

## RESEARCH ARTICLE

# The imprint of microfibres in southern European deep seas

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## Abstract

Pollution of the marine environment by large and microscopic plastic fragments and their potential impacts on organisms has stimulated considerable research interest and has received widespread publicity. However, relatively little attention has been paid to the fate and effects of microplastic particles that are fibrous in shape, also referred as microfibres, which are mostly shed from synthetic textiles during production or washing. Here we assess composition and abundance of microfibres in seafloor sediments in southern European seas, filling gaps in the limited understanding of the long-range transport and magnitude of this type of microplastic pollution. We report abundances of 10–70 microfibres in 50 ml of sediment, including both natural and regenerated cellulose, and synthetic plastic (polyester, acrylic, polyamide, polyethylene, and polypropylene) fibres. Following a shelf-slope-deep basin continuum approach, based on the relative abundance of fibres it would appear that coastal seas retain around 33% of the sea floor microfibres, but greater quantities of the fibres are exported to the open sea, where they accumulate in sediments. Submarine canyons act as preferential conduits for downslope transport of microfibres, with 29% of the seafloor microfibres compared to 18% found on the open slope. Around 20% of the microfibres found had accumulated in the deep open sea beyond 2000m of water depth. The remoteness of the deep sea does not prevent the accumulation of microfibres, being available to become integrated into deep sea organisms.

## Introduction

Although already mentioned in the published literature in the early 1990s [1], the term microplastic has been increasingly used since 2004 to describe plastic particles of a few mm in size in the marine environment [2]. Microplastics derive from fragmentation of larger plastic items entering by rivers, sewage, beach littering, runoff, tides and winds [3, 4], and also by direct release of small particles such as plastic pellets [5], cosmetic microbeads [6] and clothing microfibres [7]. Plastic has been released to the marine environment since the 1930s, and is now ubiquitous in the oceans. Plastic debris have been reported in surface and subsurface waters [8, 9, 10], in the seafloor from the shoreline [11, 12] to the deep sea [13, 14] and in polar

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ice caps [15]. The accumulation of microplastics in the marine environment, and the many questions concerning their distribution and implications for marine wildlife and human health, has recently raised public awareness. Intensive research on this topic has resulted in a rapidly increasing number of publications (see for instance [16]). Consequently, policy recommendations have been provided too to tackle this emerging environmental problem (e.g. [17]).

Microfibres are among the most prevalent type of microplastics observed in the marine environment [11, 18]. However, despite microfibres are highly visible, brightly colored and stand out against fine grained sediments or marine aggregates, only a few studies dealing specifically on plastic microfibre pollution in the marine environment have been published to date. Synthetic (polyester, acrylic, polypropylene, polyamide) microfibres may be entering the ocean via wastewaters [11, 19, 20] and atmospheric fallout [21], and have been found in surface waters [22, 23], sea ice [15] and in coastal [24, 25, 26] and deep water sediments [14, 27]. It has been already shown that microfibres are ingested by pelagic [28, 29, 30] and benthic coastal organisms [25, 31, 32, 33]. The recent discovery of microfibre ingestion and internalization by deep-sea organisms in a natural setting by [34] has underlined the need to quantify of this human waste in the deep marine environment.

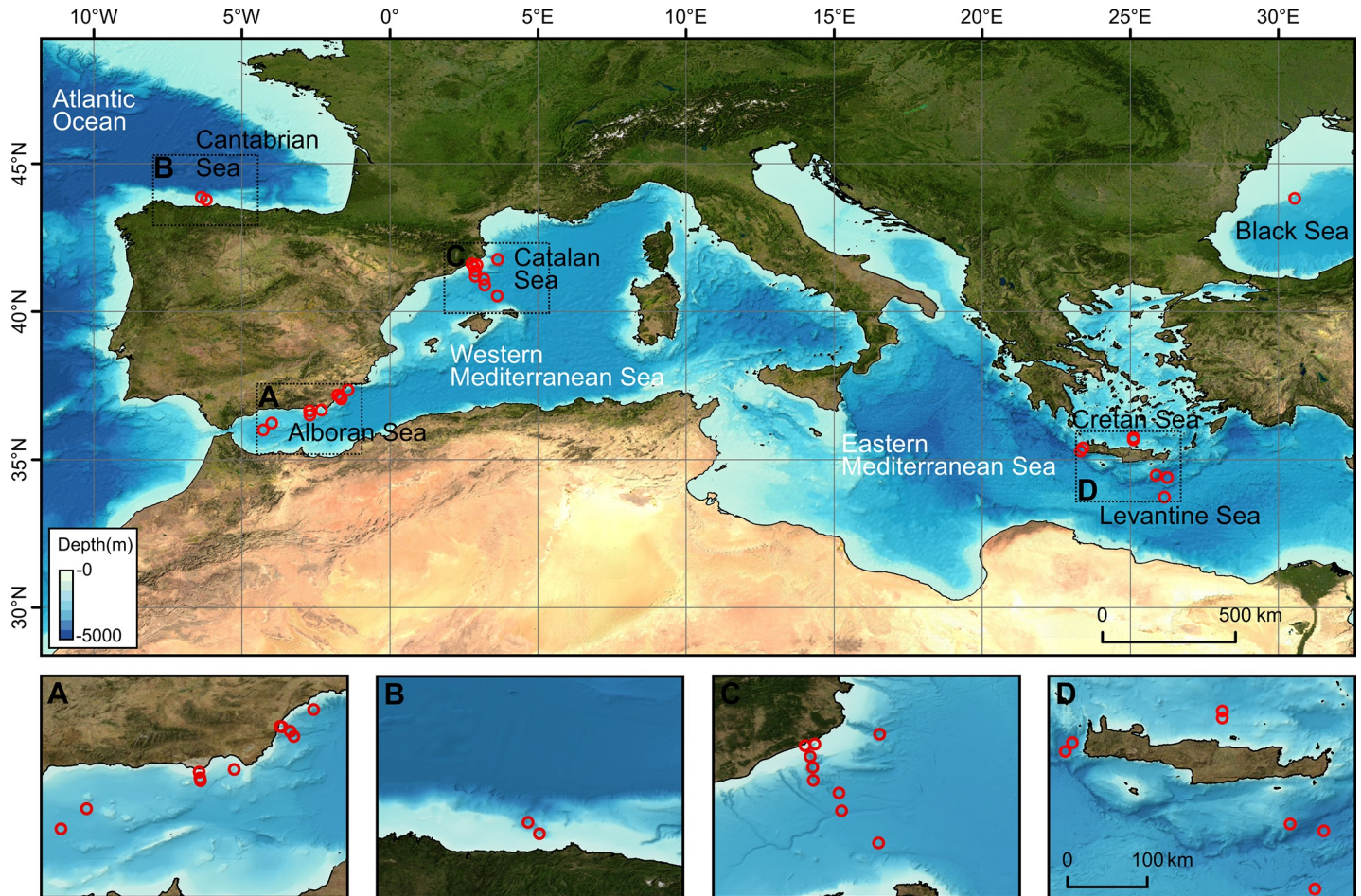
Given the particularly high concentration of microplastics found in surface waters of the Mediterranean Sea [35, 36], microfibre quantification in sediments is required to confirm or dismiss the relative importance of the deep sea as a microplastics sink. Indeed the landlocked character and limited outflow of surface waters of the Mediterranean Sea, its densely populated coastline including seasonal tourist peaks and intensive fishing, shipping and other industrial activities, made it candidate to be the sixth great floating microplastic accumulation zone after the five subtropical gyres [35, 37]. Here we present new data on the distribution of plastic microfibres after a widespread survey of seabed sediments in southern European seas including the northeast Atlantic Ocean (Cantabrian Sea), the Mediterranean Sea (Alboran Sea, Catalan Sea, Cretan Sea and Levantine Sea) and the Black Sea at depths from 42 m at the continental shelf to 3,500 m in the abyssal plain (Fig 1). Such a wide depth range allowed investigating patterns of microfibre distribution along the coastal-deep sea continuum.

