Sources, distribution, and fate of microscopic plastics in marine environments: Prof. **Richard C. Thompson*** (Plymouth University, UK)
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Abstract
Microplastics are pieces of plastic debris <5mm in diameter. They enter the environment from a variety of sources including the direct input of small pieces such as exfoliating beads used in cosmetics and as a consequence of the fragmentation of larger items of debris. A range of common polymers, including polyethylene, polypropylene, polystyrene and polyvinyl chloride, are present in the environment as microplastic particles. Microplastics are widely distributed in marine and freshwater habitats. They have been reported on shorelines from the poles to the equator; they are present at the sea surface and have accumulated in ocean systems far from land. Microplastics are also present in substantial quantities on the seabed. A wide range of organisms including birds, fish, and invertebrates are known to ingest microplastics and for some species it is clear that a substantial proportion of the population have microplastic in their digestive tract. The extent to which this might have harmful effects is not clear; however the widespread encounter rate indicates that substantial quantities of microplastic may be distributed within living organisms themselves as well as in the habitats in which they live. Our understanding about the long-term fate of microplastics is relatively limited. Some habitats such as the deep sea may be an ultimate sink for the accumulation of plastic debris at sea; indeed some recent evidence indicates quantities in the deep sea can be greater than at the sea surface. It has also been suggested that microplastics might be susceptible to biodegradation by microorganisms however, this is yet to be established and the prevailing view is that, even if emissions of debris to the environment are substantially reduced, the abundance of microplastics will increase over the next few decades. However, it is also clear that the benefits which plastics bring to society can be realized without the need for emissions of end of life plastics to the ocean. To some extent the accumulation of microplastic debris in the environment is a symptom of an outdated business model. There are solutions at hand and many synergistic benefits can be achieved in terms of both waste reduction and sustainable use of resources by moving toward a circular economy.

Keywords: microplastic, contamination, pollution, harm, policy, solutions

1. Definitions

The term microplastic is used to describe small pieces of plastic debris. There is no universally recognized definition. Small fragments of debris were first reported at the sea surface in the early 1970s [e.g. 1, 2] and Ryan and Moloney described the abundance of fragments on shorelines in the 1980s using the term microplastic [3]. In 2004, evidence of widespread occurrence of truly microscopic pieces of plastics was presented by Thompson et al who also used the term 'Microplastics' to describe these pieces, but no formal definition was presented [4]. Research interest in the topic of microplastics increased dramatically thereafter (Fig. 1). In 2008, NOAA hosted the first international workshop on the Occurrence, Effects and Fate of Microplastics [5] and a working group of the assembled participants made a somewhat pragmatic decision to define microplastic as small pieces less than 5mm in diameter. One reason for this was that they considered particles of this size might behave differently in the environment and present different types of hazards to those that were already widely recognized for larger items, where entanglement is a major concern [6, 7]. While 5mm is widely accepted as an upper bound for the definition of microplastics, the lower bound is much less clearly defined.

Particles as small as 20µm have been reported in the environment and it seems likely that even smaller particles of plastic debris in the nano particle size range are also present in the environment. However, at present the limit of detection, which relies on particle identification by spectroscopy, is around 20µm [8]. The ability to capture very small particles such as these is also directly affected by the type of sampling equipment used. For example, collection from the water column will often utilize plankton nets which are typically made of 333µm mesh. Whereas, microplastics are often extracted from sediments via a density gradient and flotation subsequently collecting the buoyant particles over filter paper which can be capable of capturing much smaller particles. Hence, at present there is no universally accepted size range or methodology for the collection of microplastics. A recent report by GESAMP, an advisory body to the United Nations, adopted the working definition of microplastics from 1nm to <5mm [9]. However our knowledge about environmental quantities of particles at the lower end of this size range is completely lacking. Within the EU, there is currently work to promote greater harmonization for future monitoring [8] however, at present, it is difficult to make formal comparisons between data collected by different research teams since methodologies vary. This is important because it fundamentally limits our ability to describe distributions and also to accurately assess abundance which is of fundamental importance not just in order to monitor changes in the levels of contamination but also to indicate the likely frequency of encounter by biota which is necessary to inform risk assessment.

