Nature of Plastic Marine Pollution in the Subtropical Gyres

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Abstract The abundance and distribution of plastic debris in the marine environment show patterns of near- and offshore generation, migration toward and accumulation in the subtropical gyres, fragmentation, and redistribution globally. Ecological impacts in the subtropical gyres include invasive species transport and rampant ingestion and entanglement; yet plastics have also created substantial new habitat, resulting in population increases in some species. Though estimates of surface abundance and weight indicate over a quarter million tons and particle counts in the trillions, there is also a rapid removal of microplastics from the sea surface. Recent studies show widespread occurrence of these microplastics throughout the vertical column and in benthic and coastal sediments. It is likely that sedimentation is the ultimate fate for plastic lost at sea. Before microplastics sink, they likely cause significant impacts to marine food chains and ecosystems. In the open ocean, plastics are mingled with marine communities, making removal at sea prohibitive. This new understanding informs mitigation efforts to divert attention away from open-ocean cleanup. Similar to the way societies dealt with widely distributed particulate contamination in the air above cities, the "smog" of

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microplastics destined to pass through marine ecosystems before finally settling on the seafloor is best addressed with preventative measures.

Keywords Garbage patch, Marine debris, Plastic debris, Subtropical gyre

Contents

1 Tracking Plastic in the Gyres

There are 11 gyres described in the world's oceans [1], 2 subpolar gyres below the Arctic Circle, 3 in Arctic waters, the circumpolar gyre around Antarctica, and the 5 subtropical gyres (Fig. 1). Plastic debris has been observed worldwide, with variation in the distribution and abundance following predictions from current models. This hydrodynamic flow, coupled with seasonal trends and variation in human inputs, influences the spatial variability of anthropogenic debris. Much attention is directed toward the subtropical gyres because of their propensity to accumulate floating debris. Here, the behavior of floating plastics in the gyres is reviewed with emphasis on the movement, characterization, some ecological characteristics, and fragmentation and fate of microplastics.

1.1 Defining a Gyre

The subtropical gyres are large-scale systems of wind-driven surface currents, flowing counterclockwise in the southern hemisphere and clockwise in the north, caused by the Coriolis effect, a force which tends to move wind and water currents to the right in the northern hemisphere and to the left in the south, creating cyclonic atmospheric and ocean movements.

Westward equatorial currents, on both sides of the equator, split when they reach continents. One branch flows toward the equator to join equatorial countercurrents. The other branch flows away from the equator, forming the western boundary currents of the subtropical gyres. These currents turn when they reach colder waters and flow eastward across the ocean again until reaching another continent, where they split again. In the northern hemisphere, one branch flows north toward the subpolar gyres, while the southern branch forms the eastern boundary currents of the North Atlantic and North Pacific subtropical gyres. In the southern hemisphere, these eastward currents also split, with one branch forming the eastern boundary current of the three subtropical gyres. The other branch continues east around Cape Horn, Cape of Good Hope, and south of Australia and New Zealand, following the direction of the circumpolar gyre (Fig. 1).

Climatological wind stress in the atmosphere contributes to these rotational fields, resulting in stable high-pressure systems [2]. Ekman transport, the movement of water perpendicular to the direction of wind, creates those surface currents that transport floating debris toward the center [3].

The subtropical gyres are characterized by warm surface waters, contrasting the colder and more biologically productive waters of the subpolar and circumpolar gyres [4]. A subtropical convergence zone (STCZ) forms where the colder waters are driven below the warmer waters in the subtropical gyre [5]. This is a physical front, where low phytoplankton productivity in warmer waters, indicated by low chlorophyll-a

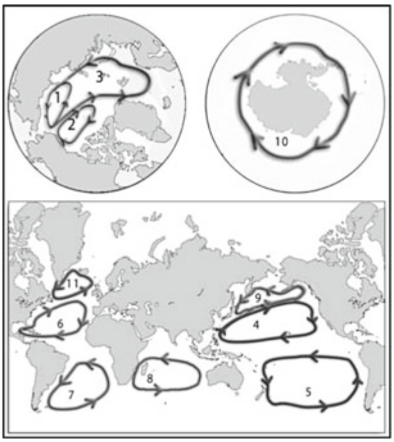

Fig. 1 Location of 11 gyre systems in the world's oceans (adapted from "Flotsametrics," [1])

values, meets higher values in the colder waters. Called the Transitional Zone Chlorophyll Front (TZCF), it is observed on satellite-derived color maps of ocean basins [6]. In the North Pacific, the TZCF and sea surface temperatures were correlated with densities of plastic marine pollution, in what is called the Debris Estimated Likelihood Index (DELI) [5]. The transitional zones between subtropical and subpolar (circumpolar) gyres are present in all five subtropical gyres, and observed plastic debris concentrations rapidly decline across these fronts [7].

The accumulation zones of plastic that form in the subtropical gyres are a result of the diminished winds and currents occurring at latitudes synonymous with continental deserts. These oceanic deserts, with low productivity, do not appear to be static regions that aggregate plastic indefinitely. There are chemical, mechanical, and biological processes at play that accelerate the fragmentation of plastic in the subtropical gyres.

1.2 Historical Observations

Plastic debris was first reported in the western North Atlantic in 1972 [8]. Two years later a substantial analysis of plankton tows in the same region reported widespread distribution of preproduction plastic pellets, foamed polystyrene spheres, and angular fragments floating near the eastern United States, Gulf of Mexico, and Caribbean Sea [9]. Explorations in the South Atlantic near Cape Town, South Africa, in 1980 reported preproduction plastic pellets and balls of tar, reportedly from the flushing of oil tankers into the sea [10]. Six years later, extensive studies in the North Atlantic sampled further offshore, coining the term “plasto-tarball” for the aggregations of plastic pellets, fragments, and tar, and this offers the first suggestion that plastic debris accumulates in the gyres. “Data from our oceanic survey suggests that plastic from both intra- and extra-gyral sources becomes concentrated in the center of the gyre, in much the same fashion that *Sargassum* does” [11].

Simultaneously, exploration of the North Pacific was under way [12, 13], and at the Second International Marine Debris conference in 1989, Day et al. reported results from 203 stations across the North Pacific, including the Sea of Japan, eastward to Hawaii, and northeast toward Alaska, and into the Bering Sea [14]. The authors observed a predictable boundary of debris concentrations in the waters surrounding the subarctic gyre below Alaska, where surface waters move away from the center. The highest observed abundance of 316,800 pieces of plastic km^{-2} was well inside the western accumulation zone of the North Pacific Subtropical Gyre [14]. Yet, this study had missed the waters between Hawaii and the west coast of the United States. For nearly a decade, the study of plastic debris fell silent. A 2001 study of the waters between California and Hawaii conducted 11 neuston tows with a mean of 334,271 pieces per km^2 [15] greater than the highest single abundance Robert Day and collaborators had reported in 1990. With wide media attention, the term “garbage patch” entered the public and scientific lexicon [16, 17], propelling public and research interest rapidly forward.

