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Peter T. Harris
GRID-Arendal

Thomas Maes
GRID-Arendal

Karen Raubenheimer
University of Wollongong

J. P. Walsh
University of Rhode Island

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Peter T. Harris[a,*], Thomas Maes[a], Karen Raubenheimer[b], J.P. Walsh[c]

[a] GRID-Arendal, P.O. Box 183, N-4802, Arendal, Norway
[b] University of Wollongong, NSW, 2522, Australia
[c] University of Rhode Island, Kingston, RI, 02881, USA

ABSTRACT

To improve our understanding and management of marine plastic pollution of the ocean, a total plastic budget is needed which quantifies the sources and sinks, as well as inputs and removal of plastic per unit time. The current state of knowledge indicates that the coastal zone and ocean water column are major locations for plastic pollution, but the fate of much of this must ultimately be the deep ocean floor. We reviewed 23 journal articles that provide 280 observations of deep-sea sediment microplastic concentration across six different off-shelf environments. We calculate the following mean concentrations of microplastic particles (number) per kg of sediment: continental slope 502; submarine canyons 784; submarine fans and continental rise 714; abyssal plains 217; trenches and troughs 2782; and abyssal hills, mountains and other ocean floor 165 particles kg^{-1}. These figures are alarming because several exceed one estimate of 'safe' levels of microplastic concentration for benthic marine life (540 particles kg^{-1}). Monitoring of the concentration of plastic particles in sediments of submarine canyons, fans and continental rise environments and in trenches and troughs should be a priority to ensure efficacy of policies and actions taken to curb ocean plastic pollution at both the national and global level. We estimate 3.05 million tonnes of microplastic resides in deep ocean sediments but acknowledge the uncertainties of this figure. If correct, this figure implies that the ocean water column (which may contain as much as 90 million tonnes of microplastic) is a major, transitory sink for MP, forming a suspended, *marine plastic cloud*. In addition to particle concentrations, further measurements of the size and mass of microplastic in deep-sea sediments and in the water column are needed to advance development of mass balance budgets for marine plastic pollution.

1. Introduction

1.1. Plastic pollution of the ocean – an issue of global concern

In March 2022, UN Member States agreed to develop a global legally binding instrument by 2024 to end plastic pollution, addressing the full life cycle of plastics, including design, production, consumption and disposal. Once in force, the agreement will require governments to adopt regulations and establish monitoring systems in compliance with the policy. Science will have a role in the quantification of baselines and setting protocols and standards for measuring plastic pollution in all human and environmental compartments, including water, biota and sediments. Mapping and monitoring will be essential for assessing compliance and measuring effectiveness of measures taken at the sub-national, national and regional (e.g., Large Marine Ecosystem) levels, including the private sector. This review provides an assessment of stocks, sources and sinks of plastic pollution in the marine environment with emphasis on deep-sea sediments. The fate and pathways of plastic pollution are assessed in the context of available data on sources and sinks to identify gaps in data and knowledge.

Plastic was first produced commercially in 1950. As of 2015, an estimated 75 to 199 million tonnes of plastic has accumulated in the ocean (UNEP, 2021). The mass of plastic in the ocean follows known dispersal pathways and will be deposited in specific environments according to natural laws of physics. Plastics can enter the ocean from rivers where they meet the coastline, blown from land, or is discharged overboard by vessels (Geyer et al., 2017). Once in the ocean, plastics may sink immediately, be consumed by biota, be dispersed in the ocean water-column or remain floating on the ocean surface. Eventually, if not stranded and buried in the coastal zone (or removed by humans), most will end up buried in deep-ocean sediments (Fig. 1).

The information on the mass of plastic residing in the coastal zone, water-column and deep-sea sediments is not well constrained (Kane et al., 2020; Harris, 2020; Galgani et al., 2022). There are no consistent methods applied in the measurement of plastic pollution in sediment, water or biota, which contributes to the wide range of reported values. Browne et al. (2015) and GESAMP (2019) noted that differences in reporting units and in assessment methods (i.e. sieve sizes, density of liquids used to separate plastic from sediment particles, etc.) compromise our ability to compare the results of different studies. Such a lack of

* Corresponding author.
E-mail address: peter.harris@grida.no (P.T. Harris).

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standards and consistent methods will hamper efforts to determine compliance and monitoring of the effectiveness of any measures taken by countries and regional authorities to curb plastic pollution of the oceans (GESAMP, 2019; Uddin et al., 2020). For example, Cai et al. (2018) cited results from 333 μm bongo (neuston) net samples collected in the South China Sea and found a difference of five orders of magnitude between bongo net and filtration methods; the bongo net method measured 0.045 particles m^{-3} whereas filtered water samples (filtered at 44 μm) yielded a net concentration of 2569 particles m^{-3}. This highlights how the diverse approaches to measurement (including size) adds some confusion (Löder et al., 2015), but many more measurements are needed and analysing sizes <100 μm is not always practical or feasible. Given this and recognizing that measuring even smaller (<50 μm) sizes is very difficult, future studies will need to factor in this limitation.

1.2. Plastic sources, sinks and dispersal in the ocean – a conceptual model

Journal articles report both macroplastics (>5 mm) and microplastics (<5 mm; microplastic) in the marine environment, both of which are included in this assessment, although we focus on microplastics when discussing the mass of plastic in deep ocean sediments. Two primary sources (rivers and direct input from the coast; eg Jambeck et al., 2015) deliver plastic waste directly into the coastal zone (Fig. 1), and they must pass through this zone to reach the open ocean ecosystems. Sea-based input such as lost fishing gear and shipping waste, varies widely across the ocean (GESAMP, 2019); it may sink directly to the seabed or, if floating accumulate in ocean gyres, or be blown and transported ashore into the coastal zone.

Transport via offshore winds may also be an important source; estimates range from 0.013 to 25 million tonnes/yr (Allen et al., 2022). Recent research indicates that the ocean is an important source of microplastics exported to the land via wind-blown transport (Brahney et al., 2021). Overall, there are no reliable estimates of the mass of plastic transported into (and out of) the ocean by wind.

Lebreton et al. (2019) estimate that between 46.7 and 126.4 Mt of macroplastics (>5 mm) were stored along the world's shorelines in 2015, a significant fraction of which will have degraded into microplastic. We interpret the "shoreline" to be the broader coastal zone including beaches, estuaries and inner continental shelf environments. The large range in the estimate raises considerable uncertainty in absolute values, but it is apparent that the coastal zone (including the inner continental shelf) is a significant sink for plastic pollution. Harris (2020) reviewed samples collected from different environments which indicated that the concentration of plastic deposited in sediments appears to decline significantly from the coastal zone to the deep ocean; median values of numbers of microplastic particles in estuarine and fjord sediments range from 200 to 7000 particles kg^{-1} and about 50 particles kg^{-1} for shelf sediments but with a wide variation in reported values (eg. Kukkola et al. (2022) recently reported MP abundance in the top 10 cm of North Sea sediments was 1050–2700 MP kg^{-1}; see also Bakir et al, 2023). For deep-sea sediments, the median value (n = 9) was 80 particles kg^{-1}, again with a very wide variation (Harris, 2020).