## Materials and methods

Seabed sediment samples were obtained using either a multicorer or a Van Veen grab at 29 stations in the southern European seas (Fig 1) during 10 oceanographic cruises, from 2009 to 2015. Once on deck, the first cm of each core/grab sample was immediately subsampled to minimize exposure to the air and stored in a clean aluminium container or a polyethylene zip-lock plastic bag and kept in a cold dry place. No specific permission was required for collecting the sediment samples for this study, as most of the activities were carried out in waters beyond national jurisdiction, except for some shallower continental shelf stations, where appropriate permissions were inherent to research projects funded by the Greek and Spanish governments. None of the field studies involved endangered or protected species.

Microfibre extraction was performed in the designated clean Microplastic Laboratory at the University of Plymouth. The laboratory was thoroughly cleaned daily, access restricted and 100% cotton muslin placed as a flap over the door opening. All precautions were taken to avoid contamination of samples, including repeatedly rinsing the used equipment with ultra-pure water, using only glass material covered with aluminium foil, wearing 100% natural fibre laboratory coat and clothing, and scrubbing hands and nails regularly. Daily records of air pollution were made and no synthetic microfibres were seen.

Plastic microfibres were extracted from 10 ml of sediment using 200 ml of saturated sodium chloride (NaCl) solution ( $1.2 \text{ g cm}^{-3}$ ) [2]. Three sequential extractions were performed using a



**Fig 1. General map of the southern European seas.** The location of surface sediment sampling stations for the analysis of plastic fibres is shown as red open circles. Black boxes mark areas that are shown as zoom-ins below. The map was generated using the GEBCO\_2014 grid ([http://www.gebco.net/data\\_and\\_products/gridded\\_bathymetry\\_data/](http://www.gebco.net/data_and_products/gridded_bathymetry_data/)) and ArcGIS version 10.3 (<http://desktop.arcgis.com/en/arcmap/>).

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glass fibre filter to separate suspended debris from settled sediment components after shaking for 30 seconds and settling for 5 minutes. This process was repeated 3 times for every sample. Blanks were run every 2 samples and did not indicate any source of potential contamination. As expected due to the low volume of sample used [38], all microplastics found were microfibrils.

We report on plastic microfibrils in 50 ml of sediment (MF50 from here onwards) for ease of comparison with other environmental matrices (e.g. ice and water) and other studies [14]. MF50 converts to microfibrils per 50 grams of dry weight assuming an average sediment dry density of  $1 \text{ g cm}^{-3}$  (based on own data) and to microfibrils per unit of area assuming a 1cm-thick sediment layer.

Since the density of the saturated NaCl solution is only  $1.2 \text{ g ml}^{-1}$ , high-density fibres such as polyester or cellulose, and regenerated cellulose, may not float. However, we found that those fibres were efficiently extracted from the sediments. Fibre adherence to air bubbles formed when vigorously shaking the saturated NaCl solution with the sediment sample may have subsequently conveyed the fibres to the surface of the supernatant, according to the Stoke's Law, from where they were then filtrated. Indeed dense fibre separation by flotation due to the action of air microbubbles have been widely used in mining and paper and pulp

industries. Air flotation as a tertiary treatment in wastewater effluents has also been proven to efficiently remove 95% of the microfibrils [39].

All filters were examined under a binocular microscope, and any debris that was of unnatural appearance was transferred to sealed containers and subsequently identified by spectrometry. A Vertex 70 Fourier transform infrared (FT-IR) spectrometer at the University of Plymouth was used for polymer identification of each microfibre found. The spectra obtained were compared to a spectral database of synthetic polymer (Bruker I26933 Synthetic fibres ATR library). Bruker's Opus spectroscopy software was used for measurement, processing and evaluation of the IR spectra. All data generated during this study are included in [S1 Table](#).

The normality of the data was tested using the Kolmogorov-Smirnov test before performing a one-way ANOVA to explain the differences between number of microfibrils in the investigated seas (i.e. Cantabrian Sea, Alboran Sea, Catalan Sea, Cretan Sea, Levantine Sea and Black Sea) and geomorphic environments (i.e. continental shelf, open continental slope, submarine canyons and deep basin). Statistical significance of the data was assumed when  $p < 0.05$ .

