution in Northern Europe, from where mechanized trawling irradiated to the rest of the world. The introduction of steam engines was pivotal to increase the autonomy, towing power and depth range of fishing vessels, a trend further enhanced with the inception of the diesel engine in the 20th century. The first reports of steam-powered trawlers come from Arcachon (France) in the 1830s, with other industrialized countries such as UK or USA following in the 1860s ([Sahrhage and Lundbeck, 1992](#)). The rapid shift from rudimentary coastal trawling and dredging toward industrial fisheries in Europe was mirrored by other countries with variable delays. For example, the diesel engine was introduced to the Japanese fishing industry at the turning of the 20th century and followed by China few years later.

Sailing trawlers in Northern Europe were commonly restricted to work at depths <100 m. Steam engines, together with the introduction of preservation of fish in ice, allowed trawlers to grasp the entire continental shelf ([Sahrhage and Lundbeck, 1992](#)). Not less important in this offshore extension of trawling activities was the introduction of the otter trawl from the 1880s to 1890s, which considerably enlarged the areas accessible to bottom fishing ([Wardle, 1986](#)). Although steam engines remained in use long after the Second World War, its numbers in European countries decreased steadily during the first half of the century, replaced by diesel engines. Following improving technologies and the food demands of a growing world population, trawl fisheries experienced a rapid increase from the 1950s and particularly the 1960s off all six continents ([Watson et al., 2006](#)). For example, the URSS obtained until the 1950s most of its fish protein from inland waters, but in the decades to come the soviet fleets exploited marine demersal resources worldwide, a race shared by most industrialized nations ([Sahrhage and Lundbeck, 1992](#)). By the 1960s trawling fleets had extended their operations to virtually all continental shelves of the world ([Wardle, 1986](#)). It is worth to note that, even (or particularly) in those areas that had been

historically targeted by trawlers, like the southern and central North Sea, fishing intensity and benthic damage have dramatically increased from the 1960s and major alterations to ecosystems were already consummated by the 1980s ([Callaway et al., 2007](#)). From the 1970s mainly, a new phenomenon took place as trawling fleets began to shift from the traditional coastal and continental shelf grounds to the continental slope and beyond.

Displacement of trawling fleets toward the deep sea

Successive waves of technological innovation, such as improved freezing technologies, navigation aids or the installation of echosounders and radar to detect fish have fostered the offshore expansion of trawling fleets. A general decline of global catches has been apparent since the 1980s ([Watson and Pauly, 2001](#)), related to the exhaustion of many shallow traditional stocks, which has further contributed to push fishing fleets offshore in search of new fishing grounds. Also, the adoption of Exclusive Economic Zones (EEZ) by many coastal countries in 1977 represented a serious blow to overseas fishing powers like Japan, Germany, Spain or the URSS that lost the access to large portions of the world's continental shelves they used to exploit without restrictions. This measure further encouraged the development of vessels and engines capable of fishing regularly at greater depths in the high seas (i.e., beyond the 200 nautical miles from coastal baselines that EEZs embrace). Additionally, subsidies and grants offered by governments have been (and still are) an important incentive to the offshore expansion of trawling industries.

The first deep (>400 m) commercial trawling fisheries opened in the 1980s, mainly in the NE Atlantic, even though exploratory deep trawling had been conducted in previous decades ([Gordon et al., 2003](#); [Bensch et al., 2009](#)). In the next decades, deep trawling expanded toward many other regions of the global ocean (see Fig. 1 in [Puig et al., 2012](#)). New countries have been joining the deep-sea race in the 2000s as is the case of Mexico ([Gracia et al., 2010](#)) or Brazil ([Perez et al., 2009](#)). Nowadays, deep-sea trawling is active to depths well beyond 1000 m ([Roberts et al., 2006](#); [Cryer et al., 2002](#)) and depth ranges continue to expand ([Morato et al., 2006](#)).

The World Resources Institute ([WRI, 2000](#)) estimated a globally trawled surface area of at least 22×10^6 km², with 40% of the world trawling grounds located at depths beyond the continental shelf-break. A recent compilation of world trawling grounds on continental slopes has shed a conservative estimate of 4.4×10^6 km² worldwide ([Puig et al., 2012](#)).

Trawling recurrence

Together with its geographical extent and depth ranges, what makes trawling a major concern among other anthropogenic impacts is the frequency with which the seabed is disturbed. [Dorsey and Pederson \(1998\)](#) estimated that every square meter of the seabed is contacted by bottom-dragged gear once a year in the Gulf of Maine, and three to four times per year on Georges Bank. [Ball et al. \(1999\)](#) in the *Nephrops norvegicus* fishery in the NW Irish Sea estimated 5–10 times a year. [Rijnsdorp et al. \(1998\)](#) noticed that beam trawling effort in the North Sea can be very patchy, and heavily trawled areas (up to 5 times per year) can coexist closely with others non impacted or rarely visited. In the deep-sea, similar numbers have been reported: A study by [Friedlander et al. \(1999\)](#) in an area of 2700 km² extending over the continental shelf and upper slope off Northern California (200–600 m depth), documented that the seafloor was trawled up to 3 times and 1.5 times on average every year. [Cryer et al. \(2002\)](#) estimated that, in a scampi fishery on the upper continental slope off New Zealand (200–600 m depth), 2100 km² of seafloor were swept each year by trawlers.

Implications of the offshore expansion of trawling fleets

In general, shallow environments are characterized by intense sediment dynamics, propitiated by substantial sedimentary inputs from terrestrial sources and their subsequent remobilization due to the recurrent action of wind waves, tides and storms. This implies that impacts of trawling and dredging in these environments tend to be masked by natural processes (Dyckjaer et al., 1995).

