Legacy plastics

Interventions to remove existing plastic from aquatic environments

A summary report

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Legacy plastics: interventions to remove existing plastic from aquatic environments summary report

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Cover image:
Waste on the beach after winter storms. Atlantic coast, France. © iStock.com / Sablin.

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Executive summary

Plastic is a persistent and bio-accumulative environmental pollutant that can cause harm at all levels of biological organisation. Environmental concentrations are predicted to triple by 2060 under business-as-usual scenarios due to increased production and the continued mismanagement of plastic waste[1]. The effects of plastic pollution on human health remains less well understood, but the negative economic impacts on tourism and reduced psychological benefits in terms of human interaction with the environment, are apparent.

In accordance with the 'waste hierarchy', preventing plastic from entering the environment must be the policy priority. However, some amount of plastic removal from the environment will likely be necessary to reduce the risk of harm to ecosystems and potentially to humans. This is due to the high amount of plastic already in the environment, the negative environmental consequences, and because these negative consequences are predicted to increase as concentrations increase.

These factors suggest that approaches to remove plastic from the environment are likely to be of increasing interest to policymakers. Already, governments around the world are negotiating a legally binding agreement on plastic pollution – the United Nations (UN) Plastics Treaty. At the time of writing, the latest draft includes a potential obligation for member states to: monitor plastic pollution within their jurisdiction; identify plastic pollution hotspots; and adopt effective mitigation and remediation measures to reduce environmental plastic pollution, including clean-up activities within identified hotspots.

This report summarises some of the technologies and other interventions that are available to clean-up legacy plastics from the environment, as well as discussing their feasibility, effectiveness and environmental impacts. The report also presents approaches to identify accumulation hotspots – which may help to prioritise areas for clean-up. The content of the report was informed by an evidence-gathering workshop hosted by the Royal Society and complemented by interviews with, and review by, leading scientific experts, including Royal Society Fellows.

Plastic clean-up technologies and interventions

Current technologies and interventions available to remove plastic from aquatic environments target plastic in either wastewater treatment facilities, rivers, estuaries, harbours or on beaches. The overall effectiveness of clean-up interventions in reducing the mass of plastic in the environment is questionable given that a substantial proportion of this debris is microplastic, which is distributed widely in the water column and sediment and is almost impossible to remove with current technologies. However, some removal approaches which target larger, macroplastic litter within pollution hotspots may deliver benefits, especially when these are located in relatively close proximity to the source of the debris, for example in rivers.

Feasibility, effectiveness and cost will vary according to the type of intervention and the habitat in question, and many clean-up technologies are specific to either certain types of plastic, certain environments, or both. It is likely that a range of interventions will be needed to target different situations.

Removing plastic from the environment close to source, before it distributes widely and / or breaks up into smaller fragments, is likely to be the most effective. The majority of plastic waste enters the ocean via rivers. Once in the oceans, it is estimated that around 88% of plastic stays close to the shoreline, with floating offshore plastic making up just 2% of marine plastic. Coastlines, shallow water habitats and beaches are rich in wildlife, high in natural capital and important for human wellbeing. Therefore, interventions that target rivers and the coastline may be particularly valuable. For example, beach cleans, and other volunteer-led activities are relatively low cost and have been shown to be effective, scalable and sustainable.

The effectiveness and environmental impact of most clean-up technologies have not been formally evaluated, and this report suggests that such evaluation should take place prior to deployment and ideally before technologies are brought to market. For any given habitat, the impacts of clean-up should be weighed against the impacts of leaving plastic in the environment.

Identifying priority areas ('hotspots') for clean-up

The report outlines the technologies, modelling and monitoring techniques available to identify hotspots of plastic pollution. These could be used to prioritise areas where clean-up may be most valuable and effective. For example, hydrographic modelling combined with empirical monitoring and remote sensing techniques could be used in combination to predict and identify areas of plastic accumulation and to help understand pathways and fluxes of pollution. Here we refer to 'hotspots' as areas where plastic pollution is most likely to cause harm to ecosystems or human wellbeing, and therefore where cleaning up would be most beneficial.

Key findings

1. **To tackle plastic pollution and its negative consequences prevention, is, and should remain, the priority.**
   Over-emphasis on clean-up interventions could divert attention away from more systemic solutions focused on minimising plastic use, including investing in more benign and sustainable alternatives, and efforts to move to a circular plastic economy through effective reuse and recycling.

2. **Some amount of legacy plastic removal may be beneficial.**
   Particularly in environments that have high natural capital and / or social value, where the risks associated with clean-up activities are shown to be lower than the risks associated with leaving plastic in the environment.

3. **Priority areas for clean-up (hotspots) in the environment can be identified according to:**
   (a) the natural and social capital value of the area
   (b) the potential hazards that plastic pollution poses in this area
   (c) the feasibility and likely effectiveness of clean-up
   (d) the risk of negative consequences from clean-up.

4. **Based on the range of options currently available, those that involve hand-picking litter from shorelines and / or intervene close to the source of plastic pollution are likely to be the most effective.**

5. **The environmental impacts and cost effectiveness of clean-up technologies remain largely unknown.**
   To address this gap, efficacy and environmental impact assessments are required in the locations where the technology is to be deployed.

1. Plastic pollution in the aquatic environment

Plastic as a pollutant

Plastics are materials that comprise a high molar mass polymer as an essential component. Marine litter, including plastic, is defined as any persistent, manufactured, or processed solid material discarded, disposed of, or abandoned, which ends up in the marine or coastal environment[2]. This includes plastic packaging, but also plastics used in fishing gear, textiles, road tyres and the full range of other applications.

Plastic is a persistent and bio-accumulative environmental pollutant and there is evidence of negative effects on economies, wildlife and human health. Larger items of plastic litter can cause serious harm to wildlife via entanglement and ingestion as well as affecting behaviour[3]. Microplastic debris has also been associated with reduced survival, growth and reproduction in a range of species[4]. Where marine debris combines with other anthropogenic stressors it has been shown to affect populations, trophic interactions and assemblages[5]. It is also well documented that plastic litter may cause indirect effects, by acting as a vector for other pollutants and pathogens, and there is potential for toxicity as chemicals leach from the plastic as it degrades. Impacts on human health are less clear: it is known that microplastics can enter the human body via the food chain, and that nano-plastics can cross the blood-brain barrier, but risk assessments are yet to be completed.

Macroplastics are plastic debris which are >5 mm in size; they are the most visible and noticeable form of debris and are therefore the easiest to target with clean-up interventions. Microplastics are defined in policy contexts such as the EU Marine Strategy Framework Directive[6] as plastic particles that are ≤5 mm in size and are far harder to remove from the environment. Macroplastic litter is already at concentrations where it is causing harm in the natural environment[7]. Global plastic litter within the environment is predicted to triple by 2040 – 2060 under a business-as-usual scenario[8, 9].

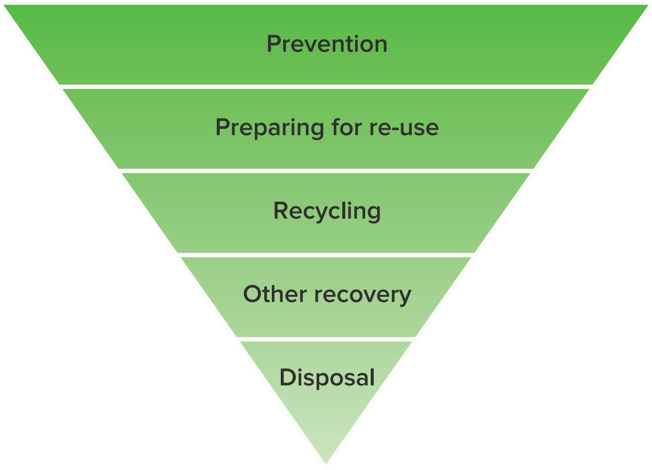
Eventually all plastic litter will fragment into microplastics and ultimately nanoplastics (< 1 µm). Recent risk assessments estimate that environmental microplastic concentrations are approaching levels that may cause ecological harm[10]. A fifty-fold increase in microplastic in the environment is also predicted between now and 2100[11], further increasing the urgency with which to address macroplastic debris.

In accordance with the ‘waste hierarchy’ (see Figure 1), reducing consumption and preventing plastic from entering the environment in the first place should remain the policy priority. Moving to a more circular economy for plastic waste by investing in effective waste collection and recycling, alongside developing safe and sustainable plastic substitutes will also be pertinent.

However, given the amount of plastic already in the environment, and that concentrations are predicted to increase, some amount of environmental plastic removal will likely be necessary to reduce the risk of harm to ecosystems and potentially humans.