Plastic items of all sizes may be permanently sequestered (over timescales of human lifetimes) in coastal sediments (Lebreton and Andrady, 2019; Lebreton et al., 2019). In the coastal zone and beyond, waves, tides and a range of physical and chemical processes act to fracture and degrade large plastic items, transforming them into microplastics that are easily mobilised and transported (winnowed) by waves and currents, especially those composed of low-density (light) polymers. Similar to terrestrial fine sediment, dispersion of plastic particles offshore is likely to be most effective from river deltas (particularly during flood events) and macrotidal estuaries (Harris et al., 2021a). However, great variability in supply, transport and accumulation of sediment is observed on continental margins (e.g., Walsh and Nittrouer, 2009), and much more research is needed to assess the undoubtedly complex spatial patterns of plastic accumulation in shelf sediments. While plastic will be winnowed and exported offshore from most shelf areas, there are deep shelf environments that may trap plastic along with fine-grained silts and clays. For example, the study by Brandon et al. (2019) of microplastic in a sediment core taken from a deep basin

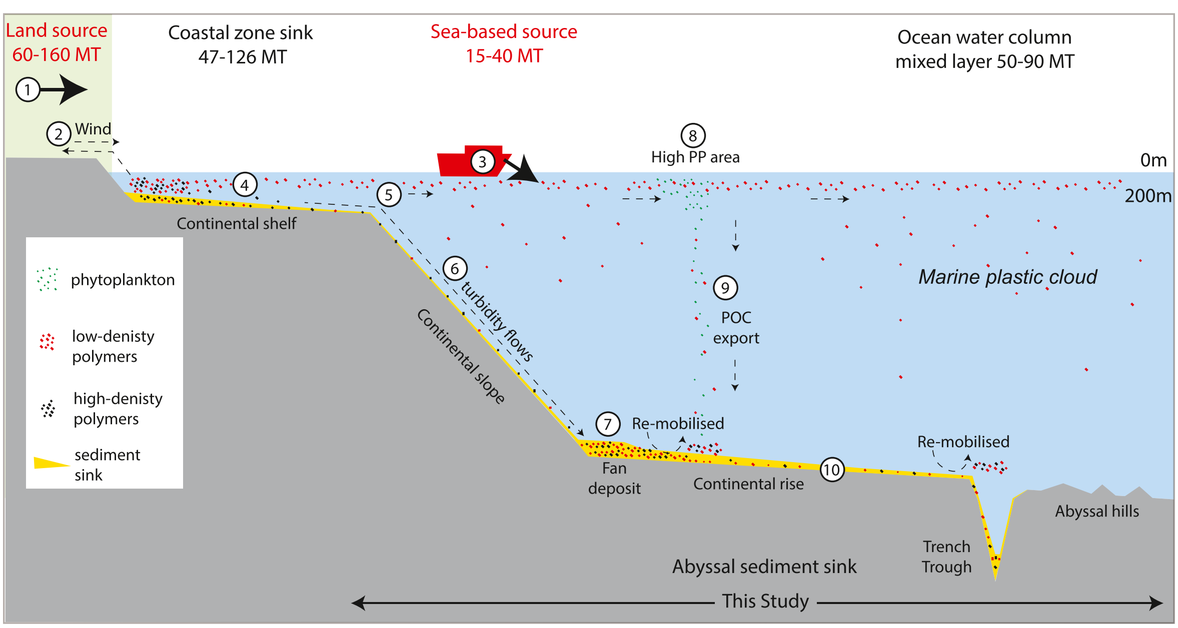

Fig. 1. Conceptual model for pathways of plastic particles in the ocean described in the text. Values in millions of tonnes (MT) from references cited in the text refer to total plastic sources (in red text), sediment sinks and mass suspended in the ocean water column (black text) as of 2015. Circled numbers are: 1) input at the coast from rivers and direct input; 2) wind input from land to ocean; 3) sea-based input, assumed to be 20% of all input; 4) macro-plastic converted to microplastics in the coastal zone, with some denser and fouled particles deposited in sediments; 5) less dense polymers are winnowed from shelf sediments by currents and waves and exported offshore; 6) mixed macro-plastic and microplastics of all densities transported down slope by turbidity currents; 7) mixed plastic incorporated into submarine fan deposits; 8) low-density microplastics incorporated into flocs in high primary productivity (PP) areas; 9) plastic exported via particulate organic carbon (POC) flux; 10) plastic deposited in abyssal sediments (this study).

perched on the California continental shelf was used to determine temporal trends in microplastic abundance in marine sediments in a rapidly accumulating, low-energy sedimentary environment which is not disturbed by human activities, bioturbation and/or storm events.

1.3. The ocean water column is a major, transitory sink for microplastic

Based on a meta-analysis of 39 studies, Erni-Cassola et al. (2019) found that polymers are segregated in the open ocean based on their density such that more buoyant types are found in surface waters and decrease in abundance through the water column, whereas denser types (polyesters and acrylics) are enriched in deeper waters. This general trend has been confirmed by Pabortsava and Lampitt (2020) who collected water samples at 12 stations along a transect of the North and South Atlantic Oceans and found total mean concentrations of plastic of ~2500 particles m^{-3}; they estimated that the mass of plastic in the 32–651 μm size-class (mean size of 81 μm) suspended in the top 200 m of the North and South Atlantic is 11.6–21.1 million tonnes, comprised of low-density microplastics (polypropylene, polyethylene and polystyrene). Extrapolating this estimate to the world ocean implies 40 to 90 million tonnes are in suspension in the upper 200 m of the ocean (Harris et al., 2021b). This estimate is conservative because it includes only three polymers (PP, PE and PS), and it ignores very high concentrations of plastic found in some nearshore areas plus plastic suspended below 200 m. Indeed, it has been reported that 70.8 particles m^{-3} were measured at 2200 m water depth in the Rockall Trough, North Atlantic (Courtene-Jones et al., 2020) and up to 13,510 m^{-3} mainly fibrous, high-density microplastic particles have been reported from the depths of the Mariana Trench between 2673 and 10,908 m water depth (Peng et al., 2018). Low-density microplastics that end up suspended in the upper water column represents approximately 60% of plastics produced according to Andrady et al. (2015).

The mass of plastic floating on the ocean surface is estimated at 233,400 tonnes for larger plastic items plus 35,540 tonnes of microplastics (Eriksen et al., 2014). Together, this is roughly 200 times less than the mass in suspension in the water column. Research suggests that the total mass of plastic residing in biota is likely less than 1 million tonnes (Lusher et al., 2017). The amounts of plastic floating on the ocean surface and residing within biota are thus very small compared with standing stocks of plastic in coastal sediments or the ocean water column.

From days to decades, microplastics are exported from the water column to the seabed. Hence the ocean water column is fundamentally different from the coastal zone or deep-sea because it behaves as a transitory, temporary storage area for plastic, and over long enough time spans stocks in this zone will decrease once the source is addressed. Remaining questions include: What is the average residence time of plastic in the water column, and what mass has already been deposited on the deep ocean floor?

1.4. Sediments on the deep ocean floor: the ultimate sink for microplastics

Hernandez et al. (2022) recently published a review of 86 papers reporting on marine litter (excluding microplastics) in marine environments located in greater than 50 m water depth. Their study focussed on marine litter in submarine canyons where they found a global average concentration of 22,488 ± 6897 items km^{-2}. Although some experts have argued that reporting mass km^{-2} might be a useful measure for marine litter (eg. Zablotski and Kraak, 2019), the vast majority of studies report only items km^{-2} because this is obtainable from visual surveys (i.e. underwater video) whereas mass estimates require trawling or other sampling technology (Hernandez et al., 2022). In their global literature survey of marine litter, Haarr et al. (2022) noted that the majority (87%) of studies on seafloor litter took place within 100 km of the shore. Thus, we presently have no global estimate of the mass of marine litter on the seafloor. Furthermore, it is important to acknowledge the different (non-standard) methods used to measure plastic mass in sediments (by sampling and/or by visual estimates via underwater video, etc.) and in the water column, which must be accounted for in building a global mass balance model.