Accumulations of plastic debris have been observed regionally in the South Pacific [18, 19], South Atlantic [20], Bay of Bengal [21], circumnavigating Australia [22], Southern Ocean [23], Mediterranean Sea [24], North Pacific [25] and North Atlantic [26], and globally [7, 27]. Recent calls for standardization of methods [28] and citizen science [29] aim to broaden the utility and monitoring capability of future efforts.

2 Sources of Plastic to the Marine Environment

A generally accepted estimate indicates that up to 80 % of plastic debris originates from land-based sources [30] and 20 % originates from maritime activities. However, despite being widely cited, this figure is not well substantiated and fails in quantifying plastic waste inputs [31]. Thus, the following sections attempt to provide a more detailed analysis.

2.1 Land Inputs

The major land-based sources of plastic debris include wastes from dumpsites in coastal regions, watersheds and rivers, industrial outfalls, littering of beaches, tourism, and recreational use of the coasts [32]. Extreme events such as storms, tidal waves, and tsunamis are also a significant immediate source of land-based plastic debris. Particularly, the pulse of debris washed into the North Pacific by the 2011 Tohoku tsunami was well documented [33, 34]. Estimating the plastic input from land to ocean is a difficult task. Early estimates from the US National Academy of Science claim that a total of 6.4 million tons (5.8 million metric tons) of waste are released into the ocean every year and of this 0.7 % is plastic, roughly 41,000 metric tons [35]. A careful reading of this reference suggests that this number is based on an extrapolation of values from estimates of wastes produced by individual households and these inferences may not be entirely accurate.

2.1.1 Waste Generated by Coastal Populations

A study calculating the amount of mismanaged plastic waste generated by coastal populations worldwide estimated that 4.8–12.7 million tons (metric tons) can potentially enter the ocean as marine debris [31]. The framework integrates data on solid waste, population density, and economic status for 192 coastal countries. The annual amount of mismanaged plastic waste generated by populations living within 50 km of the coast was estimated at 31.9 million metric tons ranging from 1.1 to 8.8 million metric tons/year for individual countries with a conversion rate from mismanaged plastic waste to potential plastic debris ranging from 15 to 40 %.

This conversion rate range was assumed conservative and based on municipal water quality data from the San Francisco Bay watershed in California, estimating that 61 % of all materials littered in the watershed was not captured by street sweeping or catchments and thus was available to enter the waterways.

The study on global plastic waste inputs also predicts an order of magnitude increase in marine littering from coastal population pressure by 2025 if no improvements are made on waste management infrastructure [31]. The work also suggests that 83 % of the global mismanaged plastic waste in coastal regions for 2010 was generated by the top 20 countries largely dominated by Asian countries (11 countries in the top 20) with China ranking first (1.32–3.53 million metric tons of annual plastic debris input) and Indonesia second (0.48–1.29 million metric tons).

Overall, this study represents the most recent estimate of potential global plastic input, with an estimated 4.8–12 million metric tons of mismanaged waste leaving coastlines globally each year from the 192 countries analyzed. This study relied on World Bank data on waste management, which excluded local incineration, burial, and informal plastic collection, collectively labeling them as “mismanagement.” Informal plastic collection, commonly called “waste picking,” in China may account for 17–38% wt. of municipal solid waste diversion [36] and may represent 3.3–5.6 million people. Across Latin America and Asia, waste picking is the livelihood of an estimated 2 % of the population [37], representing a significant contribution to keeping plastic from entering the ocean. The quantity of waste managed informally by waste pickers, or that which is locally burned or buried, is difficult to quantify per capita or per country. Therefore, this quantity was omitted from the study, although the informal collection of mismanaged waste may consist of the other 60–85 % of the mismanaged plastic waste that was estimated *not* to make its way to the ocean in each country (J. Jambeck, personal communication). Future estimates of waste inputs must include these significant factors.

2.1.2 Waste Introduced by Rivers

Plastic debris originating from intentional or involuntary dumping on river banks [38], dumpsites, and surface runoff in urban environment can potentially be introduced into rivers [39]. The plastic may sink, be deposited on riverbanks downstream, or enter the marine environment. Manufactured micro- and nanoparticles of plastics used in consumer products can also potentially enter the marine environment via runoff [40]. These include micro-sized particles used as exfoliants by the cosmetic industry [41–43] and industrial abrasives [44]. Synthetic nanoparticles in the form of microfibers from the washing of synthetic textiles are abundant in rivers and coastal sediments [45]. Several studies using floating debris-retention booms or stationary driftnets estimated the amount of plastic waste carried by various rivers worldwide.

An estimated 4.2 metric tons/day (more than 1,500 metric tons/year) of plastic waste is introduced into the ocean by the Danube River [46]. The figure was calculated using data from a 2-year survey using drift nets. Particularly, the study emphasizes significant amounts of floating pellets and spherules originating from the plastic resin industry flowing in Europe's second largest river (see also [47]).

Using an extensive regional network of floating debris-retention booms, a study quantifying floating debris in the Seine River reported that 0.8–5.1 % of total debris collected by weight was plastic [39]. The regional network intercepts between 22 and 36 metric tons of plastics, annually. Most collected plastic debris was made of polypropylene and polyethylene. In 205 days, 390 kg of debris of which 73.6 % was plastic were collected in two watersheds on the island of Hilo in the Hawaii archipelago [48], which infers more than 0.5 metric tons of plastic debris per year.

In Southern California, samples of river water, taken with a variety of nets in the Los Angeles and San Gabriel Rivers were used for a research effort quantifying the contribution of the Los Angeles basin to the issue of plastic debris release into the marine environment [49]. The study reported an extrapolated 72-h average plastic debris weight of 30 metric tons using data from rainy and dry days.

Other quantities were reported for the Thames River [50] with nearly 8,500 submerged plastic items collected during a short sampling period and for the Tamar River [51] where 82 % of collected debris were plastic. A study on anthropogenic riverine litter along riverbanks and river mouths in Chile [52] also concluded that riverine transport has an important impact on litter abundances on coastal beaches.

2.2 *Maritime Inputs*

The dumping of waste from ships, though a common practice historically, has sufficiently been reduced since the 1990 international shipping regulation MARPOL Annex V, indicated by waste management procedures on commercial, private, and military vessels.