FIGURE 1

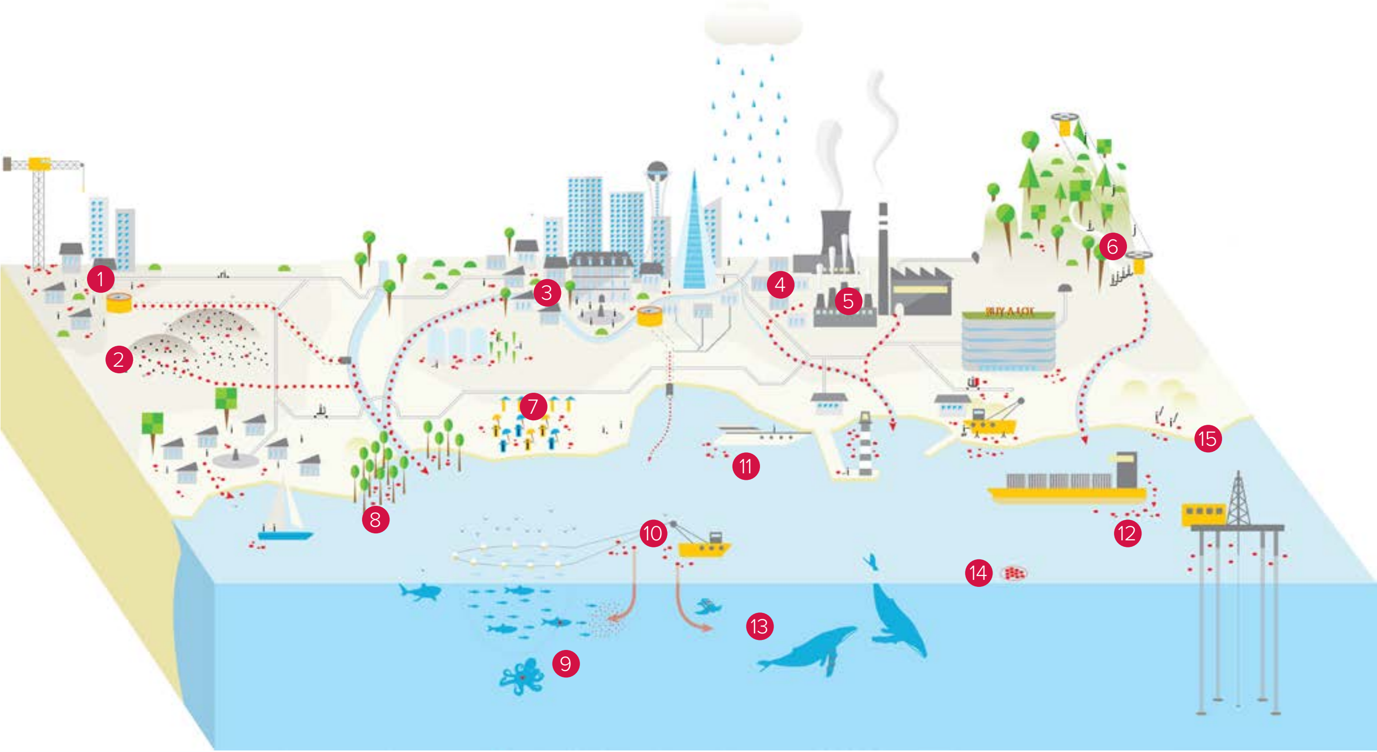
The waste hierarchy as described by Defra.



Source: Defra, UK Government.

FIGURE 2

Plastic debris sources and pathways.



KEY

① Combined sewers carry sewage as well as storm water. During heavy rains, the handling capacity of the wastewater treatment system may be exceeded, resulting in the sewage and storm water not being treated, and are directly discharged into nearby rivers or oceans.

② Run-off from landfills that are located in coastal areas or near to rivers may find its way into the marine environment.

③ Rubbish from streets can be washed into storm drains and is discharged straight into the ocean or to streams.

④ Storm drains collect runoff water which is generated during heavy rain events. The drains directly discharge this wastewater into nearby streams.

⑤ Industrial products may become marine debris if they are improperly disposed of on land or if they are lost during transport or loading/unloading at port facilities.

⑥ Litter from inland areas can become marine debris if it gets into streams or rivers.

⑦ Beachgoers may carelessly leave litter at the coast.

⑧ Plastic debris can act as anoxic sediments, smothering benthic habitats.

⑨ Plastics and microplastics are often mistaken for food by marine organisms. Toxic substances enter the food chain and toxicity is amplified by bioaccumulation.

⑩ Commercial fishermen generate marine debris when they fail to retrieve fishing gear or when they discard fishing gear or other rubbish overboard.

⑪ Boaters deposit rubbish overboard.

⑫ Rubbish from vessels released or blown into the water.

⑬ Marine debris injures or kills marine mammals, sea turtles,seabirds and other organisms due to entanglement or ingestion.

⑭ Floating plastic debris provides a surface for organisms leading to potential expansion of invasive species and new assemblages of coastal organisms further out to sea.

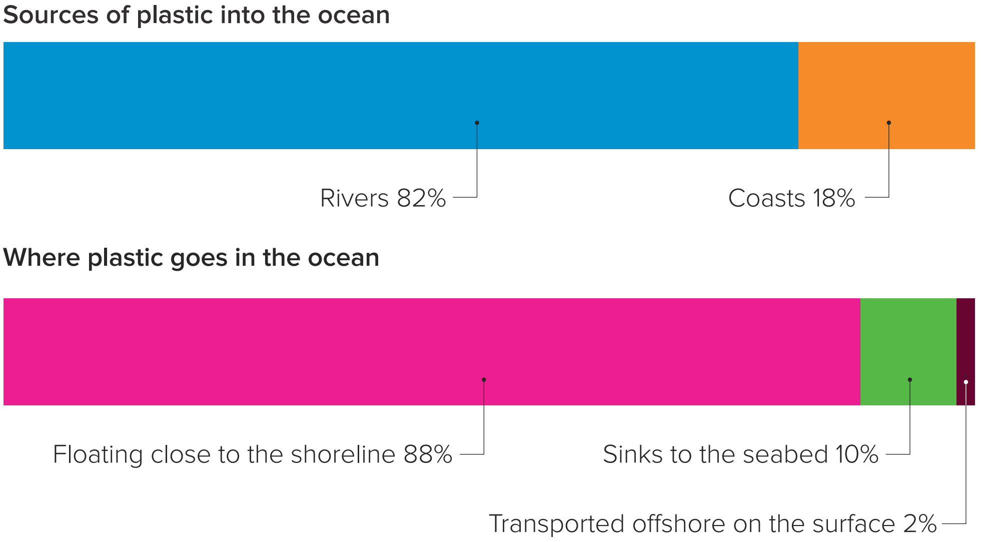
⑮ Fishermen on beaches or rivers may leave behind fishing gear.

Image: © Maphoto / Riccardo Pravettoni.

FIGURE 3

The source and fate of ocean plastic.

The shoreline is defined here as dry land bordering the ocean and shallow coastal waters with a depth less than 200 metres. Around 1.7 million tonnes of plastic enters the oceans each year. The sources of this from rivers and coasts is shown along with estimates of where this plastic goes.



Source: OECD Global Plastic Outlook, 2022. © Hannah Richie, Our World in Data, 2023.

Addressing the challenge of plastic waste along supply chains will require sustained and integrated effort from individuals, industry, governments and international organisations at local, regional and global scales[12, 13]. The transnational nature of the negative externalities associated with plastic pollution mean that it will not be straightforward to ascertain who should pay for clean-up activities or how this should be legislated.

Interventions which act to capture plastic at source, before it has the potential to enter the environment, such as municipal litter collection or filters on washing machines, are not within the scope of this report. However, it is acknowledged that upstream measures will be fundamental to tackling plastic pollution.

Sources and pathways of plastic pollution

Plastic production globally was estimated to be around 350 million tonnes per year in 2022. One quarter (82 million tonnes) of the world's plastic waste is 'mismanaged', meaning it is not stored in secure landfills, recycled or incinerated. Of that, 19 million tonnes is leaked into the environment, 13 million tonnes enters terrestrial environments and 6 million tonnes enters rivers or coastlines. 1.7 million tonnes of this is then transported to the ocean (all figures from OECD Global Plastic Outlook[14]).

Figure 2 shows in detail the pathways leading to ocean plastic pollution and Figure 3 presents the figures relating to the sources and fate. It has been estimated that the majority (82%) of plastic waste enters the marine environment via rivers[15, 16] and typically remains close to shorelines, often getting washed up, buried or resurfacing close to beaches. Debris floating offshore makes up just 2% of marine plastic pollution. Thus, many clean-up technologies aim to remove plastic from rivers before it reaches the ocean. However, in the open ocean, considerable quantities of plastic pollution and associated harms (such as entanglement) are related to fisheries activities[17].

Therefore, independently of river or coastal clean-up efforts, targeted clean-up activities in the open ocean may be beneficial to remove lost, abandoned or discarded fishing gear, alongside interventions to raise awareness among the fishing community (such as the Fishing for Litter Scheme[18].)

The negative impacts of plastic pollution

Negative impacts related to plastic pollution include physical harm to wildlife related to injury, ingestion and entanglement[19 – 25] (see Figure 4). Seabirds such as fulmars, albatrosses and shearwaters[26] are particularly susceptible to ingesting plastic litter[27 – 29], resulting in satiation and starvation. Marine mammals, turtles and fish are affected by both ingestion and entanglement, leading to starvation, injury or suffocation. For example, it has been estimated that over 60% of cetaceans are adversely affected by plastic pollution[30].

Plastic has also been shown to sorb and transport[31, 32] other pollutants and invasive species through the environment[33 – 35]. In addition, as plastic degrades it may release additive chemicals (e.g. endocrine disrupting phthalates) which have been shown to cause harm in a range of species[36]. Plastic pollution also modifies and facilitates establishment of new assemblages of organisms, for example, by providing a home for coastal species further out to sea[37], thus altering the make-up of oceanic communities[38]. Microplastics have considerable bioavailability and are also known to transfer along food chains[39] – with potential for wider ecosystem-level effects[40].

FIGURE 4

Examples of the effects of plastic pollution on wildlife.

Macroplastic litter can cause injury, ingestion and entanglement.

Microplastics of different sizes can be ingested, egested and adhere to a range of zooplankton, as visualised using fluorescence microscopy.

Source: (left) Gall and Thompson 2015[31] and (right) Cole *et al*, 2013[32].

An important caveat is that some of the evidence on negative impacts of microplastics is based on results from laboratory studies using concentrations of plastic that are greater than those currently found in most natural environments. While such experiments are important for advancing our understanding of risk thresholds, further research is needed on long-term exposures at environmentally realistic concentrations.

As the Royal Society stated in its 2019 report on microplastics, “once released into the environment microplastics are persistent, and given the high environmental concentrations expected in the future, the likelihood of negative consequences emerging is high”[41]. Given that the fragmentation of macroplastic is a key source of microplastic, such concerns amplify the need for action on larger items of debris.

Therefore, in summary, the combination of high uncertainty relating to human health impacts, and the strong evidence of negative consequences on wildlife, creates the rationale for a pro-active but considered approach to removing plastic from the environment.