Based on extrapolation of empirical data from 13 studies, Barrett et al. (2020) estimate that the mean particle concentration in deep-sea sediments is about 720 particles kg^{-1} and the total mass of microplastics that have accumulated globally is about 14.4 million tonnes (Fig. 1). For comparison, in their model Sonke et al. (2022) estimate that 1.0 million tonnes of microplastics is stored in deep sea sediments. The small number of studies and the spatial heterogeneity of plastic in deep-sea sediments, point to large uncertainty for estimates made to date. Among the several potential sources of error is the extrapolation of a few measurements over a range of different sedimentary environments (e.g., continental slope, abyssal plains, hills, seamounts and trenches, among others).

This paper aims to examine more closely the deep ocean sediments that are the ultimate sink of global marine plastic pollution. We review the existing, most recent published literature on microplastic concentrations in sediments on the ocean floor beyond the continental shelf, including the continental slope, rise, abyssal and hadal regions of the ocean, to provide an estimate of global microplastic mass residing in deep-sea sediments in the context of the existing knowledge gaps needed to parametrise mass balance models.

2. Methods

A literature review was carried out to identify published sources of information on microplastic concentrations in sediments on the deep ocean floor using Google Scholar and the ISI Web of Knowledge. The keywords “microplastic”, “marine” and “sediment” in combination with “ocean” or “deep-sea” were used to generate a list of possible peer-reviewed papers. From the selected publications, information was recorded regarding: (i) the sedimentary environment where samples were collected; (ii) the methods used to measure microplastic, (iii) the shape of microplastic particles (fibres, pellets, fragments, beads, etc.); and (iv) the number of microplastic particles kg^{-1} of sediment. It was also noted if the study measured or made reference to existing information on the mass of microplastic kg^{-1} of sediment and if sediment accumulation rates were measured at the microplastic sample site.

To calculate the mass of plastic residing in deep ocean sediments, the sample locations were attributed to one of six separate seafloor geomorphic categories, as follows: 1) slope, 2) submarine canyon, 3) submarine fan/continental rise; 4) abyssal plain; 5) deep trench, trough or other hadal areas; and 6) other deep ocean areas. These categories were extracted from the global seafloor geomorphic features map published by Harris et al. (2014). Using these categories improves on the method of extrapolating microplastic concentration values over the entire ocean floor without considering differences in ocean environments (benthic habitats) and their attendant differences in sediment (and microplastic) accumulation rates and other biophysical processes. Other assumptions made in the calculation of microplastic mass concentration follow the approach of Barrett et al. (2020), namely: assumed microplastic particle size of a 100 μm diameter sphere; microplastic density of 1.099 g/cm^3 and sediment bulk density of 0.6 g/cm^3. In order to calculate the sediment volumes for each environment, a sediment depth of 9 cm was assumed.

3. Results

Data were extracted from 23 separate research papers which covered 34 geographic locations and provided a total of 280 observations of deep-sea sediment microplastic concentration (Table 1). The geographic distribution of sample sites (Fig. 2) illustrates a bias toward Europe and a general focus of studies proximal to continental margins and a lack of studies in areas distal to the land. Our literature search found 13 studies

Table 1
List of studies of microplastic found in deep-sea sedimentary environments with information on geomorphic setting, location, analytical method, microplastic size range measured, composition of microplastic (fragments, fibres, pellets etc.). The concentration of microplastic lists the reported units with conversion to number of particles kg^{-1} dry weight (DW). Ranges are shown with (mean) in closed brackets with standard deviations where reported. Values in italics were used in the estimate of global microplastic mass reported in this study.

No.	Reference	Geomorphic Setting	Location/Comments	Microplastic Method and size range	microplastic Composition	No. Obs.	microplastic Concentration
1	Woodall et al. (2014)	Slope	NE Atlantic continental slope off Svalbard, 1000-2000m, mega-core and box-core, top 1-2 cm, microplastic present in all samples.	Floatation NaCl 1.2 g ml^{-1} 32 µm sieve; 3 extractions; microscope ID	All fibres 56.9% rayon	5	10-15 pieces per 50 ml 210-1400 pieces/kg Mean *595* pieces/kg
2	Cordova and Wahyudi (2016)	Slope	Indonesian margin, Indian Ocean, 2015. Samples collected using a 60 × 40 × 50 cm boxcore from 10 stations with depths ranging from 66.8 to 2182m water depth (8 stns > 500 m depth).	Floatation NaCl 1.18 g/l; 0.45 µm filter paper; microscope ID	41 particles, 35 fragments and 6 fibres	10	0-14 particles kg^{-1} (mean of 4.1) pieces per 100 cm^3 *24* particles kg^{-1}
3	Barrett et al., (2020)	Slope	Great Australian Bight, 6 cores 1655 to 3062 m water depth	Floatation $ZnCl_2$ solution (density of 1.37 g ml^{-1}); 0.22 µm filter		6	0 to 13,600 (mean *1260* ±680; n = 51).
4	Fang et al., (2022)	Slope	Chukchi Plateau, three voyages in 2016, 2018, and 2020; 37 box-core stations shelf to slope transect (four repeat stations)	Floatation $ZnCl_2$ 1.7 g ml^{-1}; 1 µm filter;	80-92% fibres 4-16% fragm's 3–4% films	37	33.66 ± 15.08 to 104.54 ± 28.07 items kg^{-1} *69* items kg^{-1}
5	Jones et al. (2022)	Slope	Norfolk Canyon US margin, 6 cores collected by ROV, 188 to 1118 m water depth; 2 samples contained no microplastic	Floatation NaI 1.8 g ml^{-1}; 43 µm filter; Microscope ID	100% fragments 0% fibres	2	0.10 items per 50 ml *2* particles kg^{-1} 0.56 g/L (n = 4)
6	Sanchez-Vidal et al. (2018)	Slope	Mediterranean Sea and other locations, 7 stations, multicorer or Van Veen grab, 2009–2015, 10 ml sediment samples,	NaCl solution 1.2 g/cm^3, fibres 1–3 mm size range (filter used, size?)	100% fibres	7	24.3 pieces/50g *486* particles kg^{-1}
7	Cunningham et al. (2020)	Slope	Antarctic Peninsula eastern margin, 499 to 1246 m water depth, n = 6; one core had no microplastic	Sodium polytungstate 1.6 g ml^{-1}; 25 µm filter; Microscope ID with FTIR check	56% fragments 39% fibres 5% films Mainly polyester	6	1.30 ± 0.51 microplastic/g *1300* particles kg^{-1}
8	Cunningham et al. (2020)	Slope	South Sandwich Islands, 1619 to 3342 m water depth, n = 11; one core had no microplastic	Sodium polytungstate 1.6 g ml^{-1}; 25 µm filter; Microscope ID with FTIR check	56% fragments 39% fibres 5% films Mainly polyester	11	1.09 ± 0.22 microplastic/g *1090* particles kg^{-1}
9	Cunningham et al. (2020)	Slope	South Georgia Island, 136 to 3633 m water depth, n = 13; microplastic found in every sample	Sodium polytungstate 1.6 g ml^{-1}; 25 µm filter; Microscope ID with FTIR check	56% fragments 39% fibres 5% films Mainly polyester	13	1.04 ± 0.39 microplastic/g *1040* particles kg^{-1}
10	Dhineka et al., (2022)	Slope	Bay of Bengal, 3 stations at 225m, 230m, and 1070m water depth			3	2 to 12 MPs/50 g DW *160* particles kg^{-1}
11	Feng et al., 2023	Slope	Haima cold seep, northern South China Sea, mass concentrations of the MPs in the ROV 1, ROV 2, ROV 3, and ROV 4 sites were 77.76, 471.14, 409.03, and 297.37 mg·kg−1 sediment, respectively	Floatation $ZnCl_2$ 1.7 g ml^{-1}; 1 µm filter;		4	*1412* ± 570.15 particles kg^{-1}
12	Lechthaler et al. (2020)	Slope	Portugal slope, 72 to 625 m water depth; 20 samples collected, 18 contained no microplastic; only 3 fibre particles were collected.	Canola oil 0.6 µm filter; microscope ID	All fibres	2	*200* particles kg^{-1} 0.2 fibres per gram
13	Cincinelli et al., 2021	Slope to basin	Black Sea 1000–2131 m water depth, 7 stations; 2 samples contained no microplastic; Van Veen grab and Box corer	Floatation NaCl ?? g ml^{-1}; 49 µm sieve; 3 extractions; microscope ID with FTR check	Mostly fibres 44% PE and PP	7	*21.4* particles kg^{-1}
14	Woodall et al. (2014)	Submarine canyon	Spanish margin, Mediterranean Sea, and NE Atlantic Ocean, submarine canyon continental slope, 4 stations 300-2000m water depth, megacore or boxcore, top 1-2 cm, microplastic present in all samples.	Floatation NaCl 1.2 g ml^{-1}32 µm sieve; 3 extractions; microscope ID	All fibres 56.9% rayon	4	6 to 40 pieces per 50 ml 350–1220 particles kg^{-1} *785* particles kg^{-1}
15	Sanchez-Vidal et al., (2018)	Submarine canyon	Mediterranean Sea and other locations, 15 stations, multicorer or Van Veen grab, 2009–2015, 10 ml sediment samples, 202 fibres recovered between 3 and 8 mm in size.	NaCl solution 1.2 g/cm^3, fibres 1–3 mm size range (filter used, size?); FTIR	100% fibres 80% cellulose	15	40.7 items per 50g *813* particles kg^{-1}
16	Kukkola et al. (2022)	Submarine canyon	UK southwest continental slope, 3 box core samples (19 other cores from shelf depths), 220 to 400 m water depth; microplastic concentration increases with water depth; microplastic present in all samples	Floatation $ZnCl_2$ 1.37 g mL^{-1}; 0.22 µm filter; Microscope ID and FTIR	1.2% fibres Fragments mostly polypropylene	3	*2700* particles kg^{-1}
17	Jones et al. (2022)	Submarine canyon	Norfolk Canyon US margin, 8 cores collected by ROV, 196 to 1135 m water depth; all samples contained microplastic	Floatation NaI 1.8 g ml^{-1}; 43 µm filter; Microscope ID	100% fragments 0% fibres	8	0.68 items per 50 ml *13.6* particles kg^{-1} 0.74–154.1 g/L Mean of 26.51 g/L