The current maritime sources of plastic debris include shipping, fishing, fish farming, offshore mining, illegal dumping at sea, and natural disasters [32]. Marine litter from shipping sources include merchant, public transport, pleasure, and naval and research vessels. Maritime activities were first assumed to represent 20 % of the total source of marine litter [30]. Commercial fishing gear alone was estimated to account for 5 % of the total debris found in the ocean [53]. Overall, the fishing industry is suspected to be accountable for 18 % of the marine plastic debris found in the ocean environment [44]. In areas with limited input from other anthropogenic sources, fishing gear may contribute significantly higher proportions of litter [54, 55, 118].

A study on fjords, gulfs, and channels of Southern Chile reported high quantities of expanded polystyrene [92] used as floatation device in local mussel farms and food sacks from salmon farms suggesting that aquaculture plays a significant role as input of floating plastic debris. The contribution of aquaculture in generating plastic debris with the introduction of expanded polystyrene was also suggested in the Gulf of Aqaba [56], South Korean beaches [75], and Hiroshima bay in Japan [84].

2.3 Catastrophic Events

While most litter is continuously supplied to the oceans, catastrophic events create pulses of debris. Flood events, cyclones, and tsunamis may flush large amounts of litter into the oceans [121]. This occurs infrequently and generally in local areas. Little attention has been paid to the identification and quantification of litter contributed by these catastrophic events. Several studies have shown that river floods flush large amounts of marine debris into coastal waters [48, 49, 52]. The recent 2011 tsunami in Japan is the first event that has spurred systematic research efforts in quantifying and tracking plastic (and other) litter introduced to the oceans [33, 64, 72].

Catastrophic events may introduce on a sporadic basis large amounts of plastic debris to areas that usually receive relatively small amounts of debris. They may also cause loss of large quantities of artificial structures (floats, buoys, ropes, boats, etc.) that have already been colonized by coastal organisms. In particular, this detachment of overgrown structures is cause of concern, because, if positively buoyant, these rafts may be transported over large distances. Therefore, the frequency, quantification, and impact of debris introduced to the oceans by these catastrophic events (flood events, cyclones, tsunamis) deserve more research attention in the future.

3 Fragmentation and Characterization

3.1 Mechanisms of Fragmentation

Fanciful notions of "plastic, like diamonds, last forever" parallel public misconceptions about degradation and fragmentation rates, including timescale lists of how long specific plastic products persist in the environment, and often one reads "all plastic ever produced still exists somewhere on the planet." Degradation is a chemical change that drastically reduces the average molecular weight of the polymer [44] and is completely environmentally dependent, ranging from plastic in a campfire to sequestration in benthic sediments. In addition to incineration, there are other mechanisms of degradation and fragmentation that reduce large plastic items to microplastics or break the long polymer chains. These mechanisms and rates of decay may include ultraviolet (UV) degradation, embrittlement and crushing by waves, thermooxidative degradation, hydrolysis, biodegradation, grazing and shredding by macrofauna, and abrasion along coastlines.

Plastic debris may be transported along coastlines with tidal movements, resulting in abrasion and UV degradation accelerated by thermal loading on exposed dry surfaces [59, 123]. Exposed plastics incur photooxidation where polymers are exposed to UV radiation and oxygen [130]. Evaluation of the surface characteristics of beached plastic items shows evidence of degradation from both sunlight and abrasion, each with different physical characteristics ([78]; Plastics Design [104]). Mechanical weathering from abrasion is evident by groves and gouges, fractures, adhered particles, and mechanical pits [129]. Wave mechanics drag plastics along hard- and soft-bottom shorelines and reef substrata, creating groves and gouges, whereas photooxidation results in roughened surface features, discoloration, and a flaking or dustlike decay when touched.

Floating debris exposed at the sea surface may incur these same degradation processes, though submerged debris, or even persistent wet debris, may have degradation rates delayed by biofouling, lower temperatures, or submersion beneath the photic zone.

3.1.1 Biodegradation and Fragmentation by Grazing

Of the many interactions between plastic debris and marine organisms, microbial biodegradation and grazing by macrofauna facilitate fragmentation. Floating plastics are rapidly colonized by marine organisms, beginning with biofilms, algal mats, and then invertebrates [110]. Among these microbial films, there has been evidence of biodegradation on debris surfaces, primarily on polyethylenes and polypropylene [90, 117], but also on PVC and polycarbonates [62, 116], which float primarily with trapped air. Biodegradation is further accelerated with increased debris surface area, which can be facilitated by photodegradation and mechanical breakage [98]. The dustlike residue from handling photodegraded plastics may be degraded completely by bacterial decomposition [81]. While recent studies have indicated that plastics are colonized and degraded by microbes, little is known about the rates of biodegradation and the significance of factors, such as substratum type, seawater nutrient concentrations, UV radiation, temperature, salinity, and pH.

The ingestion of plastic debris by marine organisms has been well documented [88, 102], with increasing attention toward ingestion by fishes. In the North Pacific, mesopelagic fishes have been found with ingested microplastics [68, 79] and macroplastics [77]. In the North Atlantic, ingestion has been observed in the Sargasso Sea [94], English Channel [106], Mediterranean Sea [61], and North Sea [83]. It is unknown whether these fish are ingesting plastic directly or retain plastic from the gut of smaller fish they consume.

The significance of marine life grazing, or tearing fragments of small pieces of plastic from larger ones, is not well understood. It is not uncommon to find bite marks on floating or beached debris, from scratches and scrapes from copepods [113] to bites from sharks [102]. In a study of debris washed ashore at Kamilo Beach, Hawaii, 5,518 pieces of plastic were collected, of which 15.8 % showed evidence of having been bitten [73]. Predators may be pursuing attached organisms or testing the plastic itself for edibility.

In a recent survey of plastic debris washed ashore in Bermuda, we collected plastic bottles with distinct bite marks (Fig. 2). The skulls of five marine vertebrates associated with mats of *Sargassum* sp. in the North Atlantic Subtropical Gyre were used to make impressions of their lower and upper jaws in clay for comparison to the plastic with bite marks on plastic. Three turtle species (*Caretta caretta*,