The grain size distribution of surface sediments was determined using a Coulter LS230 Laser Diffraction Particle Size Analyzer. Organic matter in the samples was first oxidized with 10% H<sub>2</sub>O<sub>2</sub>.

## Results and discussion

A total of 202 microfibrils were found in the 29 surface sediment samples analysed. Fibres length varied between 3 and 8 mm, and the most abundant colours were red (27%), white (23%), blue (21%) and black (19%). Fibre abundance ranged between 10 and 70 MF50 and averaged  $34.8 \pm 18.3$  MF50, which is equivalent to  $6,965 \pm 3,669$  microfibrils m<sup>-2</sup>. Microfibrils abundances are of the same order of magnitude as those reported in deep-sea sediments in the subpolar North Atlantic, the NE Atlantic and the SW Indian oceans [14], and significantly more abundant (2 to 8 orders of magnitude larger) than floating fibres in ocean surface and subsurface waters [22, 23, 40]. Even though low floating microfibre abundances may be directly related to the relatively large (usually 330 µm) mesh size of the net [41], this is new evidence, after [14], confirming deep-sea sediments as a major sink for microfibrils. The fibres identified by spectrometry included cellulose (79.7%), polyester (polyethylene terephthalate) (12.9%), acrylic (polymethyl methacrylate) (4.5%), polyamide (1.0%), polyethylene (1.0%), and polypropylene (1.0%) ([S1 Table](#)).

The main type of microfibre found in seafloor sediments was thus essentially not plastic but cellulose fibres, that consisted of both dyed natural cellulose (cotton, linen) and manufactured fibres composed of regenerated cellulose, e.g. rayon. Rayon is a man-made fibre produced from dissolving cellulose-based raw material, an industrial process that requires an intensive use of water and energy, and extensive insidious toxic chemical treatment [42]. Because the chemical composition and properties of the natural polymer is significantly modified during the manufacturing process, rayon has been generally considered when reporting man-made microfibrils [14, 22, 43]. The main uses of both natural and regenerated cellulose fibre are clothing and apparel, industrial textiles such as mechanical rubber goods, and feminine hygiene products. Natural and regenerated cellulose fibres have been recently found in atmospheric fallout [21], rivers [44], macrofauna [45] and fish [46, 47, 48].

The second most abundant fibre was polyester, which is the most used synthetic fibre worldwide [49]. Because of its high resistance, polyester is utilized in all types of clothing, especially high-performance outdoor wear and home furnishings. The third most abundant fibre was acrylic, which is usually blended with wool and mostly used in clothing and home furnishings too. Then we found polyamide (i.e. nylon), which is used in clothing, home furnishing

and industrial products such as fishing gear because of its lightness and resilience, and polyethylene and polypropylene, which are the lightest fibres, often used in sportswear due to their high resistance and moisture repellence.

These extremely thin (less than 0.1 mm in diameter) but resilient fibres are mostly discharged into wastewater from domestic washing machines [11, 18], each garment producing between 1,900 and 700,000 fibres [19, 18]. In the last decades, the use of synthetic polymer fibres by the clothing industry has overtaken that of natural cotton. Declining cotton production year-on-year, the price and properties of synthetic fibres (i.e. resistance, moisture-wicking), and the growing demand for clothing, have made plastic fibres more desirable to manufacturers. Accordingly, a direct link between washing clothes and marine pollution can be established based on the similar proportions of the plastic polymer found in textiles (polyester > polyamide > polypropylene > acrylic) [49], sewage (polyester > polyamide > acrylic) [18, 50], coastal habitats (polyester > acrylic > polyamide > polypropylene) [51], and the deep sea floor (polyester > acrylic > polyamide) (this study). Furthermore, the atmospheric compartment should not be neglected as an additional mode of microfibre spreading, as a similar proportion of cellulose and polyester fibres have been recently observed in the atmospheric fallout in an urban environment [21].

Our results show the dominance of cellulosic fibres over synthetic polymers. In contrast, synthetic fibres dominate the global fibre market, with 65% of the share, while natural and man-made cellulosic fibres altogether comprise only a 35% [52]. Shedding of fibres is a relatively new concept in textile development [53], and, to our knowledge, no studies have yet investigated microfibre shedding from cellulose vs. plastic textiles. Assuming a roughly equivalent release of fibres of each polymer to the aquatic environment, data suggest that polymer density is the key component controlling the spreading of microfibres to the deep.

Despite sedimentation of nonspherical particles such as fibres is still poorly understood, and may depend on drag forces on the different shapes and curvature of the fibres [54], cellulosic fibres are significantly denser than seawater and are thus more likely to sink. Accordingly, cellulose is found in large quantities in deep-sea sediments, reaching up to 27.9 MF50 (Table 1). Polyester is also denser than seawater and, consequently, is also found in high quantities in the deep sea, with up to 4.5 MF50 ml. After being injected into the marine

**Table 1. Densities and abundances of microfibres.**

Microfibre polymer, and natural and laboratory solutions	Density (g cm <sup>-3</sup> )	Abundance (MF50)
Polypropylene	0.90	0.3
Polyethylene	0.95	0.3
<b>Seawater</b>	<b>1.02</b>	—
Polyamide	1.16	0.3
Acrylic	1.20	1.6
<b>Saturated NaCl solution</b>	<b>1.20</b>	—
Polyester	1.37	4.5
Regenerated cellulose	1.44	27.9
Natural cellulose	1.50	

Densities of the different types of polymers extracted from surface sediment layers of the southern European seas, along with those of seawater and the hypersaline (saturated) solution used for microfibre extraction, and abundance of each polymer in the analysed sediments. Fibres denser than the saturated NaCl solution were recovered because they attach to raising air bubbles formed when shaking the solution in the laboratory (see Methods section). MF50: microfibres in 50 ml of sediment.