2. Sources

A wide variety of polymers are used to make a diverse array of plastic products, many of which bring considerable societal benefit. All of the most common polymers have been identified as microplastic particles. These include, in order of frequency of studies reporting: Polyethylene (PE), Polypropylene (PP), Polystyrene (PS), Polyamide (Nylon) (PA), Polyester (PES), Acrylic (AC), Polyoximethylene (POM), Polyvinyl alcohol (PVA), Polyvinyl chloride (PVC), Poly methyl acrylate (PMA), Polyethylene terephthalate (PET), Alkyd (AKD), and Polyurethane (PU) [10]. However, knowledge of the type of polymer found as a microplastic particle in the environment does little to help confirm the source of the particle since a single polymer can be used in a very diverse array of applications. Microplastics have been reported in the environment in a wide variety of colors, shapes and sizes [10, 11]. Collectively this information on polymer type, shape, and color may, to a very limited extent, help to indicate possible sources according to original usage; for example, fibers from rope/netting, versus fibers from clothing/ carpets. However, this information is of little use in identifying the geographic sources of origin. Microplastics can be described in two very broad categories which reflect their potential sources and usage; these are 'primary' and secondary microplastics.

Primary microplastics are particles which enter the environment as litter of microplastic

(<5mm) size. That is to say the release of pieces that are manufactured for use as microplastic sized particles. Sources of primary microplastics include spillage of pre-production pellets (~ 4mm in diameter, sometimes called '*mermaids tears'* or '*nurdles'*) or powders (>1mm in diameter such as those used in roto-molding) which are being transported prior to being converted into plastic products. In addition, release of plastic particles which are used as shot blasting media, particularly in the cleaning of softer metals such as aluminum [12]. Primary microplastics also include the release of exfoliant microbeads used extensively in the cosmetics industry. For example, microbeads typically around 250µm in diameter are used in a wide range of skin cleansers, shower gels, and toothpaste. When used, there is nothing the consumer can do to prevent the release of these microplastic particles into waste water and it is considered likely that a substantial proportion will then pass through waste treatment into the environment [13]. Quantities can be considerable with millions of individual plastic particles in a single 150mL container of cosmetic [14].

Commented [??1]: Is Gouin et al. correct reference? He did not deal with microbeads removal during sewage treatment. Please check it.

He based his paper on the quantity of microbeads that might pass through

So I think the reference is OK

By contrast, secondary microplastics are microplastic sized particles that have arisen as a consequence of the fragmentation, in the environment, of larger items of debris, such as packaging, rope, sanitary related products. With secondary microplastics, it is logical to assume that quantiles should broadly reflect the quantities of larger, identifiable, items of debris collected in routine monitoring. Such studies typically report single-use disposable items of packaging, sewage related debris, together with rope and netting as being some of the most common types of litter on shorelines. A further and potentially substantial input of microplastic to the environment is the release of fibers from textiles, for example as a consequence of machine washing. Fibers have been reported in residues from sewage treatment on land [15] and at elevated quantities around former sewage sludge dumping grounds in the marine environment [16]. While these fibers can in effect enter the environment as pieces that are already microplastic in size, since they were not manufactured as microplastics they are generally considered as a secondary input.

3. Distribution

The distribution of microplastics can be considered from several perspectives. The most obvious is perhaps the geographic distribution and this can be evaluated at a range of spatial scales from less than a few meters, for example within a beach [e.g. 17], to scales of several kilometers between beaches in a region for example, to global scale patterns between countries or continents [16, 18]. Distribution can also be categorized between environmental compartments for example, the quantity of microplastic at the sea surface, in the water column, on the sea bed (both subtidal and intertidal e.g. [4]) and quantities in biota, for example that have accumulated via ingestion [19, 20].