(continued on next page)

Table 1 (*continued*)

No.	Reference	Geomorphic Setting	Location/Comments	Microplastic Method and size range	microplastic Composition	No. Obs.	microplastic Concentration
18	Van Cauwenberghe et al. (2013)	Submarine fan (rise)	Nile Fan, deep-sea fan 1176m, multicore, top 1 cm, microplastic found in 5 of 11 samples studied	Wet sieve at 35 μm, Floatation NaI 1.6 g ml^{-1}.	particle	5	*70* particles kg^{-1} 1 plastic particle from core top
19	Kane et al. (2020)	Submarine fan (drift deposit)	Tyrrhenian Sea 16 box cores, top 5 cm sampled, Max 191 total pieces per 50 g. microplastic present in all samples.	Floatation $ZnCl_2$ 1.7 g ml^{-1}; >63 μm sieve; microscope ID	70-100% (91.6%)	16	1-191 (58.9) pieces per 50 g *1178* particles kg^{-1}
20	Qi et al. (2022)	Bengal submarine fan	Bay of Bengal, 9 samples, 2161 to 3890 m water depth; most MPs in 200–500 μm size range, decreasing trend from nearshore to the open sea	NaCl solution 1.2 g/cm^3, 330 μm mesh filter; microscope ID with FTIR	47.5% fragments 45.6% fibres	9	78.7 to 701.7 average of *249.2* ± 197.2 particles kg^{-1}
21	Qi et al. (2022)	Abyssal plain	Sri Lanka slope, 4 samples, 3846 to 4293 m water depth	NaCl solution 1.2 g/cm^3, 330 μm mesh filter; microscope ID with FTIR	47.5% fragments 45.6% fibres	4	114.4 to 211.45 average of *201.4* ± 67.92 particles kg^{-1}.
22	Sanchez-Vidal et al. (2018)	Abyssal plain	Mediterranean Sea and other locations, 5 stations, multicorer or Van Veen grab, 2009–2015, 10 ml sediment samples,	NaCl solution 1.2 g/cm^3, fibres 1–3 mm size range (filter used, size?)	100% fibres	5	28 pieces/50g *560* particles kg^{-1}
23	Van Cauwenberghe et al. (2013)	Abyssal plain	Porcupine Abyssal Plain, North Atlantic, 4800 m, multicore, top 1 cm	Wet sieve at 35 μm, Floatation NaI 1.6 g ml^{-1}.	Particle	3	*210* particles kg^{-1} 3 plastic particles from core tops
24	Kanhai et al., (2019)	Abyssal plain	Arctic Ocean, central basin, 855–4353 m, 11 sites, 7 contained microplastic, particles <100 μm excluded, top 2 cm, 9 particles recovered from 11 × 10 g samples = 80 particles/kg average	Floatation sodium tungstate dihydrate 1.4 g ml^{-1}; 1.2 μm filter; microscope ID	56% fibres 44% particles	7	*80* particles kg^{-1}
25	Cutroneo et al. (2022)	Abyssal plain	Mediterranean Sea south of France, 4 stations, 2443 m water depth	μRaman spectroscopy		4	*47* particles kg^{-1} 80 particles L^{-1}
26	Fischer et al., (2015)	Trench	Kuril–Kamchatka Trench, Ocean Trench, 4869 to 5766 m box core, 12 stations top 2 cm, microplastic present in all samples.	Sieved at 1 mm, 0.5 mm and 300 μm; microscope ID	75% fibres	12	60-2020 pieces per m^2 *61* particles kg^{-1}
27	Bergmann et al. (2017)	Trough	Arctic Ocean Hausgarten observatory, Spreading ridge and oceanic channel, 2340–5570 m depth, 9 stations, multicore sample top 5 cm collected in 2015, Fenton's reagent $FeSO_4 + H_2O_2$ treatment; microplastic conc. correlates with Chlorophyl-A and particulate organic carbon POC. microplastic present in all samples.	Floatation $ZnCl_2$ 1.7 g ml^{-1}; 1 μm filter; microscope ID	N/A	9	42–6595 (*4356* ± 675) particles kg^{-1}
28	Peng et al. (2018)	Trench	Mariana Trench, 11,000 m depth, 25 sample sites, gravity core, box-core, multicore or pushcore, top 6 cm. microplastic present in all samples.	Floatation NaCl 1.2 g ml^{-1}; followed by NaI 1.7 g ml^{-1}; 0.7 μm filter; microscope ID	microfibres were abundant	25	270–6200 *3225* particles kg^{-1}
29	Courtene-Jones et al. (2020)	Trough	Rockall Trough, 2200 m; megacore 0.5 cm slices to 5 cm, 1 cm slices to 10 cm; plastic mixed 10 cm depth into >150 years old sediment, 140 particles in total; no relationship found between TOC and MPs. microplastic present in all samples.	Separation using canola oil; 52 μm sieve; microscope ID; size range 0.06 mm to >12 mm	89% fibres 10% frag's 1% film 80% polyester	1	*197* particles kg^{-1} (0.197 ± 0.129) particles g^{-1}
30	Tekman et al. (2020)	Trough	Arctic Ocean Hausgarten observatory, Spreading ridge and oceanic channel, 272–5570 m depth, 5 stations, multicore sample top 5 cm collected in 2016, H_2O_2 et al. treatments; microplastic conc. correlates with Chlorophyl-A and particulate organic carbon POC.	Floatation $ZnCl_2$ 1.7 g ml^{-1}; 1 μm filter; microscope ID	N/A	5	239–13,331 (*4730* ± 5107) particles kg^{-1}
31	Qi et al. (2022)	Other deep-sea area	East Indian Ocean, seafloor ridge, 13 samples, 2360 to 4545 m water depth; most MPs in 200–500 μm size range, decreasing trend from nearshore to the open sea	NaCl solution 1.2 g/cm^3, 330 μm mesh filter; microscope ID with FTIR	47.5% fragments 45.6% fibres	13	30.30 to 294.4 average of *109.1* ± 79.68 particles kg^{-1}
32	Zhang et al. (2020)	Other deep-sea area	Western Pacific, Abyssal, 15 sites, box core top 5 cm, KOH treatment; microplastic detected in 13 sites, total of 40 particles, 4601 m–5732 m.	Floatation NaCl 1.2 g ml^{-1}; followed by NaI 1.7 g ml^{-1}; 8 μm sieve; microscope ID	45% fibres 30% films 17.5% fragments	15	0-1042 mean = *240* particles kg^{-1}
33	Van Cauwenberghe et al. (2013)	Other deep-sea area	South Atlantic, abyssal hills 2700 m, multicore, top 1 cm; 2 cores had no microplastic	Wet sieve at 35 μm, Floatation NaI 1.6 g ml^{-1}.	particle	1	*70* particles kg^{-1} 1 plastic particle from core top
34	Woodall et al. (2014)	Other deep-sea area	Indian Ocean, 3 stations 900–1000 m water depth, core top 1-2 cm, microplastic present in all samples.	Floatation NaCl 1.2 g ml- 132 μm sieve; 3 extractions; microscope ID	All fibres 56.9% rayon	3	1.4 to 4 pieces per 50 ml *59* particles kg^{-1}