Even though some deep-sea regions can experiment (whether sporadically or periodically), considerable levels of natural disturbance by the effect of, e.g., deep contour currents, benthic storms or density currents (Martín et al., 2010; Rebesco et al., 2014; Puig et al., 2014), the general rule is that hydrodynamics and sediment inputs tend to weaken with water depth and distance from the shore. In particular, beyond the reach of major storms (100–200 m depth), bottom sediments are for the most part subjected to a limited variability of physical conditions, resulting in high vulnerability and slow recovery rates from anthropogenic perturbations. Ecosystems that are infrequently disturbed by natural processes tend to have lower resilience under anthropogenic pressure (Kaiser, 1998; Collie et al., 2000) and the same can be said for the physical substratum itself.

Harbor dredging can be used as an illustrative example of the shallow water end member. Special ships (dredgers) are used to clean up the access to ports and harbors to facilitate maritime traffic. Harbor dredging can annually move enormous amounts of sediments but, the very fact that it has to be conducted periodically, demonstrates that its major morphological effects on the seabed are rapidly reversed by the forces of nature. On the other extreme, Bluhm (2001) disturbed a parcel of seafloor at 4000 m depth with a “plough-harrow” (a device intended to replicate the effects of a trawl gear) and documented with underwater cameras that the marks were still evident 7 years after the experiment.

Constantino et al. (2009) in a study of clam dredge impacts on shallow areas of southern Portugal found that the perturbations induced on the benthic environment scaled with the impact of surface waves. In a shallow estuary in Texas, Dellapenna et al. (2006) observed comparable concentrations of suspended solids 5 min after the passage of a shrimp trawl and after a 10 m/s wind event. But, in the NW Spanish continental slope at 1000 m depth, Martín et al. (2014a) have documented that trawling-induced resuspension largely outcompetes natural processes as the controlling factor of the temporal variability and magnitude of water column turbidity.

Since, in general, water depth and the level of physical disturbance upon the seabed are inversely related, it is generally assumed that artificial perturbations on the deep-sea floor leave more acute and long-lasting imprints with increasing water depth. Together with these considerations, it must be noted that the size and weight of trawling gear tend to increase with working depth, hence the strain imposed on the seafloor and the surface swept are likely larger per unit time and trawled distance in the case of deep-sea setups.

Trawling-induced sediment resuspension

It is worth to remind that sediment resuspension is not always an unwanted effect of trawling activities. In fact, bottom gears are often equipped with add-ons to maximize sediment resuspension as a means to “herd” the targeted animals toward the net (Main and Sangster, 1981). In the case of otter trawlers, the sweepnet (in occasions several hundred meters long), unless specifically modified to limit bottom contact, live up to their names and produce extensive resuspension as the gear is towed.

While measuring water turbidity in the New England continental shelf, Churchill et al. (1988) encountered anomalous near bottom patches of high turbidity that could not be readily explained by natural processes, since those events occurred under low energy conditions (weak currents and low waves). Records of fishing boat activity revealed that intense trawling occurred near the nephelometers at times when high turbidity was detected. Churchill (1989) applied a model of sediment resuspension by trawl doors and another model to elucidate the fate of the resuspended clouds of particles. He concluded that sediment resuspension by trawling could be a primary source of suspended sediment over the outer shelf of New England. On the wake of those early observations by Churchill et al. (1988) (and references therein), other authors have invoked trawling as the cause behind unresolved peaks in time series of water turbidity or downward particle fluxes measured with sediment traps (Puig and Palanques, 1998; Chronis et al., 2000).

Dellapenna et al. (2006) observed an increase in suspended matter concentrations in a shallow estuary, from a baseline of 25 mg/l to 350 mg/l measured 5 min after the passage of a shrimp trawl. Black and Parry (1999) measured up to 6 g/l within the first 20 s after the passage of a shallow water dredge. Dredging is likely the fishing technique causing the most dramatic resuspension events (Black and Parry, 1994, 1999) although there is a potential bias in such consideration if we take into account the typical shallow depths where dredging is active that has allowed for more frequent measurements of in situ suspended matter concentrations.

Over the inner continental shelf of the Gulf of Lions, Durrieu de Madron et al. (2005) observed otter trawling-induced bottom nepheloid layers (BNL) 3–6 m thick, with average suspended sediment concentrations (SSC) of 50 mg/l near the bottom. Palanques et al. (2001) measured SSC increasing up to 6 mg/l and BNL thickness up to 15 m after the passage of otter trawlers over the inner shelf off Barcelona. Increased turbidity in the water column persisted for 4–5 days after trawling ceased (Palanques et al., 2001).

Accounts of fishermen from the state of Maine (Doughty, 1998) speak of the progressive offshore displacement of the so called “mud line” (outer limit of highly turbid waters) over the years as a likely consequence of trawling and dredging activities. Similar observations were made by Caddy (1973) in the Gulf of St. Lawrence.

The evidences of such shallow-water studies on one hand, and the pervasiveness of trawling on the other, have slowly turned our view of bottom trawling, from a threat or a nuisance to investigations of the natural processes governing sediment dynamics in deep-sea regions, to an effective driver of continental slope sediment dynamics, to be considered in addition to natural processes.

Trawling-induced resuspension may not only influence locally or regionally the sediment and carbon budgets but also extend to larger contexts via lateral transport of sediments resuspended and advected from continental shelves and upper continental slopes to deeper regions. In heavily trawled areas, trawling has been proposed as a major feeder of the bottom nepheloid layer (Pilskaln et al., 1998), which can be subsequently transported by currents and tides (Schoellhamer, 1996).

Lateral advection of particles from continental margins has been proposed as a probable underestimated source that may help closing carbon budgets in the ocean (Burd et al., 2010). Bottom trawling, enhancing this lateral transport through sediment resuspension on continental margins, may thus become a contributor to global carbon cycling. Ferré et al. (2008) estimated that a third of the sediment export from the Gulf of Lions shelf to the continental slope was mediated by trawling-induced

resuspension. A 14-month study on the Ebro continental shelf evidenced that sediment resuspended by trawling is incorporated in the bottom nepheloid layer and transported across and along-shelf, being the resulting sediment transport five to nine times higher than during periods without trawling (i.e., during the closed season) (Palanques et al., 2014).