Since there are no universally recognized protocols for collection, sampling methods vary considerably among researchers, and this will have a strong influence on both the ability to detect microplastics as well as the types, sizes, and abundance of microplastics recorded [10]. The potential for bias is likely to increase the smaller the size of microplastic being sampled. Pieces >1mm in diameter can typically be identified as plastic with a high degree of confidence by unaided visual examination. However, smaller particles will require visualization via microscopy and to be certain will also need formal identification using either Fourier transform infrared (FT-IR) or Raman spectroscopy [10]. These spectroscopic approaches require expensive capital equipment and are time consuming, hence are not universally applied. Yet in my experience of the sub millimeter particles that appear 'unusual' and look sufficiently like they might be plastic for them to be subjected to formal spectroscopic identification actually only about one third are confirmed as plastic. Despite these difficulties several studies do present information on geographic patterns of distribution. Thompson et al [4] use standard approaches and FT-IR spectroscopy to illustrate the presence of microplastics at sites around the United Kingdom and, working near Plymouth, UK, also show greater abundance in subtidal sediments compared to intertidal sediments (Fig. 2). Using the same approach this team went on to sample intertidal sediments on a global scale, reporting the presence of microplastic on each of more than 20 shorelines sampled. Spatial variation among sampling sites was relatively low indicating the ubiquity of microplastics in the intertidal [16]. A much more extensive study spanning more than 20 years of routine data collection by volunteers shows the relative abundance of debris captured by plankton nets in the Atlantic Ocean. Here, there was no routine formal particle identification analysis, but the pieces recorded were typically 1mm. A key finding from this study was substantial evidence of spatial patterns. Interestingly, the debris was most abundant in locations far from land indicating the importance of transport, of example away from human population centers. Indeed, the relative abundance showed a good level of predictability based on patterns of ocean circulation which appeared to be causing debris to accumulate in oceanic gyres (Fig. 3). Recent work in the Mediterranean has also shown elevated abundance near to population centers implicating them as potential sources and the shoreline study by Browne et al. also indicated a weak correlation between abundance and the human population at a regional scale [16]. In summary, these studies have demonstrated the wide spread distribution of microplastic on shorelines and at the sea surface, with evidence of elevated abundance near to population centers and also in locations where ocean circulation causes floating items to become trapped in surface gyres [21] or possibly where particles sink to the seabed [11]. There is a considerable challenge in scaling up from individual studies, especially considering the lack of consistency in sampling, in order to produce global estimates of marine debris and even more challenging global estimates of plastic distribution [22]. However, numerical models based on floating macroplastic debris have been developed [23-25] and no-doubt models to estimate the distribution of microplastic will be evolved. Such models can be invaluable in helping to formulate predictions and to help frame hypotheses about the sources and ultimate sinks for marine debris and hence, also inform our understanding of encounter rate with marine organisms.

In addition to the studies above some of which were designed to make spatial comparisons of microplastic using standardized protocols, there have been numerous pioneering studies demonstrating the accumulation of microplastics in specific locations and environmental compartments. In terms of habitats, microplastic has to, my knowledge, been reported in every location so far examined. In addition, to the sea surface and intertidal, substantial quantities of microplastics have been reported in marine sediments. This includes substantial quantities in shallow water sediments. For example, quantities in excess of 2000 items per kilogram dry weight have been reported from sediments in the Venice Lagoon [26]. Recent work suggests quantities per unit volume in the deep sea sediment may be greater than per unit volume of water collected at the sea surface (although sampling these habitats unavoidably requires different methodology) possibly implicating the deep sea as an ultimate sink for microplastic accumulation [11]. Elevated quantities have also been reported in sea ice collected in the Arctic. Here, it appears that the process of ice formation may provide a mechanism leading to the concentration of particulate plastic from the nearby water column [27]. It should be noted that while this chapter focuses on the marine environment, there is growing evidence of widespread accumulation in freshwater lakes and rivers [28].