2. Plastic clean-up technologies and interventions

The majority of the technologies currently available to remove plastic from aquatic environments are intended to be used in either rivers, wastewater treatment facilities, estuaries, harbours or the open ocean[42]. However, given that 88% of ocean plastic is predicted to be close to the shoreline[43], this report also considers interventions that target the coastline, such as beach cleans.

Table 1 lists the remediation technologies and interventions for legacy plastics that were discussed during a Royal Society workshop. This list is intended to be comprehensive, but not necessarily exhaustive. It gives a good idea of the range of clean-up solutions available. The next sections go on to describe the feasibility and likely effectiveness of these, with information on their potential environmental impacts.

TABLE 1

Plastic removal technologies.

Table illustrating the large range of different clean-up technologies and interventions that are available to remove plastic from the environment as summarised by a Royal Society workshop.

Technology	Description	Where it intervenes	Type of plastic (micro / macro)	Location: (multiple / specific)	Stationary / mobile	Energy source	Autonomous / crewed / uncrewed	TRL*
Graphene carbon fibre aerogels	Aerogel made from protein fibres has been shown to capture microplastics	Wastewater treatment plants	Micro	Specific	Mobile	No additional	Uncrewed	1–2
Water treatment facility filters	Filters at treatment plants	Wastewater treatment plants	Micro	Specific	Stationary	No additional	Uncrewed	9
Magnetic separation	Use of a magnetic fluid that binds to microplastic particles, separating them from water and allowing for their removal using magnets	Wastewater treatment plants	Micro	Specific	Mobile	No additional	Crewed	2
Bacteria to 'eat' plastic	Bacteria either naturally able, or engineered, to break down plastics	Wastewater treatment plants	Macro and micro	Multiple	Mobile	No additional	Uncrewed	2
River barriers / booms	Traps and accumulates plastics as they float downstream	Rivers	Macro	Specific	Stationary	None	Uncrewed	9
Bubble barriers / curtains	Stream of rising bubbles pushes plastic waste to one side and pushes microplastics to the surface for collection	Rivers or canals	Macro and micro	Specific	Stationary	Electric	Uncrewed	6
Water based clean-up (using kayaks or paddle boards)	People-powered clean-ups using kayaks or paddle boards	Rivers, harbours, estuaries	Macro	Multiple	Mobile	None	Crewed	9
River based conveyer belt	Conveyor belt separates waste from water and automatically dumps the waste into containers on a separate barge docked below	River	Macro	Specific	Stationary	Electric	Uncrewed	9
Retention nets on stormwater drains	Net at the end of a stormwater drain to prevent plastics being released to the sea	Stormwater runoff, estuaries or coastline	Macro	Specific	Stationary	None	Uncrewed	8
Beach cleans by volunteers	Volunteers remove litter and debris deposited on a beach or coastline	Coastline	Macro	Specific	Mobile	None	Crewed	9
Commercial clean-ups	Large scale clean-ups to remove large amounts of plastic waste. Typically run by specialist contractors.	Usually coastline, rivers or harbours	Macro	Multiple	Mobile	None – but boat usually required	Crewed	9

TABLE 1 (continued)

Technology	Description	Where it intervenes	Type of plastic (micro / macro)	Location: (multiple / specific)	Stationary / mobile	Energy source	Autonomous / crewed / uncrewed	TRL*
Diving for debris scheme	A year-round, underwater debris and data collection effort where divers are encouraged to report on locations, types and quantities of litter collected	Coastline or shallow ocean	Macro	Multiple	Mobile	None – but boat usually required	Crewed	9
Sand sieving or filters on beaches	Manually sieving top layers of sand to pick up debris left / washed up on beaches	Coastline	Macro	Specific	Mobile	None	Crewed	8
Beach hoovers	Vacuum cleaner that can separate sand from plastics	Coastline	Macro and micro	Specific	Mobile	Petrol or battery depending on size	Crewed	7
Nurdle Trommel – beach cleaning	Drum filter to extract plastic nurdles from sand	Coastline	Micro	Specific	Stationary	Solar energy	Crewed	8
Seabins	Floating bins skim plastics and other debris from harbour water before they can reach the ocean	Estuaries or harbours	Macro	Specific	Stationary	Electric or diesel energy	Uncrewed	9
Trash wheels	Using booms, conveyor belts and solar panels, trash wheels sweep plastic out of the water	Harbours	Macro	Specific	Stationary	Currents and solar energy	Uncrewed	9
Waste Shark – autonomous moving cleaning device	A 'marine robot', roaming through water capturing plastics and other pollutants	Harbours, marinas or canals	Macro and micro	Multiple	Mobile	Solar or other form of electric energy	Uncrewed	9
Booms in ocean gyres	Ocean boom collects floating debris	Ocean	Macro	Specific	Stationary	None – but boat required to tow into place and remove the collected plastic waste	Uncrewed	7–8
Fishing for litter scheme	Fishing boats are given bags to collect the plastics and debris that gathers in their nets during normal fishing activities	Ocean	Macro	Multiple	Mobile	No additional – boats already in use	Crewed	9
Dredger boats	Boats specifically designed to dredge plastic, usually from harbours or marinas but can also be used in open ocean	Ocean or harbour	Macro	Multiple	Mobile	Petrol for boats	Crewed	9
Targeted ghost fishing clean-ups (diving)	Divers remove ghost fishing equipment from the marine environment, which is typically entangled and difficult to remove	Ocean	Macro	Multiple	Mobile	Boats required	Crewed	9
Trawl nets adapted for plastic clean-up	Fishermen are provided with special trawl nets to collect debris	Ocean	Macro	Multiple	Mobile	Boats required	Crewed	9
Biological / nature based interventions	Nature based solutions such as mussels to ingest microplastics or macrophytes and macroalgae which can act as glue for plastic particles in the water column – delaying or facilitating their removal.	Various	Macro and micro	Multiple	Stationary	None – but boat may be required to put in place and remove plastic waste	Uncrewed	2

*Technology Readiness Level
TRL 1 = Basic research. Principles observed.
TRL 2 = Concept and application formulated.
TRL 3 = Applied research. Laboratory tests. Proof of concept.
TRL 4 = Small scale prototype. Tested in laboratory environment.
TRL 5 = Large scale prototype. Tested in operational environment.
TRL 6 = Prototype of manufacturing system. Tested in operational environment at expected performance.
TRL 7 = Demonstration of system. Operating in operational environment at pre-commercial scale.
TRL 8 = Commercial system exists. Any manufacturing issues solved.
TRL 9 = Full commercial application. Technology is available for consumers.

3. The feasibility, scalability and likely effectiveness of plastic clean-up technologies and interventions

Of the technologies and interventions presented in Table 1 (see page 12), about two-thirds (17 / 24) have a Technology Readiness Level of 8 or 9 – meaning they are being manufactured and are ready to be used in the environment. This proportion is similar to other published studies[44]. There is also interest in nature-based solutions such as using mussels to filter out plastic and macrophytes to trap plastic, especially as these approaches may capture microplastics that are not targeted by other clean-up technologies. However, at present, these have a relatively low TRL, meaning they are in the research and development stage and not yet ready to be operationalised.

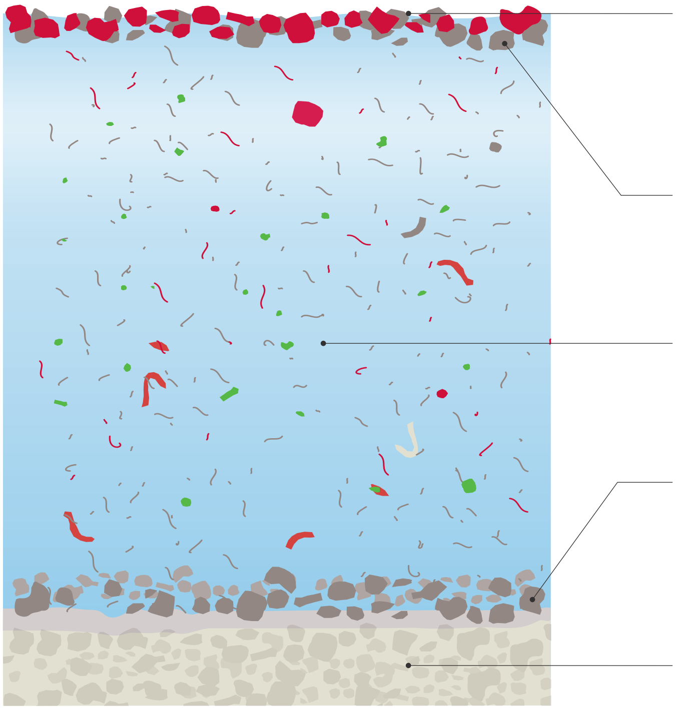
The effectiveness of most of these technologies has not been formally evaluated, and for those where it has, it is often with self-reported data which has not been validated by independent scientific assessment. This represents a substantial evidence gap, and it may make sense to assess both the effectiveness and social and environmental impacts of these technologies together (for more detail on this, see Chapter 6). One challenge in measuring the effectiveness of clean-up technologies is the lack of accurate data on the amount of plastic pollution in the environment in the first place (see Box 1, page 18). Note that the cost effectiveness of plastic clean-up technologies is considered in the next chapter.

Of the technologies presented in Table 1, few seem to lend themselves for use at scale, for several reasons. Firstly, many approaches are plastic type, context and / or location specific. So rather than scaling up one particular technology, a combination of different technologies and interventions will probably be required. Secondly, clean-up solutions are unlikely to be cost effective for regular and long-term use (see Chapter 4). This is especially true if the sources of plastic pollution have not been removed, i.e., the tap has not been switched off. Thirdly, while larger items of debris dominate by mass, a substantial proportion of environmental plastic pollution is microplastic and nanoplastic which is far harder, if not impossible, to observe, monitor, and remove. Much plastic is also distributed within the water column and buried in sediment (see Figure 5). This inherently limits the effectiveness of clean-up operations, and further highlights the importance of focusing on prevention and the clean-up of macroplastic close to source.