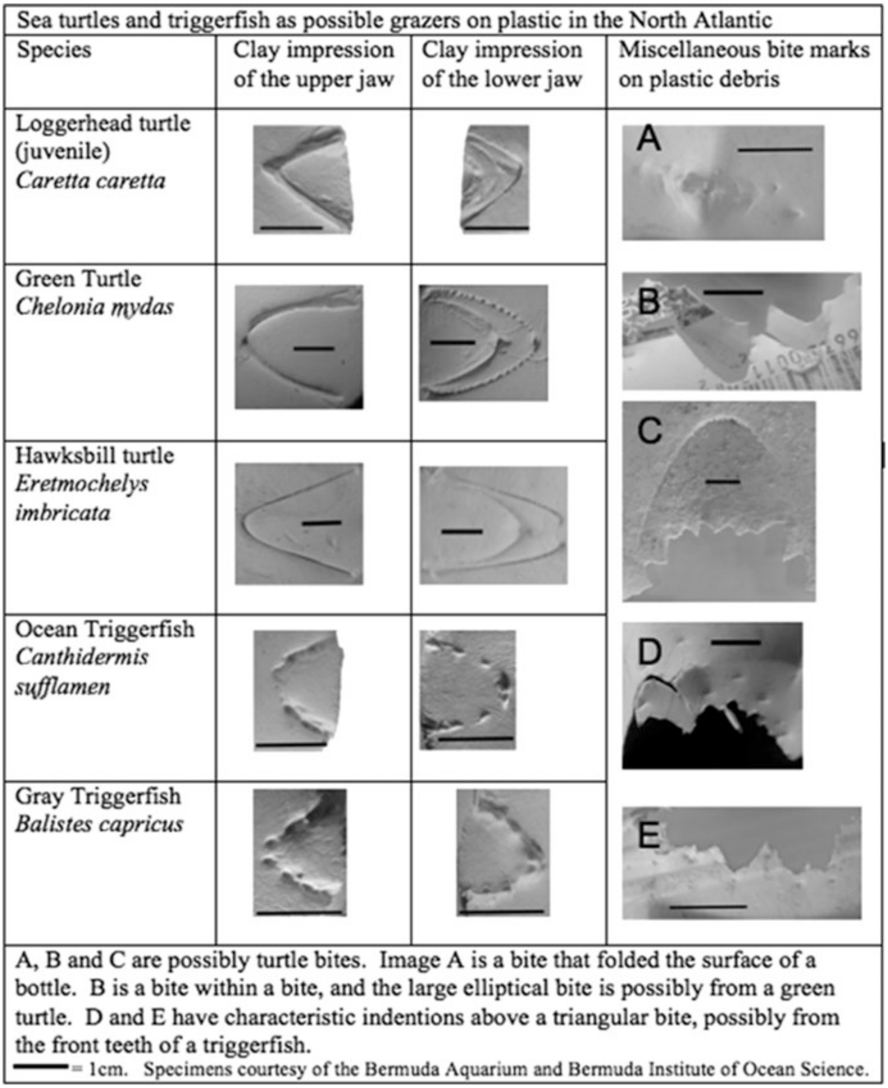

Fig. 2 Sea turtles and triggerfish as possible grazers on plastic in the North Atlantic Subtropical Gyre

Chelonia mydas, Eretmochelys imbricata) and two triggerfish species (*Canthidermis sufflamen, Balistes capricus*) were used.

Impressions of the jaw of trigger fish (Fig. 2) show a triangular arrangement of both the upper and lower teeth, which appear similar to bite mark patterns on plastic bottles (D and E). It appears that the triggerfish bite mark is performed with the upper jaw grasping the plastic while the lower teeth shear off a triangular fragment, with the two front teeth leaving indentions above the apex of the bite.

Possible turtle bite marks on plastic in Fig. 2 (B and C) appear to match the jaw size and pattern of *Chelonia mydas* or *Eretmochelys imbricata*. Bite mark A appears to be made from a bite that folded the plastic, leaving upper and lower indentions on opposite sides of the bite mark.

3.2 Characterization of Debris in the Gyres

The characterization of plastic debris in the gyres varies regionally due to debris sources, polymer type, and object design, and the migration or accumulation of debris due to current dynamics. Nearly all human activities, regardless of proximity to the ocean, utilize plastic; yet loss of plastic from these activities to the ocean can be narrowed to three broad input categories: rivers, runoff from highly populated coastal cities, and maritime activities including fishing and shipping lanes [103]. These exclude airborne plastics from recreational balloons, weather balloons [112], or wind-driven micro- and nanoplastic particles and fibers. Though many types of plastic may come from these sources, the characterization of debris may vary widely in the gyres (Table 1).

Plastic abundance in the oceans has been estimated to be 269,000 tons from 5.25 trillion particles [7]. This is significantly less than the input estimate from Jambeck et al. [31] averaging 8.0 million metric tons annually, and illuminates both the difficulty in making such estimates and the wide range of mechanisms that remove plastic from the marine environment.

Table 1 Types of plastic marine pollution

Polymer	Specific Density (g/cm^3)	Common debris items
Polypropylene (PP)	0.89–0.91	Fishing line, ropes and floats, detergent bottles, toothbrushes, combs, preproduction pellets
Low-density polyethylene (LDPE)	0.89–0.94	Fishing floats, thin grocery bags, cups and containers, preproduction pellets
Cellulose acetate (CA)	1.3	Cigarette filters
High-density polyethylene (HDPE)	0.94–0.96	Bottles for milk and dishwashing liquids, fishing floats, buckets, and crates
Thermoplastic polyester–polybutylene terephthalate (PET and PBT)	(PET) 1.29–1.40 (PBT) 1.30–1.38	Water and carbonated drink bottles
Polyvinylchloride (PVC)	1.30–1.58	Soft vinyl toys, shampoo bottles
Polystyrene (PS)	1.04–1.08	Yoghurt cups, foam meat or fish trays, egg cartons, vending cups, plastic cutlery, packing material, fishing floats
Polycarbonate	1.2	CDs and DVDs, tail lights on cars, hard plastic canteens, cigarette lighters

Density of: Seawater 1.02–1.03 g/mL, freshwater <1.015 g/mL

Many types of plastic products and polymers enter the marine environment (Table 1) through wind and waves, rivers, and wastewater treatment facilities, and many of these may be deposited in estuarine or near-shore environments. The majority of plastics produced are near neutral buoyancy (within 0.1 g/mL of seawater) and may sink with only a minute fraction of sediment attached. Other plastic products with negatively buoyant polymers may trap air, either by foaming agents, compressed fuels, or simply caps remaining on bottles. The result in the gyres is a reflection of coastal waste characterization coupled with the accumulation, fragmentation, and redistribution processes that vary regionally and by polymer and product type.

3.2.1 Distribution by Type

In all subtropical gyres debris types of floating plastics can be generally classified into five categories: fragment, pellet, line, thin film, and foamed polystyrene. These items result from the fragmentation of debris emanating from coastlines or maritime activities, such as shipping, recreation, fishing, and aquaculture, and may contribute debris to the ocean, including nets, line, floats, fish packing crates, and a range of consumer products lost overboard [92]. The variability between subtropical gyres in the distribution of particle characterization is largely unknown, though two datasets from the North Pacific (Moore 2007, 2008 unpublished data) and the North Atlantic (Eriksen 2010 unpublished data) show similar distributions of these five types (Table 2). In both subtropical gyres, fragments dominate the total particle densities, but an analysis by size class shows that pieces of line, primarily from nets and ropes, dominate macroplastic count densities.