An important component of suspended sediment transport is the net current integrated over time. Fluctuating currents such as tides tend to promote a limited transport. Palanques et al. (2001) noted that the effect of trawling in the Barcelona inner shelf was mainly localized around the trawling tracks, due to a very low net resultant of the local currents. Black and Parry (1999) measured concentrations of suspended sediments 3 orders of magnitude higher than the baseline in the wake of a dredge, but in only 30 min the concentrations were comparable to pre-dredge levels.

As it has been listed above, attempts to quantify the resuspension and redistribution of sediments caused by commercial trawling have been mostly localized in coastal environments and the continental shelf. Trawling at slope depths may have more profound effects on sediment resuspension and relocation because these parts of the continental margin tend to act as depocenters of fine grained sediments. Also, steeper bathymetries can promote the downslope excursion of resuspended sediments in the form of gravity flows (Palanques et al., 2006).

Sediment gravity flows triggered by trawling activities

Paull et al. (2003) suggested that sediment gravity flow events in submarine canyons do not require exceptional triggering events. In fact, low-energy, frequent sediment gravity flows occur in some submarine canyons and constitute a major process of across-margin sediment transport (Puig et al., 2014). Trawling-induced resuspension on steep slopes can also produce a gravity flow owing to the additional density contributed by suspended particles to the ambient fluid. Palanques et al. (2006) provided for the first time an evidence of sediment gravity flows triggered by fishing activities in La Fonera (Palamós) submarine canyon. A turbidimeter and a current-meter deployed near the seafloor at 1200 m depth in the canyon axis registered short-lived peaks of current speed and high water turbidity simultaneously, suggesting the passage of sediment gravity flows. The direction measured by the internal compass of the current-meter indicated that these flows advanced from a tributary (Montgrí gully) incised in the northern canyon flank, where a trawling fleet operates from 400 to 850 m depth. Log-books provided by local fishermen revealed that the passage of trawlers by the tributary fitted with the occurrence of the gravity flows recorded in the canyon axis. Ten years after the study by Palanques et al. (2006), a moored line equipped with a downward-looking ADCP and a chain of turbidimeters was deployed within the Montgrí Gully at a depth of 980 m, still 100–200 m below the depth range of trawling activities. This new dataset revealed frequent sediment gravity flows occurring during weekdays at working hours of the local trawling fleet (Puig et al., 2012; Martín et al., 2014a). Fig. 4 depicts two of these events during 21 June 2011. Such trawl-induced sediment gravity flows reached maximum downslope velocities of up to 38 cm/s and concentrations of more than 200 mg/l 5 m above the bottom. Instantaneous sediment fluxes up to 34 g/m² s were calculated. Sediment transport integrated in the first 50 m above the bottom yielded a minimum of 5.4 × 10³ tons of sediment exported from the fishing ground in 136 days of deployment (Puig et al., 2012). The plumes of resuspended sediment measured in the Montgrí Gully extended to at least 100 m above the bottom (Fig. 5). After the end of the working day of the local fleet (around 14 h), water turbidity faded slowly

toward background levels ~2 mg/l. A CTD (equipped with a turbidimeter) transect traversing the main fishing ground after the end of a working day documented the formation of intermediate and nepheloid layers and their excursion from fishing grounds (Martín et al., 2014a). In the neighboring Blanes submarine canyon where the same type of fishery is active, nepheloid layers have been also observed detaching from the canyon flanks (Zúñiga et al., 2009) at the depths exploited by trawlers.

Some consequences of artificial increases in water turbidity

In shallow environments, high turbidity may reduce light availability, thus hampering photosynthesis in aquatic ecosystems (Caddy, 2000). By disturbing the seabed, trawling may as well release contaminants stored in sediments or toxic algal cysts. Brown et al. (2013) claimed that bottom gears can trigger harmful algal blooms by resuspending dormant cyst and spores of problematic species. Resuspension of anoxic sediments can be lethal for some species (Yamamoto, 1960).

The downslope propagation, via sediment gravity flows or nepheloid layers, of trawling-induced resuspension from fishing grounds to deeper locations opens intriguing questions about the true extension of trawling impacts and about the best procedures to define marine protected areas or maximum working depths. High levels of turbidity caused downslope from the trawl grounds can cause problems to organisms adapted to clearer waters. For example, the resettlement of resuspended particles in quiescent seafloors may smother suspension feeders, or difficult the fixing of mollusk larvae on hard surfaces (Jones, 1992 and references therein). Enhanced concentrations of resuspended particles resulting from trawling activities may as well affect dissolved oxygen contents in the water column (Riemann and Hoffman, 1991).

Impacts on sediment accumulation rates, physical properties and carbon budgets

Sediment accumulation rates

If, as seen in previous paragraphs, sediments are resuspended by trawling gear and under certain conditions exported to other (generally deeper) locations, the next questions to pose is where do the advected particles resettle and if this artificial redistribution of sediments can define erosion and net deposition areas distinguishable above natural baselines. Very little literature exists on this particular subject.

The ²¹⁰Pb technique has proven an excellent tool to obtain sedimentation rates and chronological models in continental shelves and slopes. The time span of the ²¹⁰Pb method is in the range 100–150 years, hence well suited to Anthropocene studies. Interpreting ²¹⁰Pb data is not always an easy task as many factors can contribute to produce the particular shape of a ²¹⁰Pb vertical profile. Some authors have considered trawling as a possible cause for observed deep mixed layers or truncated profiles (e.g., Erlenkeuser and Pederstad, 1984). However, this mixing/eroding mechanism may have been overlooked too often and it is possible that some ²¹⁰Pb data interpretation would benefit from being revised taking into consideration the effects of bottom trawling on sediment mixing, erosion and accumulation.