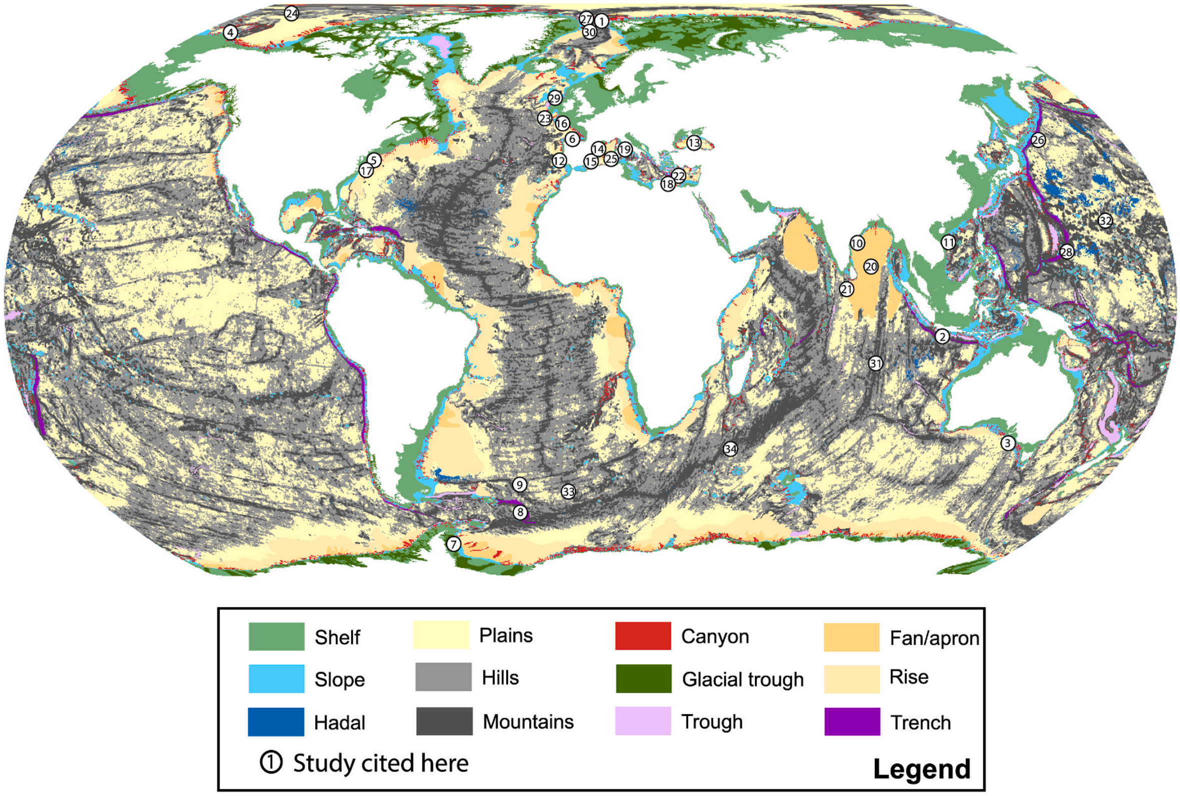

Fig. 2. Map showing the distribution of deep-sea microplastic observations used in this study to make a global estimate of microplastic mass in deep-sea sediments in relation to geomorphic feature categories. Numbers correspond to published papers listed in Table 1, as follows: 1) Woodall et al. (2014); 2) Cordova and Wahyudi (2016); 3) Barrett et al., (2020); 4) Fang et al., (2022); 5) Jones et al. (2022); 6) Sanchez-Vidal et al. (2018); 7–9) Cunningham et al. (2020); 10) Dhineka et al., (2022); 11) Feng et al., 2023; 12) Lechthaler et al. (2020); 13) Cincinelli et al., 2021; 14) Woodall et al. (2014); 15) Sanchez-Vidal et al., (2018); 16) Kukkola et al. (2022); 17) Jones et al. (2022); 18) Van Cauwenberghe et al. (2013); 19) Kane et al. (2020); 20–21) Qi et al., 2022; 22) Sanchez-Vidal et al. (2018); 23) Van Cauwenberghe et al. (2013); 24) Kanhai et al., (2019); 25) Cutroneo et al. (2022); 26) Fischer et al., (2015); 27) Bergmann et al. (2017); 28) Peng et al. (2018); 29) Courtene-Jones et al. (2020); 30) Tekman et al. (2020); 31) Qi et al. (2022); 32) Zhang et al. (2020); 33) Van Cauwenberghe et al. (2013); 34) Woodall et al. (2014).

(113 observations) of microplastic concentration from the continental slope; 4 studies (30 observations) from submarine canyons; 3 studies (30 observations) from submarine fans and continental rise; 5 studies (23 observations) from abyssal plains; 5 studies (52 observations) from deep ocean trenches or troughs; and 4 studies (32 observations) from other geomorphic areas including abyssal hills, seamounts and ridges (Fig. 2).