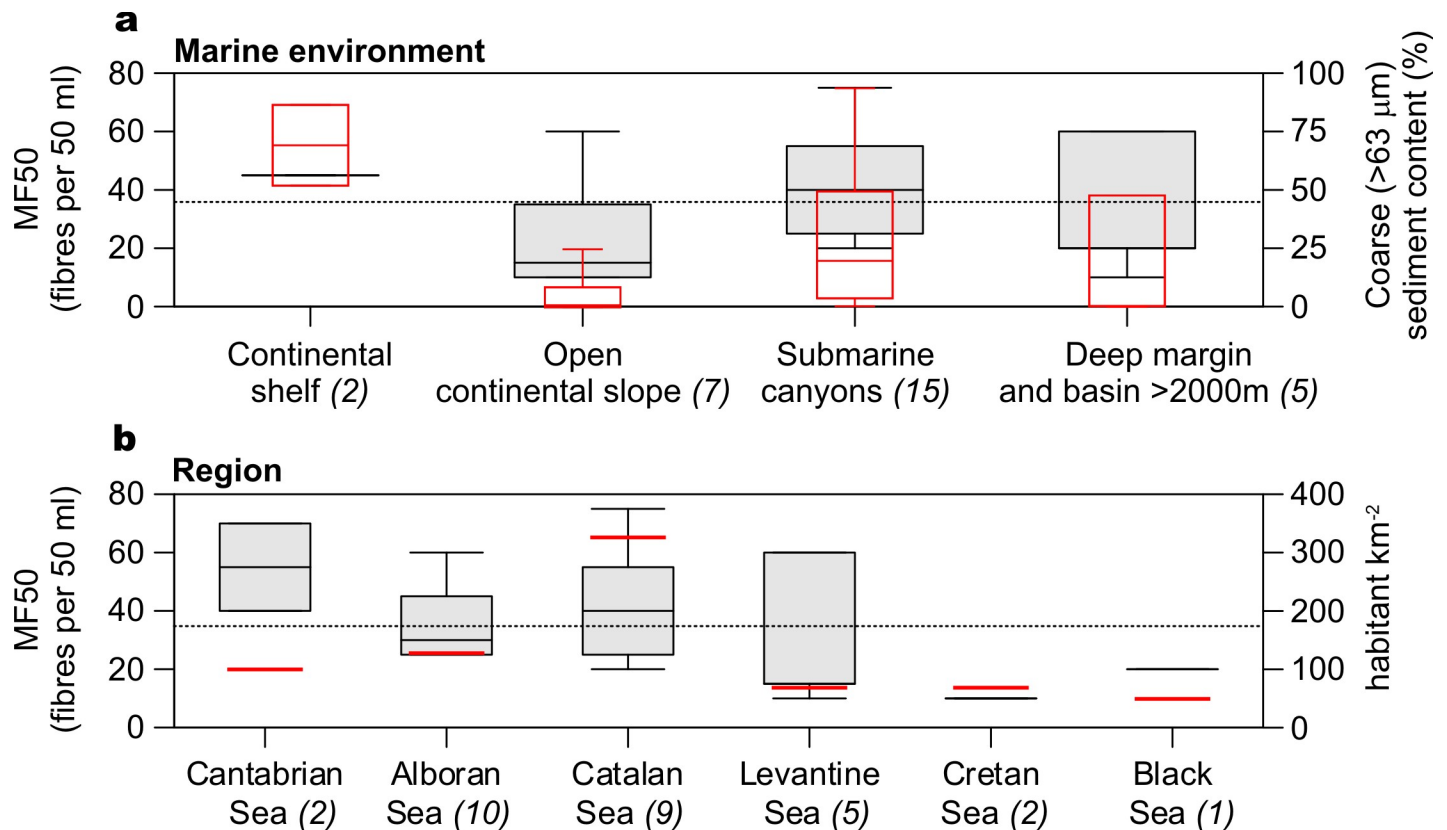
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environment from sewage disposal sites and wastewater treatment plants [55], suspended high-density microfibres may be able to settle out from the freshwater plume when the flow rate decreases and microfibre buoyancy becomes negative. Then, fibres may behave as very fine grained sediments, being repeatedly resuspended and transported towards the shelf edge and downslope by storm-induced turbidity currents, dense shelf water cascading, hyperpycnal flows or internal waves [56, 57]. In contrast, low-density microfibres such as polyethylene and polypropylene may float and sink only when negative buoyancy is reached due to ballast effect by e.g. colonization by organisms, adherence to phytoplankton and/or aggregation with organic debris [14, 58]. Accordingly, polyethylene and polypropylene are the most abundant compounds found afloat in Mediterranean Sea waters (68% of all particles [36]). Very low abundances of these two low-density polymers (<2%) in the deep sea support our view (Table 1), which, by the way, would have settled due to biofouling [58].

Very little is known about the fate of plastic debris in the marine environment. The degradation of polyester, polyamide, polyethylene and polypropylene occurs primarily through thermo- and UV-induced reactions [59, 60, 61]. Therefore, once microfibres sink in the deep sea the rate of degradation may decrease dramatically [60]. However, there are some evidences that microbes may also play a role via physical or metabolic means [62, 63]. The time required to completely degrade to CO<sub>2</sub> plastics is estimated to be on the order of hundreds to thousands of years [64]. Even less is known about the degradation of natural and regenerated cellulose in the marine environment. It has been shown that biodegradability of regenerated cellulose is higher than that of natural cellulose [65], or that dyed fibres are somehow protected from microbial degradation [66]. However it is currently unknown the durability of cellulosic material in the deep sea.

Relative abundance of fibres in different marine environments (i.e. continental shelf, open continental slope, submarine canyons and deep basin) and region (i.e. Cantabrian Sea, Alboran Sea, Catalan Sea, Cretan Sea, Levantine Sea and Black Sea) have been quantified (Fig 2, S1 Table).