Martín et al. (2014b) analyzed ²¹⁰Pb in sediment cores collected at trawled and untrawled sites at ~500 m depth along the flanks of La Fonera Canyon. At the untrawled sites, excess ²¹⁰Pb inventories were high and the vertical profiles exhibited a three-layered vertical profile characteristic of depositional systems, including a 5–10 cm topmost bioturbated layer of very low density, a region

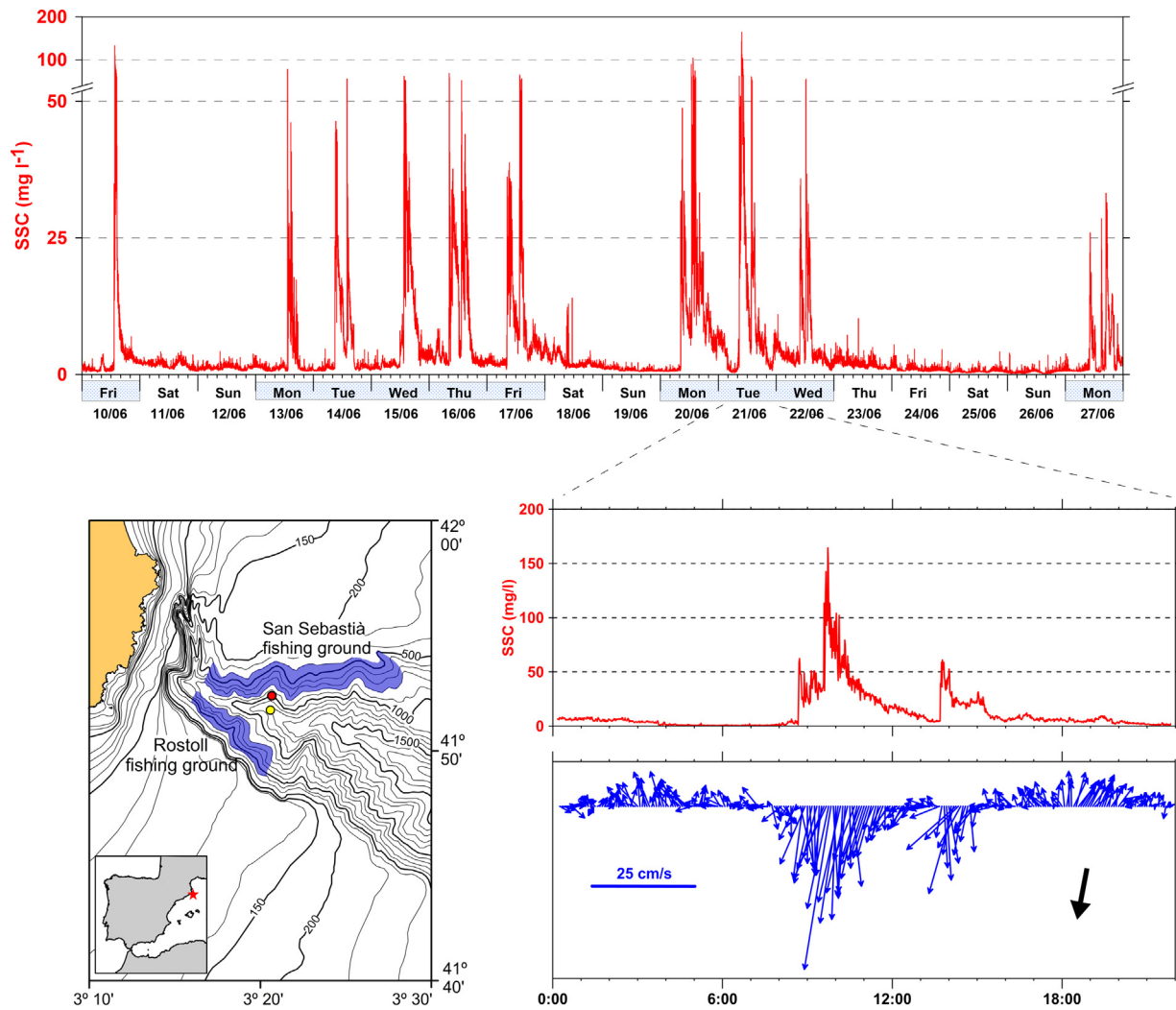


Fig. 4. Top: Selected time series of suspended sediment concentration (SSC) measured at 12 m above the bottom (mab) in a tributary of La Fonera (or Palamós) submarine canyon in the NW Mediterranean (bottom left) during 2011. Working days of the local trawling fleet are marked in the timeline (see Martín et al., 2014a for details). The map shows the location of the mooring line deployed in the Montgrí Tributary (red) and another mooring (yellow) deployed previously in the canyon axis where diluted sediment gravity flows were observed (Palanques et al., 2006; see the text for details). Blue patches over the bathymetry indicate the main otter trawl grounds on the canyon flanks. Bottom right: Current speed vectors at 5 mab and SSC at 12 mab during 21 June 2011. The black arrow represents the main direction of the tributary (191°).