Many of the technologies listed in the table require an energy source. Therefore, alongside any unwanted environmental impacts on species or ecosystems (see Chapter 4), the implications in terms of carbon emissions would also have to be considered in any scale-up of these approaches. Passive collectors, which use the flow of the river or water to collect plastic, will have lower energy costs and associated carbon emissions.

FIGURE 5

Distribution of plastics in water.



Surface microlayer
Surface microlayer containing micro and potentially nanoplastics, plus the by-products released as plastic degrades. Intersected by floating macroplastics.

Floating load
Plastics afloat at the water's surface, spanning entire size range. Mixed down when turbulence increases.

Suspended load
Plastics fine, aspherical, and angular enough to remain suspended in water.

Bed load
Plastics moving along the base of the air or water column. Mixed up when turbulence increases.

Buried in sediment
Plastic that sinks to the seabed and is buried in layers of sediment.

Source: Stubbins *et al* 2021[45].

As noted many of these technologies are either plastic type or location specific, meaning they can only be effectively implemented in certain contexts. For example: beach cleans target macroplastic litter on coastlines; river interceptor technologies such as booms, wheels or bubble curtains aim to capture macroplastic in rivers before it enters the ocean; technologies such as the Seabin (see Figure 7, page 24) capture floating macroplastic in still waters such as harbours and estuaries; and ocean booms can collect floating rubbish that accumulates in ocean gyres which is mostly macroplastic items, as well as discarded fishing gear. Technologies to remove microplastics from the coastal environment are currently very limited, for example beach sieves. Though as noted, nature-based solutions such as mussels and reed beds to filter microplastic are in the research and development stage.

Beach cleans can be effective (see Box 2, page 20) given that coastlines are a place where plastic debris accumulates, and they also often have a particularly high natural capital value. Beach cleans do however rely on engaged volunteers close to the coast (otherwise the amount of human input required would likely be expensive).

BOX 1

Measuring the effectiveness of plastic clean-up technologies – proportion, weight or volume?

Weight, volume, or absolute numbers of debris may be used to provide an assessment of the effectiveness of plastic clean-up interventions, but numbers may be very large if the items are small, and measures of weight or volume can be misleading because a singular macroplastic item could outweigh thousands of microplastics. Similarly, mass and size data may be skewed by water retention and compaction respectively.

As discussed in Chapter 5, it may be possible to use modelling, remote sensing, and environmental observations to help predict the amount of plastic in different environments. With this denominator data, it should be possible to measure the percentage of plastic removed, to give a better sense of effectiveness.

It is also worth considering the potential harm that would be prevented by removing this plastic (prioritising plastic removal according to risk of harm is discussed in more detail in Chapter 5).

The effectiveness of plastic removal is likely to be highly variable, as plastic concentrations will depend on the exact location that the technology or intervention is deployed, the weather, times of day, tides etc. Therefore, regular sampling and data collection will likely be required to adequately understand the overall effectiveness of an intervention.

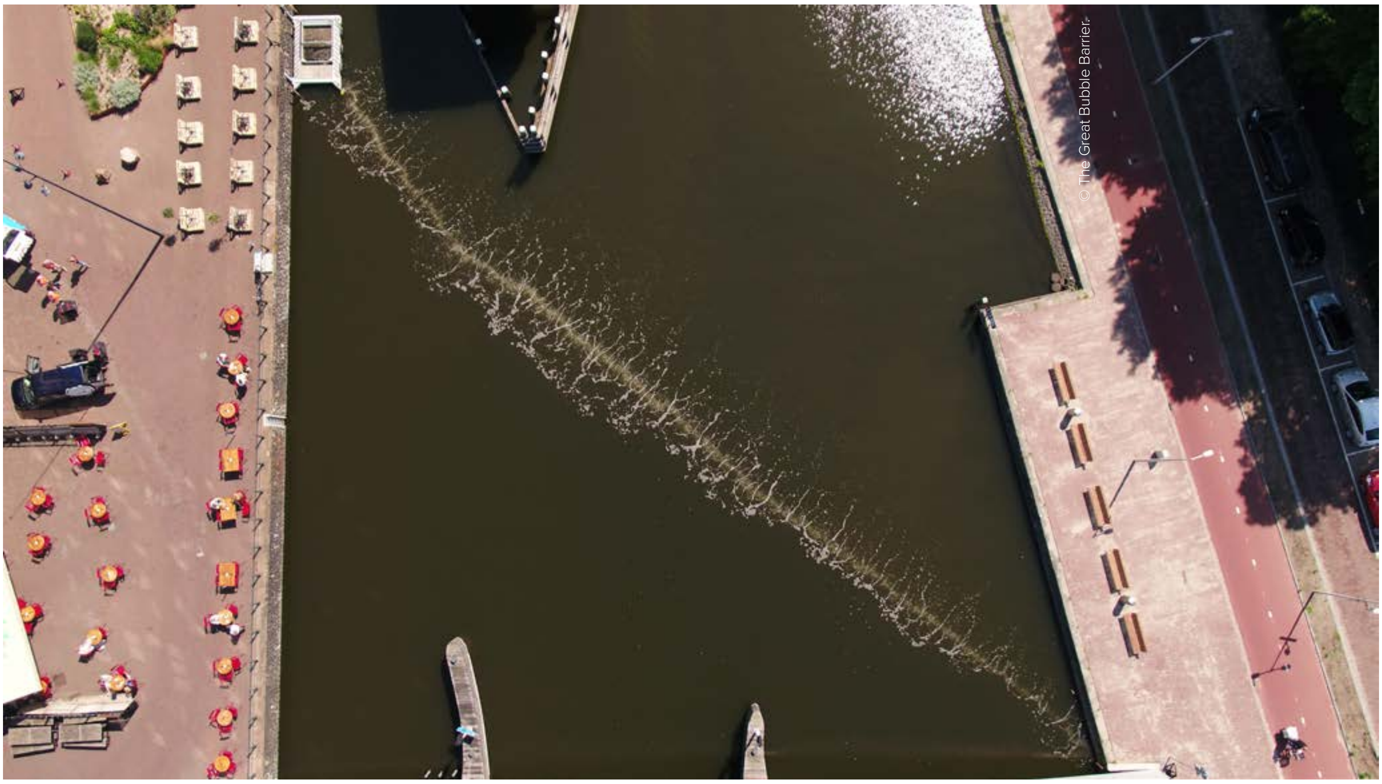
The feasibility and effectiveness of interceptors in rivers will depend on factors such as the hydrology of the river, the amount of plastic present, the human population living alongside it and the extent to which it is used for commercial activities such as transport or fishing. For a busy river, booms may be effective, especially if the river is highly polluted, but they might need to be implemented only on a portion of the river so as not to obstruct navigation by boats. Bubble curtains have been tested and implemented in some rivers (see Figure 6) – however these rely on relatively still water, and their effectiveness, scalability and environmental impact is not currently well understood. Many surface capture technologies are designed only to work in relatively calm waters, such as estuaries, harbours, marinas, or canals and these have been shown to capture a range of biota alongside plastic (see Chapter 4).

Clean-up options in the open ocean usually focus on areas with a high concentration of floating plastic. However, they can be expensive (see page 21) and since just 2% of ocean plastic is transported offshore and remains on the surface their overall efficacy is limited. Removal is likely to be more effective in coastal areas where most plastic accumulates, taking into account the considerations discussed in Chapter 4 regarding environmental impact.

FIGURE 6

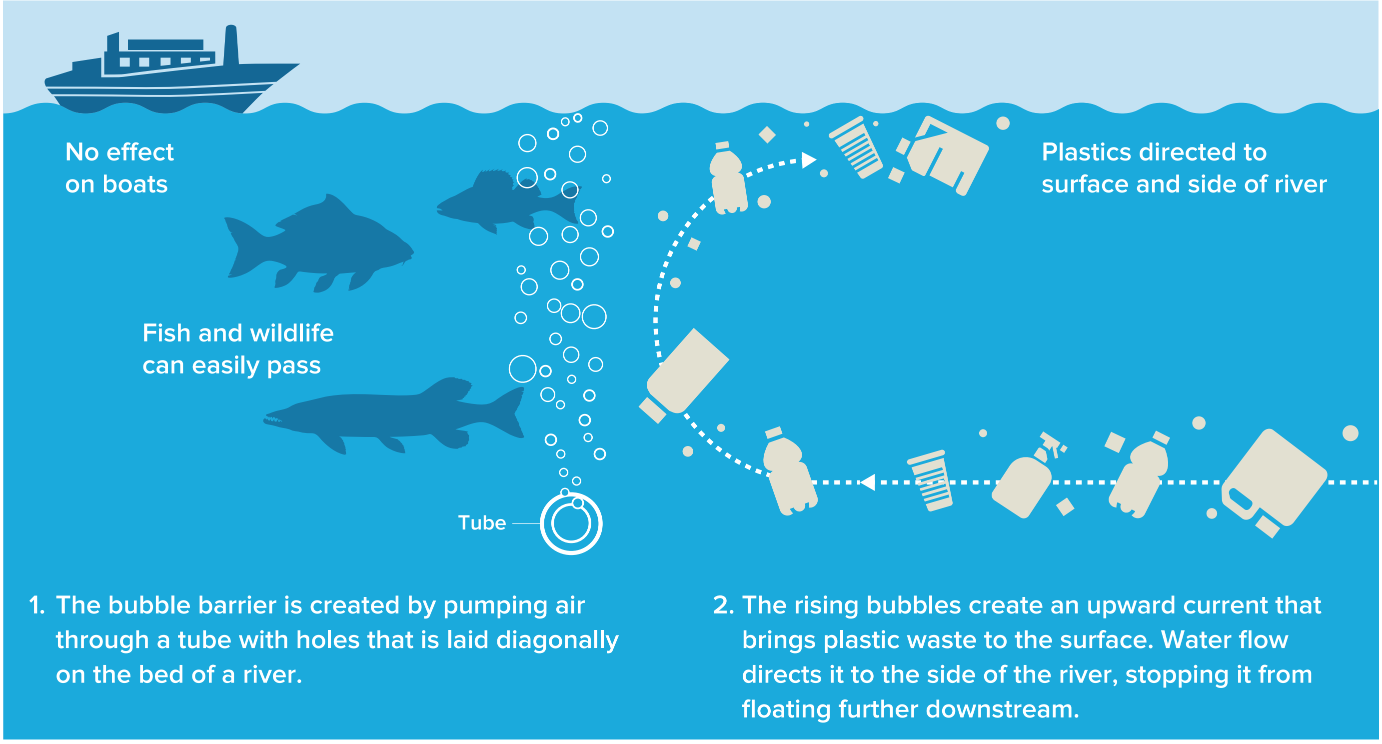
The Great Bubble Barrier in Amsterdam.