There were no statistically significant differences among geomorphic environments ( $F(3, 25) = 1.87, p = 0.16$ ) or seas ( $F(5, 23) = 2.17, p = 0.09$ ) as determined by one-way ANOVA, which illustrate the ubiquitous distribution of fibres in the marine environment. However, not achieving a statistically significant result does not mean that there is no spatial variation of microfibre abundance at all. Abundance of microfibres in each marine environment relative to the total abundance in the sea floor show that continental shelf sediments retain 33% of microfibres found in the sea floor. Beyond the shelf edge fibres are found in significantly different proportions in submarine canyons (29%) and open slopes (18%). Predominance of coarse surface sediments in shelf and, to a lesser extent, submarine canyon environments, show the preferential dispersal pathway for the sand-sized material that moves from the shelf and that ultimately may end up in the deep sea (Fig 2). Supported by many references on the important role of submarine canyons as main conduits for sediment transport to the deep sea [56, 68, 69], this would suggest that are also preferential conduits for microfibres transport. Furthermore, the role of canyons in carrying microfibres and other pollutants to the deep is tremendously reinforced when they are the loci of highly dynamic shelf to basin export processes as those occurring in the NW Mediterranean Sea, which result from intense coastal storms and dense shelf water cascading [70, 71]. These oceanographic processes cause concentrations of organochlorine compounds, polybrominated diphenyl ethers, perfluoroalkyl substances and anthropogenic metals in deep-water sediments of the NW Mediterranean Sea that are amongst the highest recorded in the marine environment [72, 73, 74, 75]. Finally, 20% of the microfibres accumulate in the deep sea beyond 2,000 m of water depth.



**Fig 2. Boxplot showing microfibres found per 50 ml of sediment (MF50) per marine environment (a) and region (b).** Volume percentage of sediments > 63 µm and human population per square kilometer in the adjacent continental landmass [67] are also shown. The caps at the end of each box indicate the extreme values. The box is defined by the lower and upper quartiles, and the line in the center of the box is the median. The dotted line shows mean microfibre abundance. Number in brackets show the number of samples.

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The highest fibre densities are found in the Cantabrian Sea, followed by the Catalan Sea and the Alboran Sea in the NW and SW Mediterranean Sea, respectively, while the lowest densities are found in the Eastern Mediterranean Sea and the Black Sea. Despite reasonable fit to human population density in the adjacent continental landmass (Fig 2), accumulation of microfibres in the deep sea may be mainly related to the prevailing oceanographic conditions and the presence of active sediment transport processes.

A recent study has provided for the first time evidence of microfibres being ingested by deep-sea organisms in a natural setting [34]. Microfibres of acrylic, polypropylene, rayon and polyester were found inside benthic organisms of a wide range of taxa from phyla Cnidaria, Echinodermata and Arthropoda at 334 to 1795 m of water depth in the Equatorial mid-Atlantic and the SW Indian oceans. However, the long-term impact of microfibre ingestion on deep-sea organisms is yet to be determined and probably depends on many factors including type of polymer and abundance of microfibres in the deep-sea floor [14], capacity to adsorb harmful chemical substances [76, 77], as well as organism physiology and ecology [34]. This applies not only to plastic microfibres but also to cellulose fibres, which associated dyes or additives could also be potentially harmful for the biota [45]. In any case, the persistent nature of microfibres [60] makes evident the need to design effective management strategies for reducing emissions to the environment, such as changes in textile composition, washing conditions or filtration of effluents [19].

## Supporting information

**S1 Table. Details of sampling location and quantity (microfibres per 50 ml of sediment, MF50) and type (polymer) of fibres found.**  
(DOCX)

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## Author Contributions

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**Writing – original draft:** Anna Sanchez-Vidal, Richard C. Thompson, Miquel Canals, William P. de Haan.

## References

1. Ryan PG, Moloney CL. Plastic and other artefacts on South African beaches: temporal trends in abundance and composition. *South African Journal of Science* 1990; 86: 450–452
2. Thompson RC, Olsen Y, Mitchell RP, Davis A, Rowland SJ, John AWG, et al. Lost at sea: Where is all the plastic? *Science* 2004; 304: 838. <https://doi.org/10.1126/science.1094559> PMID: 15131299
3. Barnes DKA, Galgani F, Thompson RC, Barlaz M. Accumulation and fragmentation of plastic debris in global environments. *Philosophical Transactions of the Royal Society B* 2009; 364: 1985–1998.
4. Jambeck JR, Geyer R, Wilcox C, Siegler TR, Perryman M, Andrady A, et al. Plastic waste inputs from land into the ocean. *Science* 2015; 347: 768–771. <https://doi.org/10.1126/science.1260352> PMID: 25678662
5. Costa M, Ivar do Sul J, Silva-Cavalcanti J, Araújo M, Spengler Â, Tourinho P (2010) On the importance of size of plastic fragments and pellets on the strandline: A snapshot of a Brazilian beach. *Environmental Monitoring and Assessment* 2010; 168: 299–304. <https://doi.org/10.1007/s10661-009-1113-4> PMID: 19680758
6. Napper IE, Bakir A, Rowland SJ, Thompson RC. Characterization, quantity and sorptive properties of microplastics extracted from cosmetics. *Marine Pollution Bulletin* 2015; 99 (1–2): 178–185. <https://doi.org/10.1016/j.marpolbul.2015.07.029> PMID: 26234612
7. Browne MA, Crump P, Niven SJ, Teuten E, Tonkin A, Galloway T, et al. Accumulation of microplastic on shorelines worldwide: sources and sinks. *Environmental Science and Technology* 2011; 45: 9175–9179. <https://doi.org/10.1021/es201811s> PMID: 21894925
8. Law KL, Thompson RC. Microplastics in the seas. *Science* 2014; 345: 144–145. <https://doi.org/10.1126/science.1254065> PMID: 25013051