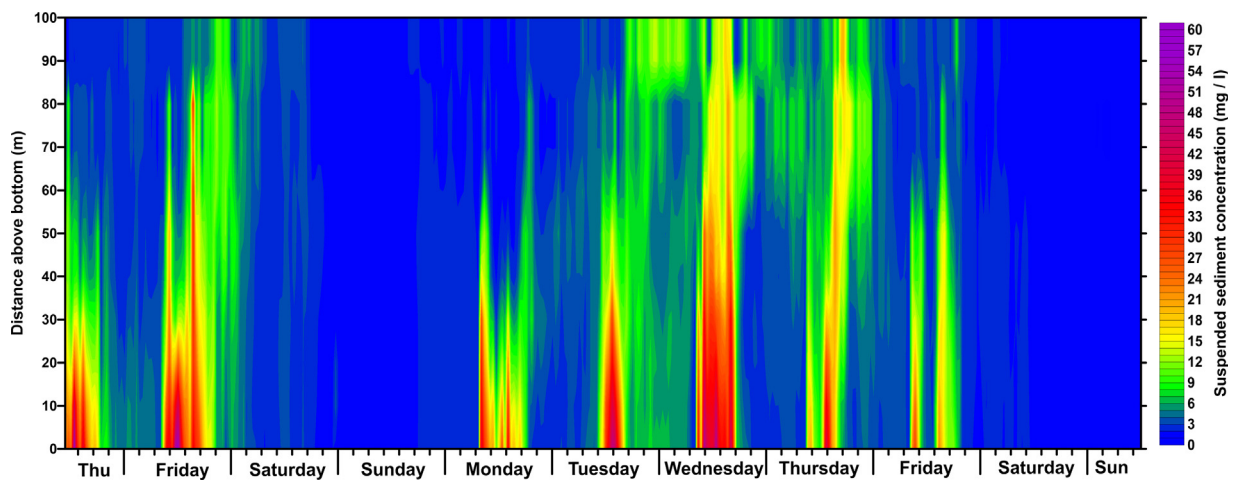


Fig. 5. Interpolated contours of suspended sediment concentration data measured by turbidimeters at 5, 10, 15, 20, 25, 30, 40, 50, 70 and 100 m above bottom in a mooring line deployed in the Montgrí gully (see Fig. 4 for location), from 1 to 11 July 2010.

of exponential ^{210}Pb decay and increasing dry bulk densities with depth and a deep layer of constant (supported) ^{210}Pb concentration. At most sites on trawling grounds, ^{210}Pb inventories, surface concentrations and vertical profiles showed evidence of erosion or thorough mixing. The topmost sediments poorest in excess ^{210}Pb were also very dense and compacted, a fact explained by Martín et al. (2014b) as the uncovering of long-buried, old sediments by sustained erosion of the overlying sediments. Sediment compaction as a direct consequence of trawling strain has also been proposed by Lindeboom and de Groot (1998).

In 2002, a sediment core was collected in the La Fonera Canyon axis (1750 m depth) and dated with ^{210}Pb and ^{137}Cs . The obtained radio-chronologies documented a doubling of the sediment accumulation rate in the 1970s, in coincidence with a change in the sediment structure from bioturbated to laminated and with a dramatic increase in installed engine power of the local trawling fleet (Fig. 6; Martín et al., 2008). The lower La Fonera Canyon could be thus acting as a depocenter where the sediments eroded in the flanks have been accumulating in recent times. A noteworthy precedent to the study by Martín et al. (2008) can be traced in Sánchez-Cabeza et al. (1999), where radionuclide dating was conducted in the continental shelf and slope off Barcelona. In that study, a doubling of the ^{210}Pb -derived sedimentation rate is apparent at all slope coring stations as well as inside the adjacent Foix Canyon, while sedimentation rates had decreased on the shelf stations at comparable time horizons, which could suggest a relocation of sediments from shelf depocenters to deeper areas during the last century.

Sediment sorting

A possible effect of trawling is the sorting of sediment grains as they are repeatedly resuspended and the lighter fractions more easily advected with water currents while heavier particles tend to settle back. This process is termed winnowing and its result is the progressive coarsening of top sediments. This effect has been observed in sediment cores from trawled grounds of the Mediterranean continental shelves (Ferré et al., 2008; Palanques et al., 2001, 2014) as an upward increasing trend in grain size. Other authors (e.g., Bhagirathan et al., 2010) found a stronger natural control on sediment grain size masking any effect from trawling. The original sediment grain size distribution of a given location is an important factor determining the significance of

winnowing. In sand-dominated bottoms off Newfoundland, Schwinghamer et al. (1998) could not detect any influence of trawling on sediment texture. Sediment sorting was also noted at some coring stations along the trawled flanks of La Fonera Canyon. Topmost coarse sediments with detectable excess ^{210}Pb were underlain by stiff mud depleted in excess ^{210}Pb , which was explained by Martín et al. (2014b) as a bed armoring process.

Implications for organic carbon budgets

An expected primary effect of sediment mixing induced by trawling is the increase of the penetration depth of oxygen thus promoting increased levels of carbon remineralization. Decreased organic carbon contents in surface sediments of trawled grounds compared to neighboring untrawled areas have been observed for example in Georges Bank (Guida et al., 2002) or the Veralal coast of India (Bhagirathan et al., 2010). Added to the effect of increased oxygenation, winnowing caused by trawling-induced resuspension may also contribute to the loss of sedimentary organic carbon, given its usual association to the finer grain size classes (Guida et al., 2002).

However, increased surface organic carbon content after the passage of trawling gear has been reported in the Thermaikos Gulf by Pusceddu et al. (2005), and Palanques et al. (2014) has documented upward increasing trends in organic carbon in trawled grounds of the Ebro shelf.

The disturbance of bottom sediments by trawling gear has been compared by Duplisea et al. (2001) to “an extreme bioturbator” that introduces large instabilities in benthic function. While some gear elements only produce scapping and resuspension of topmost sediments, penetrative gear elements such as rakes, otter boards or tickler chains can produce a deep overturning of the sediment column. As sediment layers are vertically relocated and/or mixed, different effects may result, hence the discrepancies in the literature. On one hand, surface organic-rich sediments can be buried deeper, resulting in an enhancement of anaerobic respiration as well as a removal of labile carbon from the aerobic compartment (Mayer et al., 1991). On the other, sedimentary carbon accumulated in deeper layers can be uplifted, thus increasing organic carbon contents at the surface (Pusceddu et al., 2005). Mayer et al. (1991) considered dredges, among bottom gear types, as having the greatest impact on the vertical distribution of sedimentary carbon.