Microplastics have also been widely reported in biota. A recent review indicated around 10% of all papers describing encounters between debris and species described encounters with microplastics [7]. For example, microplastics have been reported in commercially important species of fish [19, 20] and shellfish [29]. Although quantities per individual are low, typically one or two items per individual, data indicate that a substantial proportion of the individuals in some populations are contaminated with microplastics. For instance Murray et al showed that over 80% of the individuals for a population of Dublin Bay prawns contained microplastics [29]. The most extensive data on ingestion of plastic debris comes from the work of Jan van Franeker who has been sampling populations of the Northern Fulmar in European waters for over 30 years. At the outset, his surveys did not explicitly categorize microplastics, however many of the items in these birds were within the microplastic size range. He has shown that in some parts of Europe more than 90% of individuals contain plastic debris. Indeed, the quantities in some birds are substantial, and despite some of the debris being regurgitated or defecated it appears that seabirds are retaining plastic debris. Jan van Franeker has estimated that in the North Sea region Fulmars probably process by ingestion around 6 tonnes of plastic annually translating to about 0.6 tonnes contained within the living population at any given time (pers. com. van Franeker). Once a bird dies and its body tissues decay then any plastic it did contain will be released back to the environment [30].

4. Fate

Plastics have only been mass produced for around 60 years, however, it is clear that in this time, plastic debris has contaminated habitats and biota on a global scale. This is equally true of microplastics which have accumulated on shorelines from the poles to the equator at the sea surface and in the deep sea; they have also accumulated in wildlife. There are few data on temporal trends in the abundance of plastic debris and the data that do exist tend to show considerable temporal variability rather than a trend of increasing abundance as might be expected based on plastic production statistics. Microplastic is a potential exception to this with some data illustrating an increase in abundance over time. Data collected by the continuous plankton recorder in Scottish waters showed significant increases in microplastic abundance when comparing between the 1960s and 1970s with the 1980s and 1990s. Hence it has been suggested that one of the reasons an increasing trend in the abundance of macroplastic is not evident from monitoring data is that larger items of plastic are progressively fragmenting into smaller items that have not been routinely captured in monitoring studies. It is also clear that microplastics are accumulating in inaccessible and relatively under-sampled locations such as the deep sea [11] and within arctic sea ice [27] and biota [7]. Microplastics have also accumulated in beach sediments more than a metre beneath the sediment surface [31]. More generally during microplastic sampling, all protocols require a visual discrimination step. This means that microplastics that resemble natural particulates; for example white or translucent relatively spherical particles will be hard to distinguish from sand when compared to brightly coloured fibrous shaped pieces. Hence there are a variety of factors that all result in environmental monitoring under sampling microplastics.

Plastics are very durable and are resistant to degradation. Ultraviolet light weakens plastic and coupled with mechanical action, for example from wave energy, this can cause large items to fragment into microplastics. Hence, it is possible that the ultimate fate of all of the plastic in the environment is as microplastic sized pieces. In term of quantities, microplastics are substantially more abundant than macro plastics in some locations. However, by mass macroplastics are still by far the dominant size faction in the environment [17]. Therefore even if we were able to prevent additional inputs of plastic debris to the sea with immediate effect the quantity of microplastics would still continue to increase over time as a consequence of the fragmentation of legacy items already present in the environment (Fig. 4) . It is also clear that there is no effective means of removing microplastic once it is in the ocean. Hence, in addition to further research to quantify the abundance of microplastics and consider their potential effects on biota and the environment, it is essential to focus on developing measures to reduce the inputs of debris. This is a pressing priority because even if we were able to initiate this action today it could take decades before this was translated into a substantial reduction in the rate of accumulation of microplastics.

From the perspective of the longer term fate of microplastics in the ocean, polymer chemists consider that all of the conventional plastic (i.e. non-biodegradable) that has ever been produced is still present on the planet in a form that is too large to be biodegraded [32]. The exception to this is plastic that has been incinerated. Like all solid items in aquatic habitat plastic debris including microplastics readily becomes colonised by microorganism and microbial assemblages have been shown to vary according to plastic type [33, 34]. Some consider that biodegradation of conventional plastics is ultimately possible however there is little clear evidence of this. If biodegradation is occurring, it would appear that rates are incredibly slow, to the extent at least, that we should not rely on biodegradation to have any meaningful effect on the quantities of debris in our oceans when considered in relation to the substantial inputs of plastic marine debris [35].