Aerial photograph of the Great Bubble Barrier in Amsterdam. The diagonal placement of the bubble curtain in the waterway guides plastic waste to the side and into the catchment system.



© The Great Bubble Barrier

Theory of how the bubble barrier works.



1. The bubble barrier is created by pumping air through a tube with holes that is laid diagonally on the bed of a river.
2. The rising bubbles create an upward current that brings plastic waste to the surface. Water flow directs it to the side of the river, stopping it from floating further downstream.

Sources: (top) The Great Bubble Barrier; (bottom) illustration adapted from original artwork, © Guardian News & Media Ltd 2024.

BOX 2

Beach cleans – a low cost and effective solution?

Beach cleans can be a simple and effective solution for removing plastic waste from the environment. Around 80% of ocean plastic remains within 100 miles of the shore between the coastline and ocean[46, 47]. It is thought that plastic degrades very quickly in coastal environments due to the salinity, warmer temperatures and tides[48]. This means that beach clean-ups are currently one of the most effective ways of removing macroplastics from the marine environment and help to minimise the generation of microplastics.

Beach cleans have a number of potential benefits:

- They clean up the environment relatively rapidly, with little negative impact.
- They are typically low cost, relying on volunteers and are sometimes funded by local businesses or communities or can present a fundraising opportunity.
- They are easy to repeat in multiple locations facilitating data comparisons.
- They target litter on beaches and near to the shore. These are often areas which have high natural capital, due to diverse coastal ecosystems, and also a high recreational value.
- They engage citizens with the environment, provide opportunities for physical activity and social contact, have benefits to mental health from doing 'social good', and promote both a sense of community and pro-environmental behaviours[49, 50].
- They can also help identify major litter types to inform further interventions. For example, the OSPAR beach litter monitoring protocol[51] was used to inform single-use plastics bans in the UK for plates, bowls, trays, containers, cutlery, balloon sticks, plastic straws, stirrers and cotton buds.

Potential challenges include:

- Only visible plastic is collected, not that which is buried in sand or covered in organic material such as grass or seaweed.
- The quality of data obtained by citizen science methods can be variable.
- They often focus on more accessible areas, not necessarily those with the most vulnerable habitats.
- They often rely on volunteers.
- They will require regular repetition.

Image: Rubbish collected during a beach clean on the Isle of Tiree in the Hebrides, Scotland. © Ian Boyd.

Cost considerations

The cost effectiveness of clean-up technologies and interventions is not well understood[52]. This section therefore presents a set of important considerations rather than a detailed economic analysis.

Table 2 (see page 22) presents some cost estimates, where they are available, for some of the clean-up interventions that this report considers.

Key considerations include:

Denominator data and time period

- Estimates of cost per kg of plastic removed are often very simplistic with a lot of assumptions and 'cost effectiveness' assessments will vary greatly depending on the denominator used (see Box 1, page 18).
- It may be worth comparing the cost / benefit of doing a range of smaller activities over a longer time period versus undertaking one big clean-up far less frequently.

Hidden costs and benefits

- The merits of clean-up activities can be increased if co-benefits are considered, such as the psychological and community benefits or providing monitoring data into the equation (see Chapter 4 for further examples).
- It may also be worth considering revenue lost from tourism due to plastic pollution, and the potential jobs created by plastic clean-up.
- Many technological clean-up devices require considerable personnel time for maintenance and emptying, and sometimes also energy to operate – factors which are often overlooked but can add greatly to implementation costs[53].
- If not already present, local infrastructure to deal effectively with collected plastic waste will need to be put in place.

Non-linearity of clean-up effort versus benefit

- Cost-effectiveness will decline in proportion to the amount of litter remaining in a given location – hence the balance between the benefits and the monetary and environmental costs will change over time. The less plastic that remains, the harder it becomes per unit of investment to find and remove, and at some point, removal will simply become more environmentally damaging than just leaving the plastic where it is.
- The impact of leaving the plastic in the environment will also shift the longer the plastic is left, as the plastic will degrade into microplastics and then nanoplastics. Quantifying these changes and their impact should also be part of the cost-benefit analysis.

Image: The Ocean Cleanup boom.
© The Ocean Cleanup.

TABLE 2

Cost estimates for some of the clean-up interventions.

Clean-up intervention	Description of associated costs
Beach and river clean-up by volunteers	Litter picking kits range from £20 to £130 per kit. For example, Queen Mary University London's 'Big River Refresh' cost £20 per kit and the Environment Agency's litter-picking kits for communities and businesses are £128 per kit. Beach cleans can sometimes pay for themselves as companies pay to use them as a 'teambuilding' activity or they can raise money through sponsorship. For example, the Marine Conservation Society charges £750 for a day of beach cleaning. Environment Agency's cost to launch and maintain the website for the Solent Forum – where groups could get in touch and join clean-up initiatives in their region: ~£37,000.
Commercial (specialist) clean-up operations	Professional dive cleans in Plymouth, targeting the local seabed, cost ~£6,000 for the initial survey of waste present on the seabed, ~£20,000 for the first round of dive cleans, ~£6,000 for the second round, including license and insurance, experienced divers, a boat and equipment. Over two and a half years, the cost of cleaning the Elorn river (in France) and sorting the waste recovered amounts to ~£41,000 (£35,000 for removal and £6,000 for sorting). 25 tonnes of plastic litter were manually removed from the Aldabra atoll (a remote UNESCO world heritage site in the Seychelles) at a cost of ~£18,000, which equates to around ~£8,000 per day of clean-up operations or £7,000 per tonne of litter[54].
Retention nets for stormwater drains or outflows	Retention nets and their installation cost between £6,000 and £17,000. The equipment to run the drain guard trial cost almost £1,000: £90 per drain guard plus equipment needed to safely remove, personnel to collect, categorise and dispose of the litter trapped. In contrast, an external contractor was required to lift and empty nets taking between one and one and a half hours per net and costing between £800 and £1,500 for five to seven nets. Running litter characterisation of a net takes at least one day. The characterisation of 5 nets cost ~£6,000, plus around ~£11,000 for storage and sorting and characterisation of 5 tonnes of waste. It is time consuming to empty the baskets and put them back in place. Maintenance of the drain guards requires the presence of two specialist staff and two staff from the local authority. Each session cost approx. £600 – 700 and took two full days of work.
Seabins in harbours, estuaries and marinas	Seabins cost between £3,000 – £4,000 and are stationed in estuaries, harbours or marinas. Once installed, they cost around 75p per day to run. It is estimated that a medium sized marina would need five to seven seabins to capture most of the litter[55]. They can operate 24 hours a day and capture around 1.5kg of debris a day, some of which is plastic – however this varies substantially according to how much debris is in the water and where they are positioned. Extra costs are required to empty and maintain the seabins, and to characterise the debris.
Ocean booms	According to a debate in a UK Parliament Backbench Business Committee[56], the Ocean Cleanup (see image left) requires £37 million per year to fund one of its ocean boom systems.

Note: Unless otherwise indicated, the data within this table comes from Preventing Plastic Pollution's report, *Reducing and removing the legacy of plastic pollution*[57].

4. Further considerations

The environmental impacts of plastic clean-up technologies

Most clean-up solutions are likely to cause some environmental harm. This will vary according to the environment and the method used. At present, the environmental impact of many of these technologies is largely unknown and there is no requirement for an environmental impact assessment to have taken place before or during their implementation. If and as these technologies become more commonplace, guidelines for their use, including environmental testing standards, are likely to be required. Ideally, independent scientific impact assessments of these technologies would take place prior to bringing them to market, followed by additional environmental impact evaluation in the location where they will be used. As part of this process, the development of a formal definition of 'plastic clean-up technologies' may be required.

The environmental impact of a couple of technologies has been assessed:

- The Ocean Cleanup commissioned an environmental impact assessment of their ocean booms[58] (see Figure 7), which concluded the greatest risks were that larger sea mammals, turtles and fish may encounter the boom, be captured and / or become tangled in the plastic collected[59]. Large-scale clean-up operations also have environmental implications associated with the use of large vessels and equipment, which may lead to light and noise pollution[60].
- Independent research has also examined the environmental impact of Seabins[61], which are used to catch plastic in harbours and marinas. As shown in Figure 7 (see page 24), alongside plastic and other debris (average 58 items per day), the Seabin caught seaweed and marine organisms, mainly sand eels (average 13 creatures per day, half of which were deceased). Comparison with other approaches to clean harbours indicated that this device had relatively low efficiency.

The organisms and habitats impacted will vary according to where and when the technology is implemented, the type of plastic and the intended frequency of use. Neustons (organisms which live on the surface of water), along with microbial communities and vegetation have a high probability of encounter with surface capture technologies. Conversely, if small organisms can pass freely through the device, then impacts on them may be lower, however, smaller plastic items will also not be captured.

This raises important questions about the extent to which inadvertent capture of natural materials including living organisms is acceptable, and how much disruption to freshwater or marine ecosystems is acceptable, relative to the amount of plastic collected. Consideration of the environmental impact of the technologies should sit alongside a consideration of the environmental impact of leaving plastic in the environment – and the relative costs and benefits of each weighed against each other. As noted, the negative consequences of leaving plastic in the environment will change over time, as plastic is transported and breaks down into microplastics and then nanoplastics.