9. Cózar A, Echevarría F, González-Gordillo JI, Irigoien X, Úbeda B, Hernández-León S, et al. Plastic debris in the open ocean. *Proceedings of the National Academy of Sciences of the United States of America* 2014; 111 (28): 10239–10244. <https://doi.org/10.1073/pnas.1314705111> PMID: 24982135
10. Eriksen M, Lebreton LCM, Carson HS, Thiel M, Moore CJ, Borerro JC, et al. Plastic pollution in the world's oceans: More than 5 trillion plastic pieces weighing over 250,000 tons afloat at sea. *PLoS ONE* 2014; 9: e111913. <https://doi.org/10.1371/journal.pone.0111913> PMID: 25494041
11. Browne M, Galloway T, Thompson RC. Spatial patterns of plastic debris along Estuarine shorelines. *Environmental Science and Technology* 2010; 44: 3404–3409. <https://doi.org/10.1021/es903784e> PMID: 20377170
12. Sadri SS, Thompson RC. On the quantity and composition of floating plastic debris entering and leaving the Tamar Estuary, Southwest England. *Marine Pollution Bulletin* 2014; 81 (1): 55–60. <https://doi.org/10.1016/j.marpolbul.2014.02.020> PMID: 24613232
13. van Cauwenberghe L, Vanreusel A, Mees J, Janssen CR. Microplastic pollution in deep-sea sediments. *Environmental Pollution* 2013; 182: 495–499. <https://doi.org/10.1016/j.envpol.2013.08.013> PMID: 24035457
14. Woodall LC, Sanchez-Vidal A, Canals M, Paterson GLJ, Coppock R, Sleight V, et al. The deep sea is a major sink for microplastic debris. *Royal Society Open Science* 2014; 1: 140317. <https://doi.org/10.1098/rsos.140317> PMID: 26064573
15. Obbard RW, Sadri S, Wong YQ, Khitun AA, Baker I, Thompson RC. Global warming releases microplastic legacy frozen in Arctic Sea ice. *Earth's Future* 2014; 2: 315–320.
16. Bergmann M, Gutow L, Klages M. Marine anthropogenic litter, eds. Bergmann et al. (Springer, Heidelberg), pp. 1–447, 2015.
17. UNEP. Plastic debris in the ocean in UNEP year book: Emerging issues in our global environment, ed. United Nations Environment Programme, pp. 49–53, 2014.
18. Browne MA, Crump P, Niven SJ, Teuten E, Tonkin A, Galloway T, et al. Accumulation of Microplastic on Shorelines Worldwide: Sources and Sinks. *Environmental Science & Technology* 2011; 45: 9175–9179.
19. Napper IE, Thompson RC. Release of synthetic microplastic plastic fibres from domestic washing machines: Effects of fabric type and washing conditions. *Marine Pollution Bulletin* 2016; 112 (1–2): 39–45. <https://doi.org/10.1016/j.marpolbul.2016.09.025> PMID: 27686821
20. Pirc U, Vidmar M, Mozer A, Krzan A. Emissions of microplastic fibers from microfiber fleece during domestic washing. *Environmental Science and Pollution Research* 2016; 23: 22206–22211. <https://doi.org/10.1007/s11356-016-7703-0> PMID: 27658400
21. Dris R, Gasperi J, Saad M, Mirande C, Tassin B. Synthetic fibers in atmospheric fallout: A source of microplastics in the environment? *Marine Pollution Bulletin* 2016; 104: 290–293. <https://doi.org/10.1016/j.marpolbul.2016.01.006> PMID: 26787549
22. Lusher AL, Tirelli V, O'Connor I, Officer R. Microplastics in Arctic polar waters: the first reported values of particles in surface and sub-surface samples. *Scientific Reports* 2015; 5: 14947. <https://doi.org/10.1038/srep14947> PMID: 26446348
23. Desforges JPW, Galbraith M, Dangerfield N, Ross PS. Widespread distribution of microplastics in sub-surface seawater in the NE Pacific Ocean. *Marine Pollution Bulletin* 2014; 79 (1–2): 94–99. <https://doi.org/10.1016/j.marpolbul.2013.12.035> PMID: 24398418
24. Claessens M, Meester SD, Landuyt LV, Clerck KD, Janssen CR. Occurrence and distribution of microplastics in marine sediments along the Belgian coast. *Marine Pollution Bulletin* 2011; 62: 2199–2204. <https://doi.org/10.1016/j.marpolbul.2011.06.030> PMID: 21802098
25. Mathalon A, Hill P. Microplastic fibers in the intertidal ecosystem surrounding Halifax Harbor, Nova Scotia. *Marine Pollution Bulletin* 2014; 81: 67–79.
26. Stolte A, Forster S, Gerdt G, Schubert H. Microplastic concentrations in beach sediments along the German Baltic coast. *Marine Pollution Bulletin* 2015; 99: 216–229. <https://doi.org/10.1016/j.marpolbul.2015.07.022> PMID: 26198261
27. Fischer V, Elsner NO, Brenke N, Schwabe E, Brandt A. Plastic pollution of the Kuril–Kamchatka Trench area (NW Pacific). *Deep-Sea Research Part II* 2015; 111: 399–405.
28. Lusher AL, Hernandez-Milian G, O'Brien J, Berrow S, O'Connor I, Officer R (2015) Microplastic and macroplastic ingestion by a deep diving, oceanic cetacean: the True's beaked whale *Mesoplodon mirus*. *Environmental Pollution* 2015; 199: 185–191. <https://doi.org/10.1016/j.envpol.2015.01.023> PMID: 25667115
29. Desforges JP, Galbraith M, Ross PS. Ingestion of Microplastics by Zooplankton in the Northeast Pacific Ocean. *Archives of Environmental Contamination and Toxicology* 2015; 69: 320–330. <https://doi.org/10.1007/s00244-015-0172-5> PMID: 26066061