5. A personal perspective on the solutions to this global environmental problem

Is the long term fate then that our planet will become contaminated with exponentially increasing quantities of microplastics? From a personal perspective it seems the warning signs are apparent and recent papers outline some of the concerns relating to microplastics in the environment including the potential for physical damage [36] as well as toxicological harm [37]. Is it inevitable that quantities of plastic and microplastic will increase? Yes it is inevitable, unless steps are taken to reduce inputs of debris to the ocean.

Thinking more broadly about inputs of plastic to the environment, there are several important additional considerations [38]: 1) From the perspective of sustainable use of resources, it has been estimated that we use around 8% of world oil production to make plastic items, yet around a third of these items are discarded within a short time frame. Plastics are inherently recyclable, so by recycling end-of-life plastic it is possible to reduce the accumulation of debris while at the same time reducing our demand for fossil carbon [39]. 2) Plastic items are important to society; however there is something fundamentally different between the problem of plastic marine debris and several other current environmental problems. Unlike turning on an electric light or taking an aeroplane journey, the emission, in this case of debris to the oceans, is not directly linked to the benefit. So we can, in theory, obtain the benefits from plastic items without there being a need for emissions of end-of-life plastics to the oceans. 3) Together with other scientists, representatives from industry, policy makers, and NGOs, I frequently attend meetings focused on marine debris problems and solutions. While there may be discussion and sometimes disagreement about the relative importance of the various impacts; there is typically universal consensus to reduce inputs of debris to the ocean – in essence, I do not meet '*marine debris deniers'*. From a broad perspective, we already know that marine debris is damaging to the economy, to wildlife and the environment, it is wasteful and unnecessary and (as far as I am aware) we are agreed it needs to stop. That being the case, then, what are the problems that retard progress?

In my opinion, the problems that retard progress relate to prioritising solutions: who should take the action and if there are costs, who should pay [for further discussion see 38]? The solutions are well known; they principally lie on land rather than at sea and in decreasing order of merit are: 1) reduce material usage – any reduction in the amount of new plastic produced will reduce the quantity of end-of life material that results and hence reduce the potential for formation of microplastics, 2) reuse items – this will directly reduce the need for new plastic items and so also reduce the quantity of end-of-life plastic material, 3) dispose of end-of-life items properly; ideally recycle them, 4) recycle, since turning end-of-life material back in to new items in a closed loop will reduce the accumulation of waste and simultaneously reduce demand for fossil carbon, 5) energy recovery via incineration – where items cannot easily be re-used or recycled, should be considered as a poor alternative to 1 -4. Finally, but because it is overarching potentially most important we need to redesign, so for every plastic product consider, at the design stage, the hierarchy of options above in order to maximise the overall environmental footprint i.e. reduce use of fossil carbon and reduce the accumulation of waste for example, by designing so that the eventual end-of-life products can readily be used as raw material for new production. Such principles are gaining momentum, for example within the EU, there is considerable interest in the philosophy of circular economy [40]. There is public interest and response from industry, for example some manufacturers have voluntarily opted to reduce the use of microbeads in their cosmetics [14]. Public interest and concern has also translated into policy actions for example to reduce the number of single-use plastic carrier bags. There are also industry led initiatives which unless used appropriately could work against these goals, for example use of bio-based carbon from agriculture is seen as a sustainable alternative to fossil carbon. However altering the carbon source does nothing to reduce marine debris, and where land is at a premium for food housing or natural habitats, a more efficient and arguably more sustainable solution is to supply the required carbon by recycling end-of-life plastic. Similarly designing plastic products so that they degrade / disintegrate more rapidly, can compromise the potential for product re-use, contaminate recycling, and lead to rapid accumulation of fragments in the environment [39]. What is needed is policy-led coordination of actions, supported by sound science, to utilise the measures above to achieve change as efficiently and rapidly as possible. This will likely involve voluntary actions, incentives, taxes, and education [41]. In particular there is a need to re-educate, thus far my life-time has been spent in a world with rapidly increasing production of disposable short term products and packaging, and of durable goods that cannot be repaired or renewed. In short, we are in a growing culture of throw-away living; there is an urgent need to recognise there is no such place as '*away*'. Marine litter and in this case microplastics are in effect symptoms of an outdated and inefficient business model; there are choices that need to be made now in order to be more sustainable and to reduce the environmental impacts that otherwise will be left to challenge future generations.