Table 2 Distribution of five plastic types based on count densities (items/km^2) in two northern hemisphere subtropical gyres

	Fragment	Pellet	Line	Thin film	Foam
North Pacific					
>4.75 mm	2,868.4	48.3	4,869.6	672.5	12.8
1.00–4.75 mm	61,159.6	1,473.7	3,673.1	3,745.6	418.8
0.35–0.99 mm	37,256.0	41.6	2,672.0	3,506.1	33.6
Percent of total	83.0	1.0	8.8	6.9	0.4
North Atlantic					
>4.75 mm	3,502.4	0	2,077.6	688.3	12.9
1.00–4.749 mm	28,127.8	800.5	1,298.3	743.4	40.4
0.355–0.999 mm	21,385.9	3.9	255.2	95.1	5.3
Percent of total	89.8	1.4	6.2	2.6	0.01

Unpublished data from the North Pacific (Moore C. 2007–2008) and North Atlantic (Eriksen M. 2010)

4 Estimating Abundance, Weight, and Distribution

4.1 Modeling the Global Distribution of Marine Debris

Extensive modeling work on marine debris concentration at global scale has been conducted [103, 108, 125]. The various numerical models confirmed the formation of five main areas of concentration located in the subtropics and detected by early observers on the field [8, 15, 18, 26]. The high-concentration zones are maintained by converging Ekman currents in the five oceanic basins.

The first attempt to numerically reproduce the likely pathways of marine debris used a global set of trajectories of satellite-tracked drifters [108]. A probabilistic model is developed to eliminate the bias in spatial distribution of drifter data due to heterogeneous deployments. The study considers an initial state with drifting particles uniformly spread over the global ocean. Particle quantities are advected using probabilistic forcing calculated from observed surface drifter data.

An alternative approach was proposed using a global ocean circulation model for Lagrangian particle forcing [103]. Dynamics of marine debris are calculated in two stages: first a hydrodynamic model describes oceanic circulation and second virtual particles are introduced into the flow field and allowed to move freely through modeled hydrodynamic forcing. The initial Lagrangian particles are no longer uniformly spread over the ocean but released from terrestrial and maritime inputs. The rate of particle release is calculated using proxy scenarios including urban development in watersheds, coastal population pressure, and shipping activities. Industrial and recreational fishing and aquaculture are not directly considered. The origin of the particle can be retraced allowing detailed analysis of the contribution of individual sources to the major accumulation zones.

A numerical model integrating a plastic debris source function scaling with coastal population as in Lebreton et al. [103] and advecting concentration quantities with observational data from the Global Drifter Program as in Maximenko et al. [108] was eventually proposed [125]. The advection of tracers from the probabilistic model is no longer constant in time but varies with seasonal cycles. The framework allows studying the fate of marine debris on interannual to centennial timescales. A detailed analysis of the debris dynamics at large timescale shows different evolution of the major aggregation zones. With the exception of the North Pacific, the high-concentration zones in other basins are much more dispersive than previously assumed. The great oceanic garbage patches are much better connected than previously thought.

4.2 Abundance and Weight Estimates

Model-predicted concentrations of advected Lagrangian particles are compared with field data from expeditions conducting net tows and/or visual transects of plastic debris. The numerical models can be calibrated against measured quantities of floating plastic particles, allowing the formulation of regional and global estimates.

A study on the global distribution of microplastic [27] using non-accumulation, outer accumulation, and inner accumulation zones from a global distribution model [108] and data from various expeditions and regional surveys suggests that the total floating microplastic load in the world's oceans ranges between 7,000 and 35,000 MT. The research assembles data from the Malaspina circumnavigation and other reported measurements included 3,070 total samples collected around the world. Plastic measurements are spatially averaged over 2° resolution grid cells and compared with 15 major zones characterized by their degree of convergence [108]. Two sets of measurements are considered, a wind-corrected dataset and a non-corrected dataset.

The global load of microplastic in the world oceans was confirmed by a more recent study [7] which estimated 35,500 MT of floating debris with a size below 4.75 mm representing 4,850 billion particles. The study compares numerical model predictions of particle concentration [103] with wind-corrected measurements collected by expeditions from 2007 to 2013, surveying all five subtropical convergence zones and other coastal regions or enclosed seas globally, including surface net tows (680 samples) and visual transects for large plastic debris (891 samples). Differentiating microplastics, mesoplastics, and macroplastics, the study estimates that in total at least 5,250 billion particles weighing nearly 270,000 MT are currently floating at sea.

For both studies, plastics of all sizes were found in all ocean regions converging in aggregation zones located in subtropical latitudes. Generally, the frequency of occurrence of plastic debris was reported significantly high in all regions of the world's oceans with 88 % of all samples containing plastic for Cozar et al. [27] and up to 93 % for Eriksen et al. [7].

In the Northern Hemisphere, the predicted loads of microplastic were in the same order of magnitude with previously reported regional estimates. A study using an 11-year data set in the North Pacific [25] estimates a weight of about 21,290 MT of floating microplastic while Cozar et al. [27] predicted up to 12,400 MT and Eriksen et al. [7] 12,100 MT. In the North Atlantic, an estimate for the western region of the subtropical gyre using a 22-year data set [26] reported 1,100 MT for 80 billion pieces, while for the whole North Atlantic Ocean, the total microplastic load was estimated between 1,000 and 6,700 MT by Cozar et al. [27] and around 5,250 MT for 856 billion pieces by Eriksen et al. [7].

The two Northern Hemisphere ocean regions contain more than half of the global floating plastic mass with reported masses between 49 and 54 % for microplastics [7, 27] and nearly 57 % when including macroplastics [7] for a combined mass of 152,870 MT (96,400 MT for the North Pacific and 56,470 MT for the South Pacific). This increase in proportion for the two Northern oceans when including macroplastics could be related to shipping and fishing activities, significantly more developed in the Northern Hemisphere [103]. Persistent plastic objects such as buoys or fishing gears are invariably lost or even discarded at sea by the global fishing and shipping industries. Buoys represented 58 % of the total weight of observed macroplastic debris reported by Eriksen et al. [7].

In the Southern Hemisphere coastal population density and shipping traffic are much lower than in the Northern Hemisphere; yet the reported plastic densities were very high, suggesting that plastic pollution is moved more easily between aggregation zones and between hemispheres than previously assumed [103]. Cozar et al. [27] predicted a relative homogeneity between microplastic loads in the three Southern Hemisphere oceans with an estimated mass of, respectively, 800–5,100 metric tons, 1,700–5,400 metric tons, and 800–5,600 metric tons for the Indian Ocean, South Atlantic Ocean, and South Pacific Ocean, whereas Eriksen et al. [7] concluded that the Indian Ocean appears to carry a greater particle weight than the South Atlantic and South Pacific oceans combined with 7,470 metric tons in the Indian Ocean, 1,540 metric tons in the South Atlantic Ocean, and 2,340 metric tons in the South Pacific Ocean. A similar distribution is observed when including macroplastics with, respectively, 59,130 metric tons, 12,780 metric tons, and 21,020 metric tons for the Indian, South Atlantic, and South Pacific oceans. These predicted quantities suggest that there might also be important sources of plastic debris in the Southern Hemisphere, such as currents from the Bay of Bengal that cross the equator south of Indonesia (e.g., [21]).