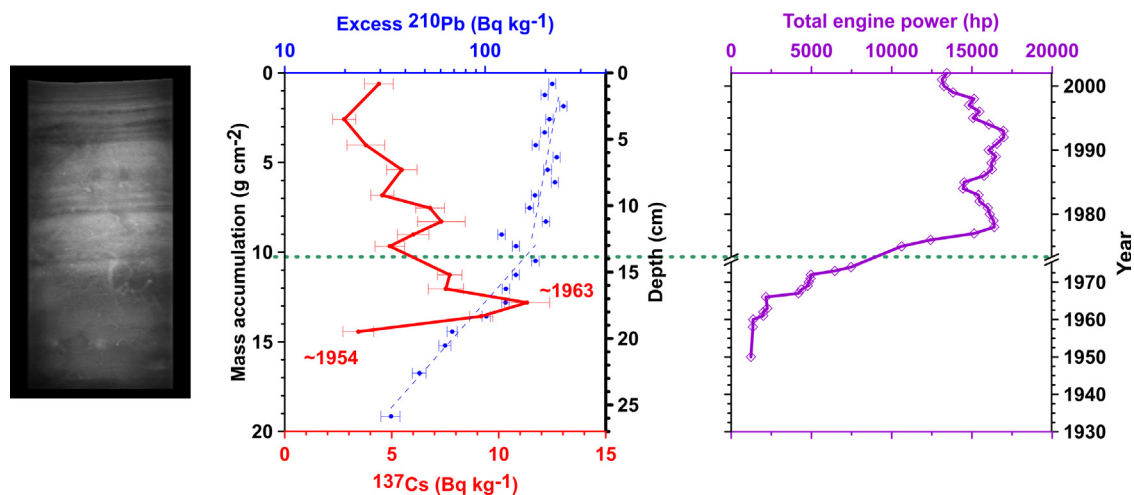


Fig. 6. X-radiographs, excess ^{210}Pb (half-life 22.3 years) and total ^{137}Cs (half-life 30.2 years) activity profiles of a sediment core collected at 1750 m depth from the axis of La Fonera Canyon. The historical evolution of total engine power installed in the local trawling fleet is also shown. Modified from Martín et al. (2008).

Another explanation that has been invoked (e.g., Palanques et al., 2014) to account for higher organic carbon contents at trawled sediments is the possible fertilization brought about by resuspension in shallow environments. Nutrient release from resuspension of sediments by natural causes has been signaled as an important contributor to primary productivity in certain regions (Fanning et al., 1982). As benthic chemical fluxes and storage at the sediment–water interface are severely affected by trawling-induced sediment stirring (Duplisea et al., 2001 and references therein), the turn-over of nutrients vital to photosynthetic plankton might be accelerated as well. In shallow waters, these nutrients released from sediments would easily reach the euphotic zone and trigger phytoplankton blooms (Brylinski et al., 1994; Dounas et al., 2007).

In spite of discrepancies in the published literature about the short- or medium-term impact of trawling on carbon contents, the expectable long-term result of repeated and vigorous sediment mixing is a general impoverishment in organic carbon, given that remineralization is most efficient when sediments are subjected to alternating cycles of aerobic and anaerobic conditions (Hulthe et al., 1998).

de Haas et al. (2002) conducted an assessment on the capacity of continental shelves to preserve organic carbon. Their conclusion was that much of the surface on present day shelves acts as a poor sink for organic carbon and that most modern accumulation is taking place at deeper locations on continental slopes or in depressions such as canyons. Few studies on trawling impacts on sedimentary carbon exist on these deeper environments.

Martín et al. (2014b) and Pusceddu et al. (2014) have documented a notable impoverishment of organic carbon in the upper 0–40 cm of the sediment column at 500 m depth in the trawled flanks of a submarine canyon, a fact these authors related not only to mixing but primarily to the chronic denudation of recent sediments by the sediment flows triggered by trawling gear (see previous section). Sañé et al. (2013) observed in the same sediments a degradation of the nutritional value of sediments, in particular regarding the content of amino acids.

Bottom trawling as a driver of seascape evolution

Biogenic habitats

Large biogenic seascapes owe their structure to one or a few dominant sessile species that provide a three-dimensional frame to highly diversified ecosystems. Some examples are sea-grass meadows, kelp forests, sponge fields or coral reefs. The first two are restricted to coastal areas, and are increasingly protected from trawling activities.

In particular, coral reefs are structurally complex habitats that foster one of the highest degrees of spatial heterogeneity, and also offer refuge and nursery areas to commercially exploited species. In recent years, a wealth of previously unknown cold water corals has been found on seamounts and along the continental slope throughout the global ocean. In these environments, reefs are very vulnerable to external disturbances such as bottom trawling (Hall-Spencer et al., 2002; Fossa et al., 2002; Murray Roberts et al., 2006). The fact that their existence was virtually unknown until recently and that their actual distribution is still a matter of debate, testifies to the lack of protection they have suffered during the first decades of commercial deep-sea trawling.

A paradigmatic case is the coral *Lophelia pertusa*, which is widely distributed in the NE Atlantic from the Arctic to Spain. Coral reefs of *Lophelia* can reach heights up to 45 m and form patches of several kilometers in diameter (Gianni, 2004 and references therein). Large areas of *Lophelia* reef off Norway and the Faeroe Islands are already severely damaged (Hall-Spencer et al., 2002).

The heavy trawling gear used offshore can easily break or grind to fine rubble a millennial coral reef in a few hauls. A single haul of a research trawl at 360 m depth in the Gulf of Alaska removed about 900 kg of red tree coral (Krieger, 2001). The consequences to the seascape are comparable to the sudden removal of the three-dimensional structure of a forest, leaving instead a carpet of wood chips overlying a naked soil. For corals, the situation is aggravated by the fact they have much lower growth rates (a few cm/y) than trees do. Radiocarbon dating of coral fragments captured in the range 800–1300 m off Ireland by trawling nets has shed ages of more than 4000 years BP (Hall-Spencer et al., 2002). Similarly, ages up to 8500 years have been obtained from coral reefs in the Sula Ridge off Norway (Gianni, 2004). The perspectives of survival for damaged coralline grounds are even darker when other human-derived threats such as ocean acidification, are considered in combination. In seamounts around Tasmania, Althaus et al. (2009) reported a 3-fold decrease in the diversity and density of megabenthos associated to corals after these were damaged by trawlers.