FIGURE 7

Items and marine organisms caught by a Seabin.

The seabin captured substantial amounts of seaweed, together with marine animals (mainly sand eels), alongside relatively small amounts of plastic and other debris[62].

Images: © Florence Parker-Jurd.

Image: Evaluating the effectiveness of a trash boom on a river in Indonesia as part of the PISCES GCRF Project. © Dr Max Kelly.

Transnational considerations

As part of a systems approach, it is useful to consider the transnational nature of plastic pollution and clean-up. Globally, the burden of legacy plastic does not fall equally. There is an unequal division in terms of countries that have the resources to develop and invest in clean-up interventions, countries that produce the most plastic waste (often due to community livelihoods which are dependent on plastic use and a lack of infrastructure such as mains water) and those that have the greatest negative impacts from plastic pollution.

It has been shown that industrialised nations are the biggest contributors to plastic pollution in the North Pacific subtropical gyre[63]. However, generally, low and middle-income countries are major plastic polluters, and are also often those who are most negatively impacted by plastic pollution. Small Island Developing States such as the Seychelles[64] are also highly impacted. These countries often lack sufficient capacity to manage their own municipal waste, let alone also the waste accumulating on their beaches from other countries or collected from the marine environment following clean-up activities.

This lack of capacity might result in plastic waste re-entering the environment due to ineffective disposal or result in the open burning of plastic which is damaging for both the environment and human health, leading to greenhouse gas and toxic chemical emissions[65]. However, any challenges relating to how to dispose of collected plastic should not be used as a reason not to remove plastic waste from important habitats and ecosystems.

When designing and implementing clean-up interventions, funding and incentives, it may make sense to target regions where they can have the most positive environmental and social impact, regardless of a country's ability to pay for this. Establishing who pays for clean-up activities will not be straightforward. For example, should the waste that a country receives on its shores be their responsibility to clean up? Or only the waste which originates in that country or the region? Or should plastic producers pay for clean-up costs? These factors complicate the application of any kind of 'polluter pays' principle. Clean-up solutions which are locally focused, empower communities, and / or have a citizen science component are likely to be more sustainable and long lasting (see Box 2 on beach cleans, page 20 and image of the PISCES GCRF project, above).

BOX 3

Recycling and reusing degraded and contaminated plastic waste.

Materials scientists are beginning to investigate how to effectively recycle degraded and contaminated plastic waste[66]. The degradation of plastic usually causes chain scission, which means that the molecular weight decreases and, as a result, the viscosity of the plastic decreases. These changes not only cause problems during processing, but also affect the properties of products made from recycled plastic, such as increased fragility. While it has been demonstrated that recycled plastic from the marine environment can be re-used, with the negative effects of degradation compensated for with different methods (e.g. colourants, solid-state polymerisation reaction, chain extender additives[67, 68]), this research is in very early stages. However recycling plastic from the ocean will always be very challenging and plastic waste collected and recycled on land is likely to have a much greater reuse value.

Reducing current levels of production and consumption, investing in better waste management and designing plastics with an end-of-life value through reuse and recycling are key approaches to help to reduce the accumulation of plastic litter and waste in the environment. Plastic waste collected from the environment via clean-up is often too heterogeneous, degraded and contaminated to be recycled at scale[69].

Materials scientists are beginning to investigate the extent to which degraded and contaminated plastic may be recycled (Box 3). Many of the polymers used in fishing gear are relatively high value because of the quantities, and by comparison to packaging litter, relative homogeneity of this debris – meaning its potential value in recycling streams is greater. For example, there is demonstrable commercial success in collecting lost or abandoned fishing gear to manufacture products such as carpets[70]. However, it will always be far more effective to recycle plastic before it ends up in aquatic environments.

Co-benefits of plastic removal

There are a number of co-benefits associated with the removal of legacy plastic from the environment, including:

Data collection

Data on the amount of plastic, type of plastic and the rate at which interventions reduce its prevalence will be helpful to a) inform monitoring efforts that identify hotspots and make long term projections, b) better target interventions, and c) aid decision making and policy development. Some interventions lend themselves more readily to data collection than others, and this function could usefully be factored into implementation. There may be potential for plastic removal and data collection initiatives to be combined with other activities in the marine and coastal environment, such as fishing or research. Collecting data on any organisms that are captured or harmed by the clean-up activity would also help to assess the overall environmental impact of the clean-up.

Cleaning up other debris

Activities that remove litter from the seabed in particular, such as the Fishing For Litter Scheme[71], are likely to capture non-plastic items of litter.

Wellbeing and awareness raising benefits of citizen clean-up

There is evidence that citizen clean-up activities such as litter picking on beaches are beneficial for mental health and lead to greater societal awareness and pro-environmental intentions regarding plastic pollution[72]. Clean-up activities can also act as useful community engagement tools[73].

Economic opportunities

Plastic clean-up interventions can sometimes create new jobs and a steady income stream for the local community[74, 75]. There may also be commercial opportunities relating to the recycling, re-use or re-purposing of plastic waste.

5. Identifying plastic accumulation hotspots to prioritise clean-up efforts

Media attention has led to the assumption that plastic accumulates in dense aggregations on the surface of the ocean (within gyres, like the Great Pacific Garbage Patch, see Figure 8). However, these gyres are actually more akin to a 'plastic soup' (see Figure 5, page 17), in which elevated concentrations of macro and micro plastic are broadly dispersed, making removal more challenging. Therefore, identifying priority areas of plastic accumulation is likely to be far more complicated that simply scooping floating plastic debris from large patches in the ocean. This section describes how the latest science and technological advancements may assist with this.

Definition of hotspots

'Hotspots' represent priority areas for clean-up. Defining hotspots will be particularly important if this is to be used to allocate funds for clean-up activities. As part of the UN's Plastic's Treaty obligations, hotspots may need to be defined at a global, regional, national or local scale. To optimise the efficiency and positive impacts of plastic clean-up operations it will be necessary to understand where plastic originates, where it is accumulating and the pathways by which it got there[76]. In terms of identifying hotspots, the following criteria are likely to be more important than the absolute concentration of plastic:

The natural and social capital of the environment

Some ecosystems have high natural capital value. For example, by providing habitats for rare or endangered species or as sources of food for local populations. Rivers, estuaries and shallow water coastal habitats are typically high in biodiversity and often of key economic importance for tourism, aquaculture or fisheries[77]. These factors make these habitats a potential priority for clean-up efforts. Other areas of the ocean will also have high natural capital value, such as UNESCO World Heritage Sites[78] or those designated as Marine Protected Areas[79].

The risks that the plastic pollution poses

The harms associated with plastic pollution are summarised in Chapter 1. Some habitats and locations are associated with a particularly high risk of negative consequences. For example, shorelines, waters that are frequented by boat traffic, migration routes, rare or unique habitats, feeding or breeding grounds.

Certain types of plastic pollution are also likely to be more damaging than others. Fishing gear is especially harmful as it readily results in entanglement, trapping sea turtles, sharks and marine mammals, while plastic bags can lead to suffocation or obstruct the digestive tract. Certain plastic polymers will also degrade more quickly and / or may be more toxic (for example PVC[80]).

The feasibility and likely effectiveness of clean-up

Generally, it will be most effective to remove plastic close to source, before it disperses widely in the environment and, in the case of larger items, breaks down into smaller fragments. Rivers are a major pathway by which plastic reaches the ocean, and deploying clean-up technologies in rivers could represent an effective way of capturing plastic whilst it is constrained and in a uni-directional flow prior to it entering tidal estuaries and the ocean[81].

Given that once in the ocean, substantial quantities of plastic can accumulate on shorelines[82], activities such as beach cleans which target the coast may be more feasible and less costly than collecting plastic from the open ocean. Plastic litter that ends up in the open ocean can accumulate in gyres (see Figure 8, page 28) or sink to the seabed.

Macroplastic that is floating on the surface of the ocean within gyres, while somewhat feasible to remove, only represents 2% of all ocean plastic. Microplastics and macroplastics that are buried in sediment or are suspended in the water column (see Figure 5, page 17) would be difficult (if not, impossible) to remove.

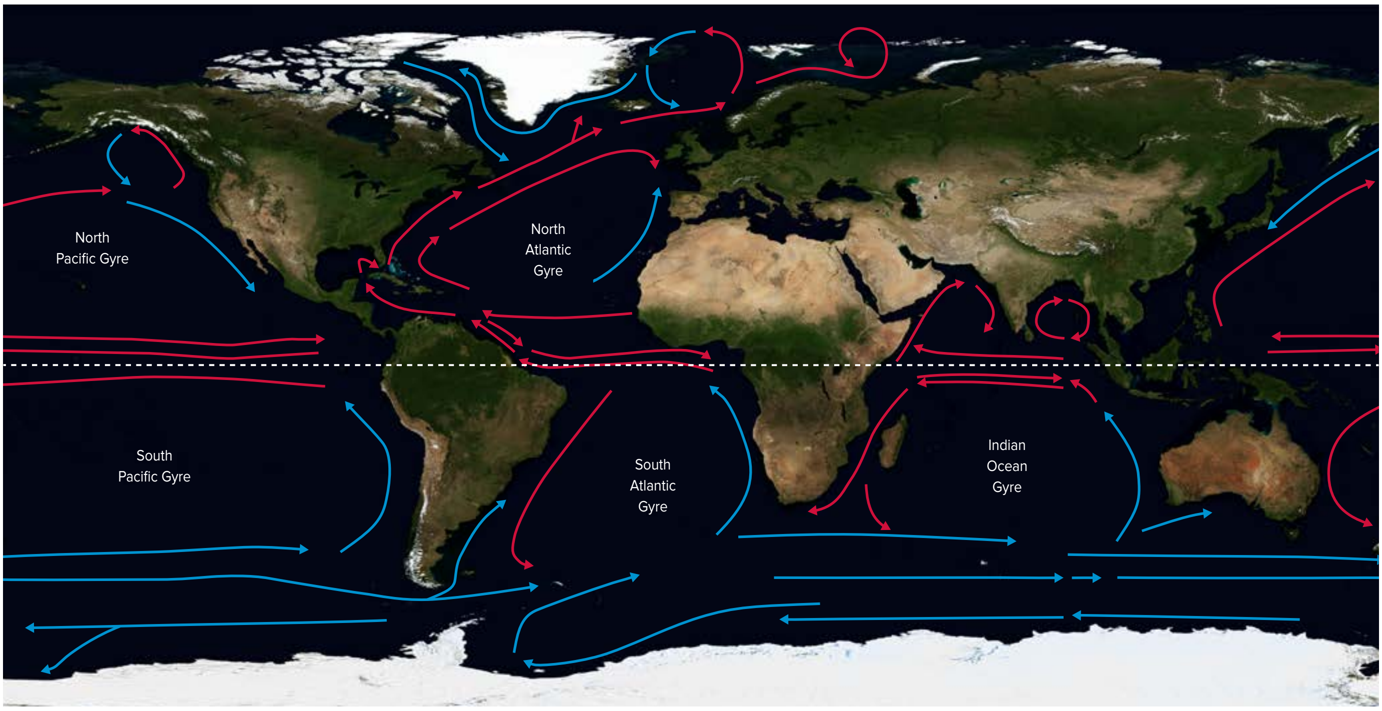
The risks of negative consequences from clean-up