Figure Legends

Fig. 1 Publications by year 1970 – July 2015, Using the search terms 'plastic pellets' and 'microplastics'. Compiled by Sarah Gall, Plymouth University. Reproduced from [9] with permission.

Fig. 2 (**A**) Sampling locations in North-East Atlantic: Location of sites near Plymouth used to compare the abundance of microscopic plastic among habitats, □ (see Fig. 1D). Other shores where similar fragments were also found, ●. Routes sampled by Continuous Plankton Recorder (CPR 1 and 2) since 1960 and used to assess changes in the abundance of microplastics, ---- . (**B**) One of numerous microscopic fragments found among sediment from beaches and identified as plastic using FT-IR spectroscopy, bar = 50µm. (**C**) FT-IR spectra of a microscopic fragment matched that of nylon. (D) There were significant differences in abundance of microplastics between sandy beaches and subtidal habitats (ANOVA on $\log_{10}(x + 1)$ transformed data, $F_{2,3} = 13.26$, $P < 0.05$, $* = P < 0.01$), but abundance was consistent among sites within habitat type. (E) Accumulation of microscopic plastic in CPR samples revealed a significant increase in abundance when comparing the 1960's and 1970's to the 1980's and 1990's (ANOVA on $\log_{10}(x + 1)$ transformed data, $F_{3,3} = 14.42$, $P < 0.05$, $* = P < 0.05$). Approximate figures for global production of synthetic fibres overlain for comparison. Microplastics were also less abundant along the oceanic route CPR 2 than CPR 1 ($F_{1, 24} = 5.18$, $P < 0.5$). Reproduced from [4] with permission.

Fig. 3 Average plastic concentration as a function of latitude for data shown in Fig. 1 of [21] (bars, units of pieces km-2), and concentration, C (color shading), of initially homogeneous (C=1) surface tracer after 10-year model integration (S2). Averages and standard errors were computed in one-degree latitude bins. The highest plastic concentrations were observed in subtropical latitudes (22-38°N) where model tracer concentration is also a maximum. Reproduced from [21] with permission.

Fig. 4 Sources and accumulation of microplastics. a) Microplastics can be generated from the break-up of large (macroplastic) items in the environment. These items include plastic packaging such as carrier bags and bottles. Microplastics formed in this way are described as secondary microplastics ((a) top two photos). Microplastics also enter the environment as a consequence of direct inputs of microplastics sized particles. Such particles are described as primary microplastics ((a) bottom photo, a plastic microbead from a cosmetic product, Courtesy of Adil Bakir and Richard Thompson, and Plymouth University Electron Microscopy Unit). b) Once in the environment plastic items will progressively fragment into smaller and smaller pieces. Here, we see the relationship between the number of fragments formed by breakdown of the items shown in (a, red line = carrier bag, blue line = bottle and black line = microbeads from a cosmetic product) and the total surface area of plastic. c) This fragmentation will lead to formation of smaller particles and be associated with increased abundance increased potential for ingestion and increased surface area and hence increased potential for chemical transport. d) Microplastic fragments recovered from the Tamar Estuary, Plymouth Courtesy of Mark Browne, Plymouth University and e) Microplastic fragments recovered from surface waters in the North Atlantic (courtesy of Kara Lavender Law, SEA Foundation).

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