A general effect of trawling, whatever the modality, is the preferential removal of erected, sessile, biogenic structures and large, long-living macro- and megafauna (Reise, 1982; Smith et al., 2000; Jennings et al., 2001; de Juan et al., 2007). In this consideration, not only large coral formations are relevant since crustaceans, mollusks or echinoderms also provide spatial complexity and define habitats richer in emergent structure than flat trawled soft bottoms.

Soft sedimentary bottoms

The impact of fishing on biogenic substrata, particularly deep-sea corals, has become in recent times the epitome of collateral damage on deep-sea habitats caused by trawling, due to the higher profile of coral reefs in public opinion (e.g., Revkin, 2000). Nonetheless, abiotic (sedimentary and rocky bottoms) largely dominates the global ocean in terms of surface. In particular, soft muddy bottoms account for the largest portion of the global seabed and therefore constitute the largest biome on Earth. These muddy seascapes, once considered ‘deserts’ with limited abundances and diversity of fauna, are now recognized as diversified ecosystems (Snelgrove, 1999). Rocky bottoms will not be considered here since these are less prone to be affected in its basic relief by bottom gear and, in fact, fishermen tend to avoid dragging their nets along them.

On short spatial and temporal scales, different bottom gears generate different traces of their passage over muddy ground. Dredges have been alternatively reported to flatten seafloor features and leave deep trenches. Bulldozing rakes like those used to harvest scallops, when operated in a heterogeneous mixture of different sediment grain sizes, have the effect of roughening the bottom due to the uncovering of boulders and gravel embedded within the fines (Caddy, 1973). Beam trawlers tend to flatten the seafloor, leveling off ripples, bioturbation holes and mounds, sand waves and other bed forms. In the deep-sea, where muddy bottoms prevail and otter trawling is the leading fishing method, the expected result of chronic trawling is a homogenization of the small scale relief caused by sweeplines and ground gear, criss-crossed by deeper tracks imprinted by the otter boards. Modern awareness of such changes is often restricted to otter track marks, given its relative visibility. Trawl marks are better preserved in mud than in sandy sediments. Fauna in sandy environments is also less affected by trawling impacts than in muddy or biogenic sediments (Collie et al., 2000; McConnaughey et al., 2000). Along numerous continental shelves and slopes of the world, a dense tapestry of overlapped otter trawl marks is the most evident morphologic feature observed by multi-beam and side scan sonar

surveys or underwater video recording (Krost et al., 1990; De Alteris et al., 1999; Friedlander et al., 1999; Palanques et al., 2014). Acoustic surveys have spotted otter trawl tracks from the continental shelf to 1400 m depth along the Northeast Atlantic continental margin off Scotland, Ireland and Norway (Fossa et al., 2002; Roberts et al., 2006).

However, the net, long-term effect of repeated trawling or dredging over the same spots is, in all cases, a general flattening and homogenization of the seafloor relief, whether biogenic or abiotic. Flattening of the seafloor microtopography caused by passing gears was noticed since long by means of underwater photography (e.g., Smith et al., 2000), but trawling can indeed cause changes at larger spatial scales.

Concerns on the modification of the seafloor morphology by trawling are almost as old as trawling itself (de Groot, 1984). In the 1970s, French scientists observed that in sheltered bays of Corsica the bottom topography had dramatically changed after being visited by heavy trawlers (de Groot, 1984).

A fisherman from New England gives an enlightening account on the capacity of heavy bottom gears to modify the topography over spatial scales larger than the gear elements. Bennett (1998) describes the bottom relief of a fishing ground well known to him for 30 years as rows of hills 15 m high. He had to temporarily discontinue his activity there due to the opening of that sector to large bottom trawlers and scallop dredges. When he came back two years later, the echo-sounder revealed an unrecognizable relief, in short: “those hills were gone” (Bennett, 1998). Concomitantly, captures were poor, suggesting that the reshaped seafloor was no longer suitable for the once rich stocks of fish and seafood.

Analysis of high-resolution multibeam data in La Fonera submarine canyon (Puig et al., 2012) revealed a noticeable smoothening of the northern canyon flank at depths less than 800 m. The fact that the lower limit of the smoothed bathymetric range coincided with the maximum trawled depths reported by the fishermen operating in the area, pointed to trawling as a potential seafloor shaping agent within this depth range. Concurrent analysis of satellite-based navigation tracks of bottom trawlers showed a striking spatial coherence between active trawling grounds and the smoothed areas. Puig et al. (2012) documented the transformation of a dendritic network of tributaries with up to 5 orders of bifurcation into a smoothed seafloor relief due the repeated sediment erosion and stirring by trawling gear, acting along the canyon flanks on a daily basis and over several decades. Although sediment gravity flows were active in the canyon flanks and the sediments showed evidence of sustained erosion (Martín et al., 2014b), Puig et al. (2012) concluded that the flattening of the seafloor at large spatial scales was not only the result of erosion but the net result of chronic sediment displacement, erosion, stirring, resuspension and resettlement of particles over the years, altogether contributing to blur and homogenize the original morphology of the seascape.

As above, so below: the deep-sea and the Anthropocene

Unlike the major anthropogenic changes that terrestrial and coastal habitats underwent during the last centuries such as deforestation, river engineering, agricultural practices or urbanism (Hooke, 2000; Price et al., 2011), those occurring underwater are veiled to our eyes and only recent advances on remote sensing and deep sampling technologies are beginning to reveal the extent and magnitude of anthropogenic impacts on the seafloor.