The potential negative environmental impact from plastic clean-up technologies is described in Chapter 4. There are still many unknowns, but a certain amount of disruption to ecosystems from plastic clean-up seems likely. These risks should be compared to the negative impacts of leaving plastic in the environment.

FIGURE 8

The five gyres created from a large system of rotating ocean currents.

Most gyres are very stable, but some experience some seasonal variation.



Source: National Oceanic and Atmospheric Administration (NOAA)[83].

Identifying hotspots

Modelling

Modelling plastic pollution pathways and accumulation requires knowledge of multiple factors including the type of plastic litter, its size and shape, where it is released, flow directions and velocities of rivers, ocean currents, wind, waves, tides and prevailing weather conditions – which in many locations have a strong seasonal component. Numerous hydrographic modelling studies have predicted the spatial distribution of hotspots based on plastic litter and environmental monitoring data combined with broad scale ocean circulation patterns (see Figure 9) [84–90], or have scaled up empirical data on the quantities of plastic recorded in rivers or from land[91–94].

While these studies provide an insight, they also have a substantial degree of uncertainty about the timing and location of hotspots and the concentration of plastic present. Microplastics are challenging to sample and model because they are not easily observed due to their small size[95, 96]. Moreover, sources of microplastic also include not only direct inputs but also the fragmentation of larger plastic pieces[97]. These limitations mean that models of plastic pollution may not be sufficiently accurate to help guide clean-up activities. To be effective it is likely that plastic distribution models would need to be complemented by reliable, regular and consistent real-world sampling and observations (see Environmental monitoring section, below), which would also act to calibrate and refine these models so that their accuracy improves over time.

FIGURE 9

Debris dispersal.

Debris continuously enters the ocean from coasts and rivers, and is transported by ocean currents, waves, and winds. The colours in this modelling prediction represent the concentration of debris, and the simulation shows how the distribution of debris in the Indian Ocean is strongly driven by the monsoons.

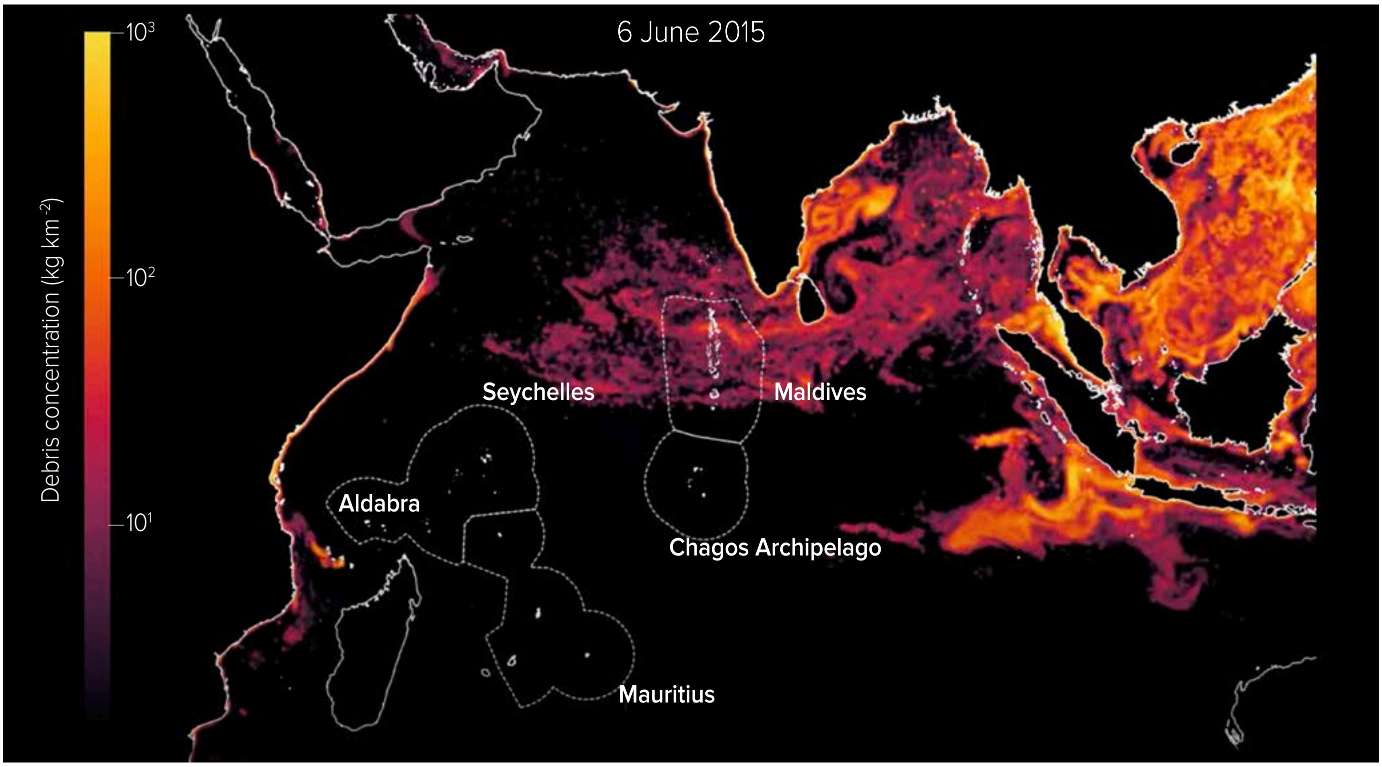


Image: Still from a video based on a numerical model developed by Vogt-Vincent *et al*. 2023. © Noam Vogt-Vincent[98].

Remote sensing

Remote sensing technologies including satellites, drones, sensors on boats, underwater cameras and unmanned vehicles are likely to prove useful for identifying the pathways, fluxes and places of accumulation for plastic debris[99]. Some of these platforms are also starting to utilise machine learning and artificial intelligence to help identify the presence and sometimes even type of litter in the environment[100, 101].

The level of resolution and the potential to locate hotspots for targeted clean-up will depend on the platform used. Drones, flying a few tens of meters above beaches, have been used to quantify plastic litter and litter types with good precision [102, 103] and their use for plastic hotspot identification seems promising. Satellites have the potential to collect lower spatial resolution data at broader scales, but at present using satellites to locate larger accumulations of plastic debris is mostly experimental.

One recent approach has been to identify discontinuities in the satellite data that appear to be associated with litter, rather than the litter itself[104]. However, the use of satellite data to monitor plastic pollution may ultimately be limited to larger macroplastics and / or areas with very high concentrations.

As these technologies develop further, it is likely that detailed visual information will increasingly be integrated with hydrological models and used to accurately map the distributions of plastic at sea as well as transport by rivers. However, imaging litter that is submerged below the water surface or obscured by sand or remains a key limitation[105 – 107]. Underwater drones and remote sensing technologies mounted to boats have been used to provide some estimates of submerged plastic pollution[108, 109]. The data from these instruments could be combined with that of above-water sensing methods to get more accurate predictions of plastic both on and below the surface of water. However, monitoring plastic buried by sediment will remain a challenge.

Image: Volunteers taking part in the Marine Conservation Society's Great British Beach Clean. © Aled Llywelyn and Billy Barraclough.

Environmental monitoring and citizen science

To support plastic hotspot identification and corroborate, calibrate, and refine modelling efforts, empirical environmental monitoring of plastic pollution will continue to be essential. Long-term monitoring can help identify hotspots, measure the effectiveness of clean-up and monitor associated environmental and societal impacts (both positive and negative). Some of this data may come from citizen science. Examples include the Great British Beach Clean[110] organised by the Marine Conservation Society, 100 Plastic Rivers[111, 112] led by the University of Birmingham, and the 'waterloggers' project at Bangor University[113], where wild swimmers collect samples of river water which are then analysed for microplastics.

Data from beach cleans (see image above) is routinely used to monitor macroplastic and has been used to develop UK policy relating to bans on the most polluting plastic items such as plastic bags and cotton buds.

Using information from these citizen science activities for monitoring purposes has some challenges. For instance, the activities can be idiosyncratic and frequently do not have set sampling criteria, such as the number or size of samples taken[114]. However, citizen science can allow data collection in multiple geographical areas which would not otherwise be obtained, at relatively low cost and effort.

Well-designed quantitative surveys can provide more robust data; however, these require substantial investments if they are to be conducted on a broad spatial scale (for examples see OSPAR[115], CSIRO[116], and NOAA[117]). Ocean monitoring has typically employed nets, with the plastic then classified and counted by hand. This has obvious biases towards floating surface objects and those large enough to be discerned by the human eye, but small enough to fit in a net[118]. Given changing ocean circulation patterns and weather conditions, sampling plastic in the ocean can give highly variable results and so large sample sizes are required to reveal statistically significant results – further adding to the cost[119].