30. Jemec A, Horvat P, Kunej U, Bele M, Krzan A. Uptake and effects of microplastic textile fibers on freshwater crustacean *Daphnia magna*. *Environmental Pollution* 2016; 219: 201–209. <https://doi.org/10.1016/j.envpol.2016.10.037> PMID: 27814536
31. Devriese LI, van der Meulen MD, Maes T, Bekaer K, Paul-Pont I, Frère L, et al. Microplastic contamination in brown shrimp (*Crangon crangon*, Linnaeus 1758) from coastal waters of the Southern North Sea and Channel area. *Marine Pollution Bulletin* 2015; 98: 179–187. <https://doi.org/10.1016/j.marpolbul.2015.06.051> PMID: 26456303
32. De Witte B, Devriese L, Bekaer K, Hoffman S, Vandermeersch G, Cooreman K, et al. Quality assessment of the blue mussel (*Mytilus edis*): comparison between commercial and wild types. *Marine Pollution Bulletin* 2014; 85: 146–155. <https://doi.org/10.1016/j.marpolbul.2014.06.006> PMID: 24969855
33. Murray F, and Cowie PR. Plastic contamination in the decapod crustacean *Nephrops norvegicus* (Linnaeus, 1758). *Marine Pollution Bulletin* 2011; 62: 1207–1217. <https://doi.org/10.1016/j.marpolbul.2011.03.032> PMID: 21497854
34. Taylor ML, Gwinnett C, Robinson LF, Woodall LC. Plastic microfibre ingestion by deep-sea organisms. *Scientific Reports* 2016; 6: 33997. <https://doi.org/10.1038/srep33997> PMID: 27687574
35. Cózar A, Sanz-Martín M, González-Gordillo JI, Ubeda B, Gálvez JA, Irigoien X, et al. Plastic Accumulation in the Mediterranean Sea. *PLoS ONE* 2015; 10 (4): e0121762. <https://doi.org/10.1371/journal.pone.0121762> PMID: 25831129
36. Suaria G, Avio CG, Mineo A, Lattin GL, Magaldi MG, Belmonte G, et al. The Mediterranean Plastic Soup: synthetic polymers in Mediterranean surface waters. *Scientific Reports* 2016; 6: 37551. <https://doi.org/10.1038/srep37551> PMID: 27876837
37. Lebreton LCM, Greer SD, Borrero JC. Numerical modelling of floating debris in the world's ocean. *Marine Pollution Bulletin* 2012; 64: 653–661. <https://doi.org/10.1016/j.marpolbul.2011.10.027> PMID: 22264500
38. van Cauwenberghe L, Claessens M, Vandegehuchte MB, Janssen CR. Microplastics are taken up by mussels (*Mytilus edulis*) and lugworms (*Arenicola marina*) living in natural habitats. *Environmental Pollution* 2015; 199:10–17. <https://doi.org/10.1016/j.envpol.2015.01.008> PMID: 25617854
39. Talvitie J, Mikola A, Koistinen A, Setälä O. Solutions to microplastic pollution—Removal of microplastics from wastewater effluent with advanced wastewater treatment technologies. *Water Research* 2017; 123: 401–407. <https://doi.org/10.1016/j.watres.2017.07.005> PMID: 28686942
40. Moore CJ, Moore SL, Leecasterà MK, Weisbergà SB. A Comparison of plastic and plankton in the North Pacific Central Gyre. *Marine Pollution Bulletin* 2001; 42: 1297–1300. PMID: 11827116
41. Hidalgo-Ruz V, Gutow L, Thompson RC, Thiel M. Microplastics in the marine environment: a review of the methods used for identification and quantification. *Environmental Science and Technology* 2012; 46: 3060–3075. <https://doi.org/10.1021/es2031505> PMID: 22321064
42. Monosson E. Toxic textiles. *Science* 2016; 354 (6315): 977. <https://doi.org/10.1126/science.aak9834> PMID: 27884997
43. Woodall LC, Gwinnett C, Packer M, Thompson RC, Robinson LF, Paterson GLJ. Using a forensic science approach to minimize environmental contamination and to identify microfibres in marine sediments. *Marine Pollution Bulletin* 2015; 95: 40–46. <https://doi.org/10.1016/j.marpolbul.2015.04.044> PMID: 25936572
44. Dris R, Gasperi J, Rovher V, Tassin B. Synthetic and non-synthetic anthropogenic fibers in a river under the impact of Paris Megacity: Sampling methodological aspects and flux estimations. *Science of The Total Environment* 2018; 618: 157–164. <https://doi.org/10.1016/j.scitotenv.2017.11.009> PMID: 29128764
45. Remy F, Collar F, Gilbert B, Compere P, Eppe G, Lepoint G. When Microplastic Is Not Plastic: The Ingestion of Artificial Cellulose Fibers by Macrofauna Living in Seagrass Macrophytodebris. *Environmental Science and Technology* 2015; 49: 11158–11166. <https://doi.org/10.1021/acs.est.5b02005> PMID: 26301775
46. Lusher AL, McHugh M, Thompson RC. Occurrence of microplastics in the gastrointestinal tract of pelagic and demersal fish from the English Channel. *Marine Pollution Bulletin* 2013; 67: 94–99. <https://doi.org/10.1016/j.marpolbul.2012.11.028> PMID: 23273934
47. Lusher AL, Burke A, O'Connor I., Officer R. Microplastic pollution in the Northeast Atlantic Ocean: validated and opportunistic sampling. *Marine Pollution Bulletin* 2014; 88: 325–333. <https://doi.org/10.1016/j.marpolbul.2014.08.023> PMID: 25224764
48. Collard F, Gilbert B, Eppe G, Parmentier E, Das K. Detection of Anthropogenic Particles in Fish Stomachs: An Isolation Method Adapted to Identification by Raman Spectroscopy. *Archives of Environmental Contamination and Toxicology* 2015; 69: 331–339. <https://doi.org/10.1007/s00244-015-0221-0> PMID: 26289815