4.3 Discrepancy with Source Estimates

Estimates of plastic waste entering the ocean are one to three orders of magnitude greater than model-predicted mass of floating plastic debris from regional and global observation data set [31]. This large discrepancy can be attributed to both mechanisms of plastic debris removal at sea and methodological assumptions made to estimate plastic entering the ocean from land-based sources.

Both Cozar et al. [27] and Eriksen et al. [7] reported global estimates of floating debris, omitting estimates of plastic debris in the water column and on the seafloor and using crude estimates of the vertical distribution of microplastics, and making estimates based on limited data sets. These authors also observed a tremendous loss of microplastic from the ocean surface. Most small microplastics are fragments resulting from the breakdown of larger plastic items and are expected to be more abundant than larger microplastics. Eriksen et al. [7] observed the opposite in all regions except in the South Pacific where large and small microplastic counts were nearly equal. This discrepancy in abundance suggests that the ultimate fate of buoyant microplastics is not at the ocean surface.

There are mechanisms at sea that remove microplastics from the sea surface. UV light degradation, coupled with embrittlement and wave mechanics, reduces macro- to microplastic, as well as some microbial biodegradation and grazing by fishes, seabirds, and turtles. These microplastics may then be subject to biofouling and lose buoyancy, and ingested particles may sink as fecal pellets. Collectively, these poorly understood variables may explain the underestimation and discrepancy with coastal input estimates.

In Jambeck et al. [31], coastal inputs of plastic from the 192 coastal nations surveyed were derived from World Bank data on per capita consumption of plastic, waste management strategy, and populations living within 50 km from the ocean. The authors estimate that an average of 8 million metric tons of plastic enters the oceans. It is unknown what percentage of this total washes ashore soon after leaving land. The significance of local incineration, burial, and recovery by waste collectors is not accounted for in this study, and is difficult to quantify. Collectively, these variables contribute to a possible overestimation of actual debris loads entering the ocean.

Therefore, while Eriksen et al. [7] possibly underestimate plastic debris loads with a global estimate of 269,000 tons floating at the sea surface, Jambeck et al. [31] likely overestimate plastic entering the ocean, with an 8 million tons annual input estimate; if the variables identified above were quantified and contributed to these estimates, the disparity between them would likely close significantly.

5 Ecological Impacts

Interactions between plastic debris and marine organisms range from entanglement [69, 88, 102] to ingestion (Ryan, this volume; Browne, this volume), and settlement substratum (e.g., [63, 87]). Plastics, as any other clean substrata that enter the ocean, are immediately colonized by marine organisms. Colonization may occur before the plastic has become marine debris, as is the case for buoys and ropes used in fishing and aquaculture activities. Many floating structures anchored in coastal waters are colonized by a wide diversity of organisms. When these structures are detached and lost at sea, attached coastal organisms are transported via these floating plastics. They may travel along the coasts, spreading and connecting coastal populations. If these floating plastics are pulled into oceanic currents, the associated biological community can be transported over long distances, including across large ocean basins. The recent arrivals of large debris from the 2011 Japan tsunami on the NE Pacific coasts with extensive communities of coastal organisms bear testimony to this [72, 76, 93].

Large amounts of floating plastic debris also enter the oceans in a clean state. These plastics are then colonized by oceanic travelers. Some of the most common colonizers on floating substrata are gooseneck barnacles from the genus *Lepas*. These sessile organisms rapidly settle on any substratum floating at the sea surface, including macroalgae, wood, volcanic pumice, and plastic debris [87, 91, 126]. Small plastic pieces have also been found as foundation substratum for the gooseneck barnacle *Dosima fascicularis* [115]. Many other sessile organisms (algae, corals, oysters, bryozoans) have been reported from floating plastic litter [58, 65, 82, 119]. A wide diversity of mobile organisms also use plastic debris as rafts. These include mostly snails and crustaceans (e.g., [66, 71, 89]), but also polychaetes and others have been found on floating plastics [87, 99]. The larger a plastic item, the more species can grow on it (Fig. 3). Also, larger items can support larger organisms, but this relationship has not been examined specifically.

Floating plastic debris are not homogeneously distributed in the oceans. Currents and winds accumulate any floating objects in patches and frontal systems [57]. Here, plastic debris and floating objects of natural origin (algae, wood, pumice) are mingled in intricate patches (diameters of centimeters to several meters) or in drift rows (a few meters in width and kilometers in length). These

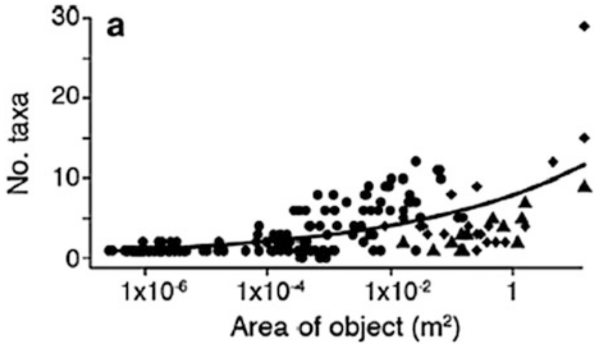

Fig. 3 Relationship between surface area of floating litter and the species richness of associated organisms (from [87])

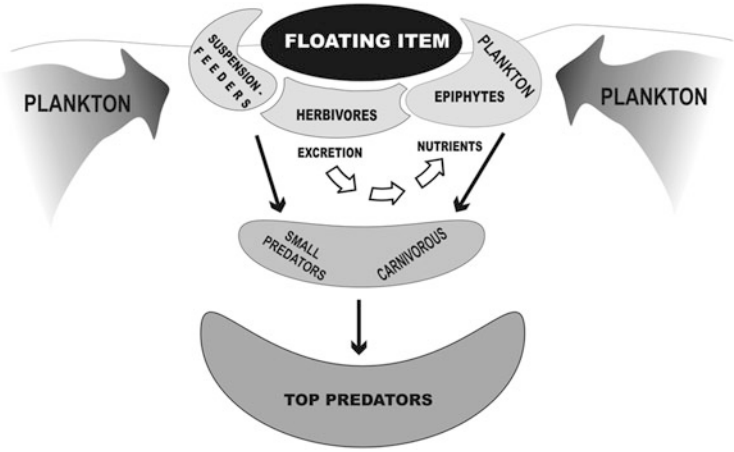

Fig. 4 Trophic interactions around floating objects (from [120])

heterogeneous and dense agglomerations of debris and natural floating objects represent concentrations of organic matter (dead or alive). In the nutrient-poor waters of the subtropical gyres, these agglomerations of floating material are true oases that provide habitat and food for many different organisms [57]. They attract many consumers such as turtles, fishes, or seabirds, which seek food and shelter around these floating patches (Fig. 4). The floating items serve as catalyst for multiple trophic interactions (Fig. 4).