Repeated stirring, homogenization and erosion/oxygenation of surface sediments leads to a progressive cascading of detrimental effects. A succession takes place from the most fragile and complex biogenic biomes to less structured habitats where scavengers and

small-sized infauna, such as polychaetes and nematodes, dominate (Jennings et al., 2001). But probably that is not the last step in the descending ladder of homogenization. In heavily trawled areas on the flanks of the La Fonera Canyon, Pusceddu et al. (2014) documented a decrease in abundance and diversity of the meiofauna, in particular nematodes, due to the chronic stirring of the sediment column and the erosion of topmost sediments containing labile organic matter.

The evolution of marine biogenic seascapes under chronic trawling pressure can be schematized in two major steps. First, the three-dimensional structure above the bottom (provided by epifauna, large macrofauna or bioturbation mounds) is removed and substituted by a fine-grained bottom with much less abundant sessile organisms sprouting from the seabed and in general a less complex spatial structure. This transition could be compared with the transformation of a forest into a wasteland or a field of weeds (Watling and Norse, 1998). Next, the soft bottom is in turn plowed repeatedly and as a consequence the inner three-dimensional structure of the sediments is also altered. The sediment column is progressively mixed, homogenized and oxygenated, thus limiting its capacity to retain organic matter. This second step can be compared with the transformation of the former forest (now a plain of grasses and weeds) into a ploughed crop field (Puig et al., 2012).

Many deep-sea fisheries are hardly sustainable in the long term given that deep-sea animals are in general long-lived, slow growing and mature at an advanced age, all of which translates into low turn-over rates and, ultimately, living resources whose long-term sustainable exploitation is irreconcilable with current management practices (Koslow et al., 2000; Clark, 2001; Glover and Smith, 2003). Although many demersal fisheries (particularly deep-sea fisheries) have collapsed rapidly, others seem to endure in spite of sustained fishing effort. Those collapsing more rapidly belong to long-lived and slow-growing species that are associated to complex biogenic seascapes (Clark, 1999). Once removed their fragile habitat, they follow the same fate. Other deep-sea animals like certain shrimps are more resilient and adapted to less structured habitats such as muddy bottoms. An example is the fishery for the deep blue and red shrimp (*Aristeus antennatus*) in the NW Mediterranean, which has been heavily fished for at least 70 years and still sustains good levels of commercial productivity (Demestre and Martín, 1993). Due to their mobility and foraging habits, these species can partly benefit from the trawling activity, which acts as to unbury infauna and kill or harm benthos, thus offering easy preys to the scavengers and small predators. Caddy (1973) documented with underwater cameras how predatory fish and crabs were attracted to the tracks left behind by dredges and gathered on them at much higher densities than outside tracks. Malakoff (1998) commented on one of these ‘paradoxes’: in certain grounds of the North Sea, chronic trawling has wiped out much of the sessile benthos such as anemones or sponges, but the Dover sole, a flat-fish, seems to be relatively comfortable in this modified – flatter – habitat. We could say that these ecosystems have been prompted to a new equilibrium: a degraded stable state (Suding et al., 2004).

Some positive feed-backs seen in modified lands, as for example the increased likelihood of erosion of the fertile soil following wildfires or agricultural practices can also be found in the seafloor under human pressure. In a similar way as soils, the sediment column of marine soft bottoms partly owes its cohesion to a bio-mineral fabric that bounds together sediment grains. The critical shear stress for sediment resuspension has been observed to be inversely related to the frequency of resuspension (Churchill et al., 1994). Sediments may thus lose cohesiveness by intense stirring and shaking by trawling gear. In fact, Schoellhamer (1996) observed that sediments resuspended by trawling, once newly

deposited are more susceptible to resuspension by trawling or natural causes than undisturbed bottom sediments.

Koslow et al. (2001) sampled with a dredge seamounts where the highly priced orange roughy has its habitat, and found that 24–43% of the invertebrates collected were undescribed species. These high degrees of endemism (and fragility) has led deep-sea biologist to realize that many benthic species will be extinct before we even suspect their existence. Likewise, we could argue that the deep seabed may undergo substantial morphological changes before we are even able to map it conveniently. In other words, we could be, at present, mapping recently altered deep-sea reliefs in the belief that their shape is the result of longer-term natural processes. The same may apply to budgets of carbon and other elements.

Conclusions

Anthropogenic disturbance of benthic systems by bottom fishing gear has increased dramatically after the Second World War and these impacts have continuously extended to the deep-sea since the last 40 years.

The impact of bottom trawling on the seafloor depends on substrate and gear type. A third major factor is the level of natural disturbance in a given location, which is, in general, strongly tied to water depth. In highly dynamical environments, like those typical of shallow bottoms, natural processes tend to mask or hamper the anthropogenic effects, while on the deep-sea, the effects of artificial sediment resuspension, stirring and plowing can be disproportionately high compared to natural baselines, resulting also in long-lasting effects for both the abiotic and living components of the seabed. The continuous offshore expansion of trawling activities can thus result in durable impacts on the deep seafloor.

Chronic trawling in low energy environments promotes a general homogenization of habitats, causing significant loss of bio- and geodiversity.

The chronic stirring, mixing, erosion and oxygenation of sediments induced by recurrent trawling produce durable changes in the physical properties of sediments (grain size, cohesiveness, density) and may cause as well an impoverishment of the content and quality of sedimentary organic matter.

Trawling-induced resuspension can make substantial contributions to water turbidity and feed nepheloid layers. Furthermore, trawling over steep slopes can trigger sediment gravity flows and in this way affect larger (and deeper) areas than those within fishing grounds. The subsequent redistribution of sediments can result in the denudation of recent sediments in certain areas and the apparition of newly formed depocenters in others.

Commercial bottom trawling has become a force capable of rivaling natural processes as a driver of sediment dynamics in continental margins and may ultimately lead to large-scale changes of the seafloor morphology.

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