49. Carmichael A (2015) Man-Made Fibers Continue To Grow. *Textile World* <http://www.textileworld.com/textile-world/fiber-world/2015/02/man-made-fibers-continue-to-grow>, 2015.
50. Murphy F, Ewins C, Carbonnier F, Quinn B. Wastewater Treatment Works (WwTW) as a Source of Microplastics in the Aquatic Environment. *Environmental Science & Technology* 2016; 50: 5800–5808.
51. Browne MA. Sources and pathways of microplastics to habitats in Marine anthropogenic litter, eds. Bergmann et al. (Springer, Heidelberg), 229–244. 2015.
52. CIRFS (European Man-made Fibres Association). World man made fibres production. <http://www.cirfs.org/KeyStatistics/WorldManMadeFibresProduction.aspx>, 2016.
53. Carney Almroth B, Åström L, Roslund S, Petersson H, Johansson M, Persson NK. Quantifying shedding of synthetic fibers from textiles; a source of microplastics released into the environment. *Environmental Science and Pollution Research* 2018; 25:1191–11199. <https://doi.org/10.1007/s11356-017-0528-7> PMID: 29081044
54. Rong X, Qi D, He G, Zhu JY, Scott T. Single curved fiber sedimentation under gravity. *Computers & Mathematics with Applications* 2008; 55: 1560–1567.
55. Zubris KAV; Richards BK. Synthetic fibres as an indicator of land application of sludge. *Environmental Pollution* 2005; 138: 201–211. <https://doi.org/10.1016/j.envpol.2005.04.013> PMID: 15967553
56. Canals M, Puig P, Heussner S, Durrieu de Madron X, Palanques A, Fabrès J. Flushing submarine canyons. *Nature* 2006; 444: 354–357. <https://doi.org/10.1038/nature05271> PMID: 17108962
57. Puig P, Palanques A, Martín J (2014) Contemporary sediment-transport processes in submarine canyons. *Annual Reviews in Marine Science* 2014; 6: 53–77.
58. Kaiser D, Kowalski N, Waniek J. Effects of biofouling on the sinking behavior of microplastics. *Environmental Research Letters* 2017; 12: 124003.
59. Cooper DA, Corcoran PL. Effects of mechanical and chemical processes on the degradation of plastic beach debris on the island of Kauai, Hawaii. *Marine Pollution Bulletin* 2010; 60: 650–654. <https://doi.org/10.1016/j.marpolbul.2009.12.026> PMID: 20106491
60. Andrady AL. Microplastics in the marine environment. *Marine Pollution Bulletin* 2011; 62: 1596–1605. <https://doi.org/10.1016/j.marpolbul.2011.05.030> PMID: 21742351
61. Andrady AL. Persistence of Plastic Litter in the Oceans in Marine anthropogenic litter, eds. Bergmann et al. (Springer, Heidelberg), 57–72, 2015.
62. Zettler ER, Mincer TJ, Amaral-Zettler. Life in the “Plastisphere”: Microbial Communities on Plastic Marine Debris. *Environmental Science and Technology* 2013; 47:7137–7146. <https://doi.org/10.1021/es401288x> PMID: 23745679
63. Yoshida S, Hiraga K, Takehana T, Taniguchi I, Yamaji H, Maeda Y, et al. A bacterium that degrades and assimilates poly(ethylene terephthalate). *Science* 2016; 351: 1196–1199 <https://doi.org/10.1126/science.aad6359> PMID: 26965627
64. Barnes DKA, Galgani F, Thompson RC, Barlaz M. Accumulation and fragmentation of plastic debris in global environments. *Philosophical Transactions of the Royal Society B* 2009; 364:1985–1998.
65. Park CH, Kang YK, Im SS. Biodegradability of Cellulose Fabrics. *Journal of Applied Polymer Science* 2004; 94: 248–253.
66. Chen R, Jakes KA. Cellulolytic biodegradation of cotton fibers from a deep-ocean environment. *Journal of the American Institute for Conservation* 2001; 40 (2): 91–103.
67. Eurostat. Population density by NUTS (Nomenclature of Territorial Units for Statistics) 3 region (Code: demo\_r\_d3dens). 2018. [accessed 10/10/2018]. Available from: [https://ec.europa.eu/eurostat/web/products-datasets/-/demo\\_r\\_d3dens](https://ec.europa.eu/eurostat/web/products-datasets/-/demo_r_d3dens)
68. Paull CK, Ussler W III, Greene HG, Keaten R, Mitts P, Barry J. Caught in the act: the 20 December 2001 gravity flow event in Monterey Canyon. *Geo-Marine Letters* 2003; 22: 227–232.
69. Masson DG, Huvenne VAI, de Stigter HC, Wolff GA, Kiriakoulakis K, Arzola RG, et al. Efficient burial of carbon in a submarine canyon. *Geology* 2010; 38: 831–834.
70. Sanchez-Vidal A, Canals M, Calafat AM, Lastras G, Pedrosa-Pàmies R, Menéndez R, et al. Impacts on the deep-sea ecosystem by a severe coastal storm. *PLOS ONE* 2012; 7 (1): e30395. <https://doi.org/10.1371/journal.pone.0030395> PMID: 22295084
71. Canals M, Company JB, Martín D, Sanchez-Vidal A, Ramirez-Llodra E. Integrated study of Mediterranean deep canyons: novel results and future challenges. *Progress in Oceanography* 2013; 118: 1–27.
72. Salvadó JA, Grimalt JO, Lopez JF, Durrieu de Madron X, Heussner S, Canals M. Transformation of PBDE mixtures during sediment transport and resuspension in marine environments (Gulf of Lion, NW Mediterranean Sea). *Environmental Pollution* 2012; 168: 87–95. <https://doi.org/10.1016/j.envpol.2012.04.019> PMID: 22595764

73. Salvadó JA, Grimalt JO, Lopez JF, Durrieu de Madron X, Pasqual C, Canals M. Distribution of organochlorine compounds in superficial sediments from the Gulf of Lion, Northwestern Mediterranean Sea. *Progress in Oceanography* 2013; 118: 235–248.
74. Cossa D, Buscail R, Puig P, Chiffolleau JF, Radakovitch O, Jeanty G, et al. Origin and accumulation of trace elements in sediments of the northwestern Mediterranean margin. *Chemical Geology* 2014; 380: 61–73.
75. Sanchez-Vidal A, Llorca M, Farré M, Canals M, Barceló D, Puig P, et al. Delivery of unprecedented amounts of perfluoroalkyl substances towards the deep-sea. *Science of The Total Environment* 2015; 526: 41–48. <https://doi.org/10.1016/j.scitotenv.2015.04.080> PMID: 25918891
76. Koelmans AA. Modeling the role of microplastics in bioaccumulation of organic chemicals to marine aquatic organisms. Critical review in *Marine anthropogenic litter*, eds. Bergmann et al. (Springer, Heidelberg), 313–328, 2015.
77. Rochman CM. The complex mixture, fate and toxicity of chemicals associated with plastic debris in the marine environment in *Marine anthropogenic litter*, eds. Bergmann et al. (Springer, Heidelberg), 117–140, 2015.