Consumer interactions are important on and around these aggregations of floating materials (Fig. 4). Consumers also feed on the fouling communities on floating plastics. As on natural substrata, there is a relatively basic succession on floating debris, initiated by micro- and macroalgae, which attract grazers and are followed by suspension feeders (gooseneck barnacles, hydrozoans, bryozoans), which in turn attract numerous predators. These consumers continuously eliminate a large proportion of the fouling community. These interactions between growing fouling communities and consumptive removal of these result in continuous variation of buoyancy on these plastic items, which may be particularly important for smaller items where effects of the associated fouling community become more important for the overall buoyancy.

On these patches of larger floating plastic debris, the macroscopic organisms growing on this debris will also be exposed to high concentrations of microplastics. Consequently, they face the risk of ingestion of large quantities of small plastic particles. This has been shown for suspension-feeding gooseneck barnacles *Lepas* spp. collected from larger floating plastics: many of the larger individuals of *L. anatifera* and *L. pacifica* had consumed large amounts of microplastics [85]. Whether around these aggregations of floating plastic debris in the gyres contaminant concentrations also are enhanced is not known at present; however, the observation that all sorts of small materials from the sea surface (including tarballs and/or coal particles) are accumulated there suggests that this might be the case. Thus, transfer of contaminants to associated organisms might also be enhanced in these patches of floating plastics and organic matter.

The increasing amounts of plastic debris not only represent substratum for many sessile and mobile organisms, but they also serve as attachment sites for their eggs. Many fishes and invertebrates attach their eggs to floating objects [86, 95, 107, 127]. These egg attachment substrata may have been of limited supply in the past, as for example suggested for flying fishes [96] and ocean striders [86]. The ubiquitous presence of floating plastics may reduce this limitation for those species that require attachment substrata for successful reproduction.

The intricate nature of the patches of floating materials makes the separation of natural items and plastic debris difficult (Fig. 5). It also illustrates that removal of

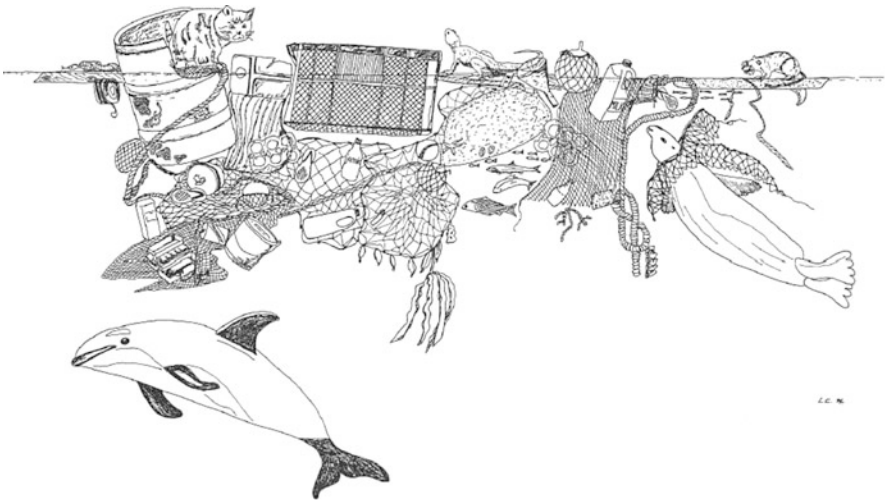

Fig. 5 Artist's representation of litter patch of multiple debris items accumulating in drift rows in the open ocean. From Winston et al. [127]

floating plastic debris from the open ocean will cause substantial ecological impacts, because many open ocean rafters and other organisms are inseparably associated with this litter [131].

6 Fate of Microplastics

The fate of microplastics in the subtropical gyres is a complex set of interactions that change as different variables come into play. Particle size impacts buoyancy, which impacts UV and chemical degradation, and subsequently impacts biofouling and biodegradation. In turn, sedimentation on island shores or the abyssal plains is a likely fate if ingestion by mesopelagic fishes does not occur. Collectively, these are responsible for the tremendous loss of microplastics from the subtropical gyres.

6.1 Loss of Microplastics from the Sea Surface

Two independent studies of the abundance and distribution of microplastics produced similar global estimates, with Cozar et al. [27] providing a range of 6,600–35,200 metric tons and Eriksen et al. [7] estimating 35,500 metric tons of particles <5 mm floating on the ocean surface. Both studies also reported substantial losses of microplastics, with Cozar et al. [27] estimating a 100-fold decrease in the abundance of microplastics compared to estimated total land inputs, and Eriksen et al. [7] showing a 40 % decrease in the global abundance of small microplastics (0.33–1.00 mm) compared to large microplastics (1.01–4.75 mm) based on very conservative fragmentation estimates. There are likely multiple mechanisms at play that remove microplastics from the ocean surface and cause a differentially increased rate of loss for particles less than 1 mm.

The deposition of microplastic particles in global environments logically follows the global distribution. Microplastics have been found in ice cores [111], on the seafloor [74, 128], and in coastal sediments worldwide [45, 67].

6.2 Vertical Movement

The mechanisms of fragmentation due to UV degradation and biodegradation are likely to accelerate as plastic particles decrease in size due to the increased ratio of surface area to volume, providing more sun exposure or more area for plastic-eating microbes to colonize a smaller mass of material. This increase in surface area for microplastics not only increases biofouling, but also increases the likelihood that neutral buoyancy or sinking will occur because the compensation for material buoyancy is less with relatively smaller volumes as microplastics fragment further.

Microplastics have been found suspended in the vertical column [80, 114] with an estimated 42 % of the total microplastic load beneath the surface [101], but rates of sinking and rising, and the influence of sea state, are poorly known. The buoyancy of biofouled particles is impacted by other factors beneath the surface. A substantial loss of colonization occurs when particles sink [60]. Changes in available sunlight, salinity, and temperature affect diversity and abundance of colonizing organisms, as well as fluctuations in the carbonate compensation depth (CCD) [124] dissolving heavy $CaCO_3$ and giving rise to particles with a lightened load.