The details of our calculation are listed in Table 2 where the data have been assembled in relation to the six geomorphic categories. The variation between sampling methods, laboratory treatment of samples and reporting (among other factors) makes impossible any meaningful statistical analysis of these data (Tables 1 and 2), but some trends are evident. We note generally greater mean numbers of microplastic particles kg^{-1} of sediment from slope, canyon and fan/continental rise environments (~700 particles kg^{-1}) compared with abyssal plain and other ocean floor environments (~200 particles kg^{-1}). The greatest average concentration of ~2800 microplastic particles kg^{-1} occurs in trench/trough environments (Table 2). These general trends have been noted previously by other authors; for example, Qi et al. (2022) noted a general trend of decreasing microplastic particles kg^{-1} of sediment from nearshore to the open sea in the Bay of Bengal. Peng et al. (2018, 2020) and Tekman et al. (2020) noted that trenches or troughs may serve to focus the accumulation of microplastic giving rise to elevated concentrations of microplastic particles kg^{-1} in sediment of these environments.

We estimate a global mass of 3.05 million tonnes of plastic to be residing in deep ocean sediments (Table 2). This value is only ~20% of Barrett et al.'s (2020) estimate of 14.4 million tonnes which was based on their measured microplastic concentration of 1260 particles kg^{-1}.

Table 2
List of geomorphic feature collective categories and estimated mass of microplastic mass contained in each as described in the text. The surface area of each specific features is from Harris et al. (2014). Slope area is calculated minus canyon area; abyssal plain area is minus combined fan and rise area; other ocean floor is abyssal area minus the area of combined abyssal plains, fan and rise. The mean number of microplastic particles kg^{-1} of sediment is extracted from data listed in Table 1, where values are weighted based on the number of observations. The total area of geomorphic features excludes the (global) continental shelf area in this analysis.

Geomorphic feature name	Geomorphic feature area km^2	Mean Number of microplastic particles kg^{-1}	Number of observations	Mean microplastic kg/km^2	Mass of microplastic per Geomorphic feature (tonnes)
Slope	10,818,960	502	113	15.9	172,000
Canyon	8,787,300	784	30	24.8	218,000
Fan/Rise	29,832,040	714	30	22.6	675,000
Abyssal plain	71,031,690	217	23	6.88	489,000
Trench/Trough	4,808,770	2782	52	88.2	424,000
Other ocean floor	205,732,170	165	32	5.23	1,076,000
TOTAL	**331,010,930**		**280**		3,054,000

Using a smaller value of ~720 particles kg^{-1} based on average numbers found in 13 publications, Barrett et al. (2020) made a second global mass estimate of 8.4 million tonnes, which is still much larger than our estimate of 3.05 million tonnes. In our study we found that a concentration of ~700 particles kg^{-1} may apply to the surface areas of slope, canyon and continental rise (~50 million km^2; Table 2), but the total mass calculation is controlled largely by the concentration of microplastic that applies to abyssal plains and other deep ocean areas which cover ~270 million km^2 in the global ocean (Table 2). For these large areas we determined much smaller concentrations of microplastic (165 and 217 particles kg^{-1}; Table 2), and this is the main factor that explains the difference between our total mass estimate of 3.05 million tonnes compared with those of Barrett et al. (2020).

4. Discussion

In order to manage and understand marine plastics in the ocean, a total plastic budget is needed which quantifies the sources inputting plastic and the sinks removing plastic per unit time (Koelmans et al., 2017; Turrell, 2020; Sonke et al., 2022). The harmful effects of lost fishing gear (plastic nets and ropes) are well documented (eg. Richardson et al., 2019; Gilman et al., 2021) but microplastic pollution is also potentially harmful to marine life. Based on data available in the literature, Everaert et al. (2018) derived a safe concentration of 6650 buoyant particles m^{-3} for the water column and 540 particles kg^{-1} for sediment. Above these safe levels adverse ecological effects are expected to occur.

From the overview presented in Fig. 1, it is apparent that coastal zone and ocean water column storage combined account for most if not all of the approximately 75–199 million tonnes of plastic believed to have been lost to the ocean up until 2015 (UNEP, 2021); it is thus feasible that the mass of microplastic currently residing in deep ocean sediments may be relatively small. However, if the water column is merely a temporary sink for plastic which will eventually settle onto the ocean floor, then over the long term, understanding the fate of plastic pollution in deep-sea sediments becomes crucial. An error analysis of the assumptions made in our estimate of the total mass of plastic (Table 2) illustrates the sensitivity of the estimate to assumed microplastic size as well as microplastic concentration.

4.1. Apparent microplastic concentration measured in marine sediments

The main assumptions made in our calculation (Table 2) are: an assumed microplastic particle size of a 100 μm diameter sphere having a density of 1.099 g/cm^3 and sediment bulk density of 0.6 g/cm^3. The average size of microplastic particles has been examined by several authors. Barrett et al. (2020) reported a mean size of 100 μm; Courtene-Jones et al. (2020) reported a modal size of 0.5–1.0 mm whereas Bergmann et al. (2017) reported that 80% of microplastic's were smaller than 25 μm. Thus, there is no broadly accepted mean size for microplastic particles in deep-sea sediments. In any case, if our range in mean size is ± an order of magnitude (i.e. 10 μm–1000 μm) then the estimated mass of microplastic residing in the ocean ranges from 3050 tonnes to 3.05 billion tonnes (Fig. 3). This sensitivity derives from the uncertainty of mean particle size (radius) combined with the assumption of shape and the non-linear equation for the volume of a sphere (volume = $4/3\,\pi\, r^3$). The error in assuming a density of 1.099 g/cm^3 (the density of major plastic polymers ranges from 0.92 to 1.5 g/cm^3; eg. Harris, 2020) is comparatively trivial.

The assumption of sediment dry bulk density of 0.6 g/cm^3 is within the middle of the range for unconsolidated surficial deep-sea sediment. The porosity of the surface layer of unconsolidated deep-sea sediments ranges from 0.4 to nearly 0.9 (Nafe and Drake, 1963), the latter in the case of rapidly accumulating biogenic ooze. The mean wet bulk density of ocean sediments is 1.7 g/cm^3 (Tenzer and Gladkikh, 2014) and the dry bulk density varies from 0.17 g/cm^3 in siliceous oozes to 1.05 g/cm^3 in calcareous oozes (eg. Marshall, 1975). The error in assuming a sediment bulk density of 0.6 g/cm^3 is therefore comparatively small.

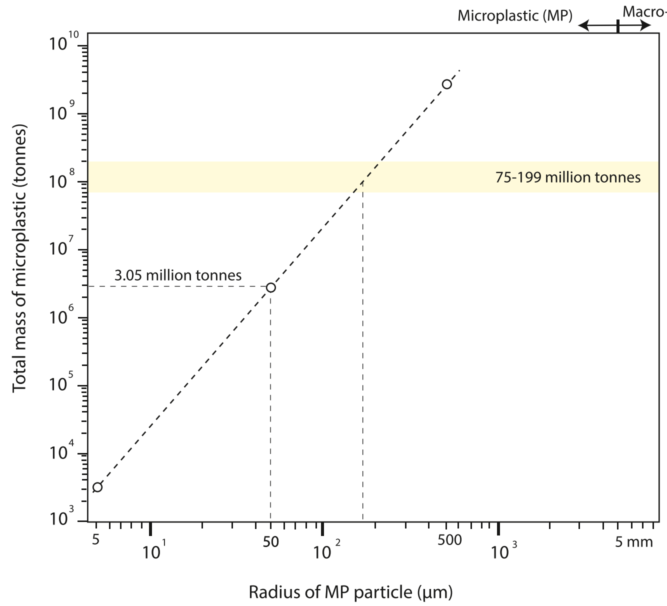

Fig. 3. Sensitivity of estimated mass of microplastic in the deep ocean to the assumed size of plastic particles. The size of 100 μm (radius of 50 μm) yields an estimated mass of 3.05million tonnes based on the calculation made here (Table 2) by applying the same assumptions used by Barrett et al. (2020). A size of 360 μm (radius of 180 μm) corresponds with to ~100–200 million tonnes, which is within the range of all plastic estimated by UNEP (2021) to be in the ocean as of 2015 (represented by the yellow-shaded zone).

While the assumption of a sphere shape may broadly apply to plastic fragments it is hardly an accurate shape for representing fibres. Fibres were the dominant microplastic type in the studies by Woodall et al. (2014), Fischer et al. (2015), Sanchez-Vidal et al. (2018), Kanhai et al. (2019), Courtene-Jones et al. (2020), Lechthaler et al. (2020), Cincinelli et al. (2021) and Fang et al. (2022). The assumption of a spherical shape overestimates the volume of fibre-shaped particles (Kooi and Koelmans, 2019), which consequently introduces error into the total mass estimated here (Table 2).

Available data sets indicate that there is no correlation between microplastic mass per kg of dry sediment weight and the number of particles kg^{-1} (Harris, 2020). The significance of this fact is demonstrated by the sensitivity of the mass calculation to the assumed particle size, which shows exponential changes in calculated mass with small changes in mean size (Fig. 3). The method used to determine the statistic of "mean particle size" plays a critical role in mass balance calculations. In the field of sedimentology, the determination of particle size statistics is based on frequency size distribution by measuring the mass of particles. Researchers often use nested sieves or settling columns into which dried sediment is introduced and the mass of each size fraction is determined. With the advent of laser particle size and Coulter counter instruments, it became possible to calculate frequency size distribution determined by particle number or mass, the latter by assuming a particle density and spheroid shape. Particle-size statistics for microplastic and microplastic particles calculated in these two different ways are not comparable. Plots of data (Harris, 2020, their Fig. 7) comparing size distributions of plastic particle numbers versus plastic particle mass by Martins and Sobral (2011) illustrate large numbers of very small particles in size-frequency distributions based on particles kg^{-1} are not necessarily an indication of higher mass concentration of microplastic. A small number (10%) of large macro-plastic particles (>10 mm in size) comprises the majority (89.6%) of the sample mass.

In the science of marine plastic pollution, both particle mass and particle numbers are relevant for different reasons. Particle numbers are particularly important for toxicology effects on biota (eg. Everaert et al., 2018) whereas the mean size based on particle mass is needed for mass balance calculations. Measurements of the size and mass of microplastic in sediments in addition to counting particle numbers are necessary to advance the development of mass balance budgets for marine plastic pollution.

The apparent plastic concentration in any given sedimentary environment is a function of three separate processes: 1) plastic input rate (g cm^{-2} y^{-1}); 2) the sediment accumulation rate (g cm^{-2} y^{-1}); and 3) depth and rate of bioturbation (cm^{-2} y^{-1}). The implications are that plastic particle concentrations in areas of high sediment input and/or high mixing rate (high dilution; eg. river deltas) may appear to be low compared to locations having lower sediment input and/or low mixing rate, but with the same plastic input rate. Conversely, plastic particle concentrations in areas of low sediment input and/or low mixing rate (low dilution, e.g., deep ocean sediments) may appear to be high compared to other locations. Of the 23 papers included in the present study (Table 1), only Jones et al. (2022) and Feng et al., 2023 reported microplastic mass per unit sediment volume in addition to particle numbers. Quantification of the mass flux of microplastic to the seafloor via sediment trap studies has been carried out in the Baltic Sea (Enders et al., 2019) and North Atlantic (Reineccius et al., 2020), but very few such studies have been carried out globally. Also, measuring plastic accumulation rates in the seabed requires more attention. It should be noted that while sediment accumulation in the deep-sea and biological mixing are often viewed as constant over decades to centuries, the rate of plastic input to the deep-seabed is likely increasing rapidly over the last century (eg. Uddin et al., 2021).

Of particular relevance here is the depth of sediment over which the measured microplastic concentration is applicable. Typical sediment accumulation rates in the abyssal global ocean are 0.01 to 0.0001 cm y^{-1} with values dropping off exponentially with distance from land (Restreppo et al., 2020). Hence, the thickness of sediment that has accumulated over the last 50 years (time since the widespread use of plastics) is of the order 0.5 to 0.005 cm, and therefore, the occurrence of plastic below ~0.5 cm depth in the sediment is likely related to biological mixing or potentially a physical sediment transport process (e.g., sediment slumping or turbidity flows, incorporation into migrating bedforms, etc). Bioturbation is known to affect ^{210}Pb profiles in sediment cores, and in the deep-sea, the rate of mixing is often much greater than the sedimentation rate, resulting in a surface mixed layer many cm in thickness (eg. Nittrouer et al., 1984; Smith and Schafer, 1984; Feng et al., 2021). If the average depth of sediment (and microplastic) mixing via bioturbation and/or physical sediment transport processes is less than 9 cm, then the microplastic mass in our calculation (Table 2) is over-estimated. Several papers included in this study of microplastic concentration measured microplastic only in the top 1–2 cm of core samples, and in such cases overestimates could occur if the mixing is not sufficiently strong or deep (eg. Van Cauwenberghe et al., 2013; Woodall et al., 2014; Fischer et al., 2015, Table 1). Conversely, along continental slopes and seaward of high sediment input point sources, sedimentation rates may be much higher (mm-cm/y; see Walsh and Nittrouer, 2009 for examples and additional references), and thus the 9-cm assumption could be a significant underestimate. The assumption of an average depth of 9 cm provides a good first-order estimate (Barrett et al., 2020) but points to the need for the inclusion of more information about sample sites selected for measurement of microplastic.

4.2. Settling of microplastic through the water column and dispersal by deep ocean currents

The processes that control the delivery of microplastic to the deep ocean floor are complex, but can be divided into two main groups: 1) settling through the water column; 2) advective transport from the continental shelf to the deep-sea by currents and density flows. Flocculation together with the colonisation (biofouling) of the floating microplastic particles with algae, especially in locations of high surface productivity, enhance the likelihood of microplastic particles sinking to the seabed as “passengers” of the biological carbon pump. Particle sinking speed depends on particle density, size and also shape (Van Melkebeke et al., 2020). At the Hausgarten observatory near the Arctic island of Svalbard, Tekman et al. (2020) reported plastic particles in the water column that were mainly low-density polymers at concentrations of up to 1287 particles m^{-3} and as high as 13,331 particles kg^{-1} in sediments. A key finding was the correlation between microplastic concentration in the water column with chlorophyll-A and particulate organic carbon (POC; Tekman et al., 2020). Conversely, in oligotrophic oceans Lobelle et al. (2021) found plastic particles 1 to 0.01 mm in size did not sink at all in their model. Thus the export of microplastic to deep-sea sediments will be greatest beneath productive locations of greater POC flux to the seabed (Harris, 2020, their Fig. 13). There is also evidence for increased concentrations of macro- and micro-plastic “fallout” beneath garbage patches floating on the ocean surface (Egger et al., 2020).

Krause et al. (2019) present evidence that once on the deep ocean floor there is very little degradation of plastic particles. It follows that MP fragments found on the deep seafloor became fragmented <u>before</u> they arrived in the deep ocean. We conclude that fragmentation of plastic objects is most likely a process that occurs predominantly in the coastal and inner shelf environments, but we acknowledge that much further research is needed to verify this.

Given that the primary source to the ocean water column is microplastic exported from the continental shelf (Fig. 1), and that concentrations are estimated to be high in the water-column and surficial shelf seabed sediments that may be remobilized, deep-sea fluxes will continue (and likely continue to increase) for decades. Unfortunately, we must wait for the stock of coastal plastic (source to the open ocean) to be depleted before the concentration suspended in the open-ocean, upper water column (Fig. 1) will begin to decrease.