This yo-yo effect, the vertical rise and fall of particles, increases the bioavailability of microplastics to a wide diversity of filter feeders and selective foragers living at different depths beneath the surface. Studies of mesopelagic fishes in the North Pacific Subtropical Gyre observed ingested microplastics, 35 % in one study [68] and 9 % in another [79]. As negatively buoyant particles sink deeper, they may be subjected to deeper currents. Wind-driven gyre currents dissipate beneath the surface, and neutrally buoyant particles may ride the ocean conveyor to regions far outside the subtropical gyres, only to rise there again. The oceans' eddy and wind fields play a significant role in establishing the variability of the oceans overturning, while the ocean conveyor transports deeper waters globally [105]. This variability in the lateral and vertical movement of warmer and more saline waters, as well as wind-driven convergence, is likely a significant transporter of microplastics out of the zones of accumulation and fragmentation in the subtropical gyres.

6.3 Trends

Increasing or decreasing trends in the abundance of microplastics are difficult to ascertain. In the example of floating tarballs, which were reported simultaneously with the occurrence of microplastics in the early 1970s [8, 9], a policy-driven reduction in the washing of oil tankers effectively reduced the number of tarballs found in surface tows in subsequent decades. A decreasing trend was informally established for tar, as reports of their occurrence diminished.

For microplastics, trends are more difficult to establish due to the varied input of plastic type, volume, and location [122]. Also, changes in waste management policies and the import of poorly designed plastic products affect the regional export of plastic to the ocean. "An analysis of 22 years of floating plastic debris in the western North Atlantic found no evidence for an increasing trend in plastic debris abundance in the region of the ocean where floating debris accumulates due to ocean surface currents, despite a strong increase in global plastic production and in plastic in the United States municipal waste stream during that period. However, because of large spatial and temporal variability in the data set (e.g., see Law et al. 2014), such a trend could be difficult to detect. A more sophisticated statistical analysis is underway on an updated North Atlantic data set to determine if there is evidence of an increase in floating plastic abundance between 1986 and 2012" (K. L. Law, personal communication).

These processes described here collectively create a life span for microplastics, though it is difficult to quantify on what timescales particles are removed. It is safe to say that the frequently used slogan “Plastics, like diamonds, are forever” is inaccurate for floating plastics in the subtropical gyres.

7 Conclusions

Our new understanding provides us with new language and focus to describe and mitigate the problem while offering a call to action to engage citizen science to monitor plastic marine pollution over time.

Early metaphorical descriptors of “patches” or “soup” of plastic in the gyres perpetuate public misconceptions about the resilience, residence, and characterization of floating debris. The nature of plastic debris in the subtropical gyres, reflecting the trends of increased input of plastic waste, rapid fragmentation, and global distribution out of the gyres is more akin to “smog” (Fig. 6), like the particulates of carbon in air pollution over urban centers distributed by atmospheric currents and slowly settling to the ground. Similarly, plastic smog is a particulate of hydrocarbon distributed by ocean currents and slowly settling to the seafloor.

This perspective supports that mitigation efforts are more successful when land based. When the issue of air pollution dominated the environmental movement in the 1970s the public and policymakers could look skyward and recognize that preventative measures were the only viable long-term solution. The issue of plastic debris drifting in the middle of the ocean lacks the benefit of visibility to quickly educate the public, leaving persistent misconceptions to drive mitigation efforts. The most common fallacy is recovery from the open ocean. Such proposals usually do not have an adequate understanding of ocean dynamics, marine ecology, and life

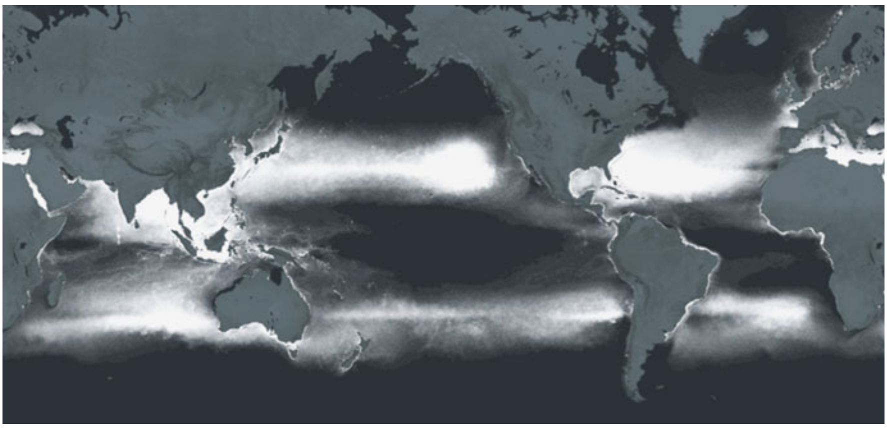

Fig. 6 5.25 trillion particles of plastic in the surface waters of the global ocean

cycles of plastics, aside from the fact that these projects are not engineered for the harsh conditions in the vast expanse of the world's oceans.

However, the abundance of plastic materials designed for durability at sea, primarily fishing gear, may justify recovery programs implemented by those engaged in maritime activities. In a recent global estimate of plastic marine pollution 269,000 tons of debris were estimated to be floating in the world's oceans, of which 58.3 % were fishing buoys and 12.1 % derelict fishing nets [7]. Fishing for Litter campaigns in Ireland, the UK, and Scotland report increasing success in the tonnage of debris recovered by incentivizing fishermen to recover anthropogenic waste from surface and bottom trawling operations [100].

These citizen-driven efforts, including coastal cleanup events, are applicable to contributing valuable information on plastic abundance and distribution. As a means of waste prevention, incentivized waste collection programs do not discourage littering and may perpetuate poor product usage and handling by not directly addressing sources of waste. Upstream strategies, such as leasing nets or accountability for returning the tonnage of nets purchased, could significantly decrease the loss of fishing equipment, thereby rectifying current anomalies in the fishing gear value chain [70].

To date, field data on plastics floating in the subtropical gyres has been limited to a few thousand stations worldwide. Although there is typically good correspondence between drifter models and surface abundance data [18], there is a disparity in the amount of data to calibrate these models. There is an ongoing need to expand data collection. Citizen science programs are now providing robust data sets on beach accumulation [28], sorption of toxicants on plastics [97], and microplastics in seawater [109]. These efforts generate regional or global datasets with an efficiency of time and funding that professional scientists cannot match alone.

The future of research in the subtropical gyres is largely to refine our understanding of fate and impacts of plastic debris, while mitigation efforts are being driven back to land by the realities of plastic life cycles in the oceans. With better communication of new science, and increased attention to improve waste management and smarter plastic product design, the problem of plastic debris drifting in the furthest reaches of the planet can be controlled.

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