The marine plastic input and transfer is not constant over time. Between 2008 and 2020 global plastic production increased from ~250 million tonnes/year to ~370 million tonnes/year (Tiseo, 2022) i.e. an increase of about 10 million tonnes per year (a growth rate of around 4%). It follows that, given an increasing amount of plastic is lost into the ocean, the mass of plastic entering the coastal zone and subsequently transported offshore to the ocean water column has been and will continue to increase until major changes occur. Based on our analysis, only a relatively small mass of plastic (3.05 million tonnes) has reached the deep ocean floor today, and although this amount will continue to grow, likely in a non-linear way (e.g., Brandon et al., 2019) the mass of plastic presently found in deep sea sediments is small compared with the mass apparently suspended in the water column. Thus there is a “*marine plastic cloud*” suspended in the oceanic water column that is increasing in concentration over time and from which export to the deep ocean sediments is slow in relation to human lifespans. We must therefore conclude that the mass of MP suspended in the ocean water column will continue to increase and is not in a steady state, an important consideration for designing future monitoring programmes and improving on mass balance models and assumptions made therein (Sonke et al., 2022).

Plastic items are transported to deep-sea sediments via submarine canyons, thus effectively bypassing the water column (Fig. 1). Recent field surveys of marine litter have reported concentrations of anthropogenic litter, including plastic debris, along canyon thalwegs (Kane and Clare, 2019). In their studies of MPs in submarine canyons, Woodall et al. (2014) and Cincinelli et al. (2021) reported fibres including rayon were the main microplastic type. In contrast the studies by Kukkola et al. (2022) and Jones et al. (2022) reported mainly fragments comprised of a mixture of both high and low-density polymers. Although data are sparse, it is apparent that concentrations of litter in canyons exceeds that found on canyon interfluves on the open continental slope (eg. Jones et al., 2022), which is contrary to the notion that plastic is settling mainly from the water column as a uniform, hemiplegic drape. Spatial heterogeneity in plastic distribution on the seabed must therefore be explained by other biophysical processes such as convergent circulation patterns or sediment-gravity flows (such as turbidity currents) rapidly transporting terrestrial sediment (and microplastic) to the deep-sea.

More specifically, where a canyon head incises the shelf, sediment (and plastic) in transit along the shelf (under a boundary current, for example) may be intercepted by the canyon and removed offshore. In one example from a canyon system located in the South China Sea, Zhong and Peng (2021) noted that litter was concentrated in canyon thalweg scours; this was interpreted by the authors as evidence that litter is transported down-canyon in turbidity currents, passing through the canyon on its way to the deep-sea basin. The mass of plastic transported off the shelf and down the continental slope via this pathway is unknown but is potentially significant.

Once sediment has arrived in the deep-sea, it and associated microplastic can be resuspended and transported by bottom currents. Locally high elevations of plastic particles have been reported from a submarine fan deposit located at the mouth of a canyon system in Italy where they appear to have been concentrated by bottom currents (Kane et al., 2020). Contour currents that give rise to sediment drift deposits located adjacent to many continental margins are supplemented by so-called "benthic storms", strong current events generated by surface current gyres (Hollister and McCave, 1984; see review by Stow and Pye, 1994). Such bottom currents have been measured and shown to resuspend sediments to create a near-bottom zone of elevated suspended sediment known as a "nepheloid layer". Microplastics including high-density polymers are also incorporated into such nepheloid layers (Erni-Cassola et al., 2019) which accounts for its dispersal and transport toward deep trenches (eg. Peng et al., 2018).

4.3. Effects of microplastic pollution on deep ocean benthic habitats

The widespread occurrence of high concentrations of microplastic particles in the ocean water column and in ocean sediments is alarming. The estimated values of microplastics suspended in the water column (~2500 particles m3) are already 40% of the threshold value of Everaert et al. (2018) of 6650 particles m^{-3} for the safety of pelagic species (see also Courtene-Jones et al., 2017). In addition, the results from our analysis indicate that microplastic pollution impacts are disproportionate among different deep-sea benthic habitats, with remote abyssal hills and mountains being affected less than habitats in submarine canyons, fans and continental rise environments and in trenches and troughs.

It is known that MP is ingested by deep sea fauna (Taylor et al., 2016) including habitat-forming organisms (Corinaldesi et al., 2021) and the presence of MP alters sediment microbial community composition and nitrogen cycling processes (Seeley et al., 2020).

We highlight that for many areas examined in this study "safe" levels of sedimented microplastics (i.e. 540 particles kg^{-1} sediment; Everaert et al., 2018) are already exceeded. This is shown by the mean values in submarine canyons, fans and continental rise environments and in trenches and troughs reported in the papers reviewed here (Table 2). It is acknowledged that there is wide variation within these geomorphic regions so not all areas have the same excessive levels of microplastic concentration (Table 1). Additional ecotoxicological research is urgently needed to confirm the effects where these concentrations are harmful to species residing in particular habitats.

5. Conclusions

The conversion of large plastic objects (macroplastics) into ever smaller microplastic particles happens along river courses long before reaching the sea (van Emmerik et al., 2022). Thus, a significant fraction of plastic mass discharged by rivers at the coast is probably already in the form of degraded and fragmented secondary plastic (Lebreton et al., 2019). In any case, macroplastic pollution is converted into microplastic in the coastal zone via abrasion by waves and currents and weathering over decadal timescales. From a policy perspective, the removal and reduction of large plastic objects from rivers and coastlines will therefore eventually mitigate microplastic pollution of the ocean.

Once it has arrived in the coastal zone, microplastic is partitioned between low-density polymers (polypropylene, polyethylene and polystyrene) and high-density polymers (Erni-Cassola et al., 2019). Low-density polymers are exported offshore to become main contributors to plastic in suspension in the open ocean (Pabortsava and Lampitt, 2020). The mass of low-density microplastic polymers in suspension is likely to have accumulated over a long period (decades) in order to account for the total mass residing there; water column storage or deep-sea sedimentation is not likely in steady-state in terms of the (increasing) rate of input versus the (slow) rate of sedimentation export to the abyssal ocean floor. The very small mass that has apparently accumulated in the abyssal sediments (~3.05 million tonnes) compared with the mass in suspension (40–90 MT) points to a very slow rate of export from the water column to the seabed. Thus there is a "*marine plastic cloud*" suspended in the oceanic water column that is increasing in concentration over time and from which export to the deep ocean sediments is slow in relation to human lifespans. However, we must acknowledge the uncertainty of our estimate of 3.05 million tonnes and note that further measurements of the size and mass of microplastic in sediments in addition to counting particle numbers are necessary to advance development of mass balance budgets for marine plastic pollution.

High-density polymers are apparently more likely to be trapped along the world's coastline. However, as has been observed for fine terrestrial sediments, some plastic particles of all sizes and densities inevitably escape the shelf either down submarine canyons or directly to the slope and potentially to adjacent submarine fans and the continental rise where measured mean concentrations exceed 700 microplastic particles kg^{-1}. In particular, trough and deep-sea trench geomorphic features appear to trap excessive amounts of microplastic where measured mean concentrations exceed 2700 microplastic particles kg^{-1}. These figures are alarming because they already exceed the 'safe' concentration for benthic marine life (540 particles kg^{-1}) proposed by Everaert et al. (2018). The risk to benthic ocean life is thus an urgent consideration for curbing the flow of plastic pollution into the ocean. Monitoring of the concentration of plastic particles in the water column and in sediments of submarine canyons, fans and continental rise environments and in trenches and troughs should be a priority to ensure the efficacy of policies and actions taken to curb ocean plastic pollution at both the national and global levels.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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