Conclusion

Plastic is a persistent and bio-accumulative environmental pollutant, which has been shown to cause harm at all levels of biological organisation. It has been estimated that one quarter (82 million tonnes) of the world's plastic waste is 'mismanaged', meaning it is not stored in secure landfills, recycled or incinerated. Of that, 19 million tonnes are leaked into the environment. Policy interest in plastic pollution is also expected to increase, due to legally binding agreements such as the UN Plastics Treaty.

In accordance with the waste hierarchy (see Figure 1, page 7), preventing plastic from entering the environment in the first place should remain the policy priority. However, some amount of environmental plastic removal will likely be necessary to reduce the risk of harm to ecosystems and potentially humans. This is due to the high amount of plastic already in the environment, and predictions that concentrations will continue to increase steadily under business-as-usual scenarios[120 – 122]. It is against this backdrop that this report has summarised some of the technologies and interventions that are currently available to clean-up legacy plastics from the environment.

The large number of evidence gaps make it challenging to assess the feasibility, effectiveness and positive and negative impacts of plastic clean-up technologies. Many technologies or interventions are plastic-type or location specific – meaning that few lend themselves for use at scale. It is therefore likely that a range of interventions would be needed to target different situations. However, technologies which intervene as close to source as possible are likely to be both more feasible and more effective – targeting plastic waste before it disperses or breaks down into smaller fragments. Capturing plastic in rivers before it reaches the ocean, or capturing plastic close to the shoreline, where substantial quantities accumulate, are likely to present the most straightforward clean-up locations. Coastlines often have high natural and social capital; therefore beach cleans can be effective at reducing harm, are relatively low cost (if conducted by volunteers) and are also likely to have few negative environmental consequences and a range of co-benefits.

The environmental impacts of most technological clean-up approaches are unknown and there is no requirement for an environmental impact assessment to have taken place before or during implementation. If these technologies become more commonplace, guidelines for their use, including environmental testing standards, are likely to be required. Based on data from clean-up technologies that have been evaluated, it seems likely that negative environmental impacts on biota represents a key risk. Examples of negative impacts include unintended entrapment (particularly of surface-dwelling organisms), disturbance from the large vessels and equipment needed for ocean clean-up solutions – such as light and noise pollution – and the risk that larger sea mammals may encounter booms or become entangled. It is important to understand such negative effects in more detail so that they can be compared to the negative impacts of leaving plastic in the environment.

This report has outlined how science and technology can help identify ‘hotspots’ as priority areas for plastic clean-up. A definition of plastic pollution hotspots will be an important component of the UN Plastics Treaty and it is suggested that this be defined based on criteria outlined in this report: the natural and social capital value of the environment; the risks that the plastic pollution poses to either ecosystems or humans; the feasibility and likely effectiveness of clean-up and the risk of negative consequences from clean-up.

Scientific advances such as remote sensing, when combined with detailed hydrographic models and machine learning, offer much promise as a suite of techniques for assisting with the identification of hotspots. Whilst these techniques will still need to be complemented and refined by regular empirical data collection, establishing data sharing platforms on plastic pollution will mean that hotspots of pollution will likely be able to be identified with increasing precision. This data would also help with understanding the efficacy of plastic pollution reduction policies at both national and international levels.

Overall, science and technology could offer an important contribution to legacy plastic clean-up, hotspot identification and longer-term plastic pollution monitoring. While legacy plastic clean-up in aquatic environments may have some value in complementing policy efforts that focus on prevention and reducing plastic pollution at source, it is important to recognise that clean-up is not, on its own, an effective solution to the plastic pollution problem.

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The members of the Review Group involved in producing this report are listed below. The Review Group members acted in an individual and not organisational capacity. No conflict of interest was declared for this report. Members contributed on the basis of their own expertise and good judgement.

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References

1 Based on current trends of a 4.5% annual growth in plastics production between 2017 and 2100 – and that between 1.75% and 4.67% of yearly plastic production becomes marine. See Everaert G, Van Cauwenberghe L, De Rijcke M, Koelmans AA, Mees J, Vandegehuchte M, & Janssen CR. 2018. Risk assessment of microplastics in the ocean: Modelling approach and first conclusions. *Environmental pollution*, 242, 1930-1938.

2 UN Environment Program. 2009 Marine Litter. A Global Challenge. Nairobi: UNEP. See https://www.unep.org/resources/report/marine-litter-global-challenge (accessed 31 October 2023).

3 Gall SC, & Thompson RC 2015. The impact of debris on marine life. *Marine pollution bulletin*, 92(1-2), 170-179. (https://doi.org/10.1016/j.marpolbul.2014.12.041)

4 Cole M, Lindeque P, Fileman E, Halsband C, Goodhead R, Moger J, Galloway TS. Microplastic ingestion by zooplankton. 2013 *Environmental science & technology* 47.12, 6646-6655. (https://doi.org/10.1021/es400663f)

5 Gall SC, & Thompson RC. 2015. The impact of debris on marine life. *Marine pollution bulletin*, 92(1-2), 170-179. (https://doi.org/10.1016/j.marpolbul.2014.12.041)

6 See https://research-and-innovation.ec.europa.eu/research-area/environment/oceans-and-seas/eu-marine-strategy-framework-directive_en (accessed on 21 March 2024).

7 Gall SC, & Thompson, R. C. 2015. The impact of debris on marine life. *Marine pollution bulletin*, 92(1-2), 170-179. (https://doi.org/10.1016/j.marpolbul.2014.12.041)

8 Breaking the Plastic Wave: A Comprehensive Assessment of Pathways Towards Stopping Ocean Plastic Pollution. The Pew Charitable Trusts and SYSTEMIQ. 2020. See https://www.pewtrusts.org/en/research-and-analysis/articles/2020/07/23/breaking-the-plastic-wave-top-findings (accessed on 20 March 2024).

9 Lebreton, L, & Andrady, A. 2019. Future scenarios of global plastic waste generation and disposal. *Palgrave Communications*, 5(1), 1-11. (DOI:10.1057/s41599-018-0212-7)

10 Defined according to Everaert *et al*, 2018. A safe concentration of microplastics is 6650 buoyant particles m−3 below which adverse effects are not likely to occur. Everaert G, Van Cauwenberghe L, De Rijcke M, Koelmans AA, Mees J, Vandegehuchte M, Janssen CR. 2018. Risk assessment of microplastics in the ocean: Modelling approach and first conclusions. Environ Pollut. 242(Pt B):1930-1938. (doi: 10.1016/j.envpol.2018.07.069.)

11 Everaert G, Van Cauwenberghe L, De Rijcke M, Koelmans AA, Mees J, Vandegehuchte M, Janssen CR. 2018. Risk assessment of microplastics in the ocean: Modelling approach and first conclusions. Environ Pollut. 242(Pt B):1930-1938. (doi: 10.1016/j.envpol.2018.07.069.)

12 Hardesty BD, Harari J, Isobe A, Lebreton L, Maximenko N, Potemra J, Van Sebille E, Vethaak AD, Wilcox C. 2017. Using numerical model simulations to improve the understanding of micro-plastic distribution and pathways in the marine environment. *Frontiers in marine science*. *Frontiers in marine science* 4, 30. (https://doi.org/10.3389/fmars.2017.00030) .

13 Lampitt RS. 2023. Stakeholder alliances are essential to reduce the scourge of plastic pollution. *Nature communications* 14, 2849

14 OECD. Global Plastics Outlook. 2022.. See https://www.oecd.org/environment/plastics/ (accessed 1 November 2023).

15 Lebreton LC, Van Der Zwet J, Damsteeg JW, Slat B, Andrady A, Reisser J. 2022 River plastic emissions to the world's oceans. *Nature communications* 8, 15611.

16 Schmidt C, Krauth T, Wagner S. 2017. Export of plastic debris by rivers into the sea. *Environmental science & technology* 51, 12246-53.

17 Lebreton L *et al.* 2022 Industrialised fishing nations largely contribute to floating plastic pollution in the North Pacific subtropical gyre. *Sci Rep* 12, 12666. (https://doi.org/10.1038/s41598-022-16529-0)

18 See https://fishingforlitter.org/ (accessed 20 March 2024).

19 Thompson RC, Olsen Y, Mitchell RP, Davis A, Rowland SJ, John AW, McGonigle D, Russell AE. 2004 Lost at sea: where is all the plastic? *Science* 304.5672, 838. (doi:10.1126/science.1094559)

20 Krause S *et al.* 2021 Gathering at the top? Environmental controls of microplastic uptake and biomagnification in aquatic food webs. *Environmental Pollution* 268, 115750. (https://doi.org/10.1016/j.envpol.2020.115750)

21 Schmidt C, Krauth T, Wagner S. 2017 Export of plastic debris by rivers into the sea. *Environmental science & technology* 51, 12246-53.

22 Cole M, Lindeque P, Fileman E, Halsband C, Goodhead R, Moger J, Galloway TS. Microplastic ingestion by zooplankton. 2013 *Environmental science & technology* 47.12, 6646-6655. (https://doi.org/10.1021/es400663f)

23 Free CM, Jensen OP, Mason SA, Eriksen M, Williamson NJ, Boldgiv B. 2014 High-levels of microplastic pollution in a large, remote, mountain lake. *Marine pollution bulletin* 85.1, 156-163. (https://doi.org/10.1016/j.marpolbul.2014.06.001)

24 Lechner A *et al.* 2014 The Danube so colourful: a potpourri of plastic litter outnumbers fish larvae in Europe's second largest river. *Environmental pollution* 188, 177-181. (https://doi.org/10.1016/j.envpol.2014.02.006)

25 Lau WW, Shiran Y, Bailey RM, Cook E, Stuchtey MR, Koskella J, Velis CA, Godfrey L, Boucher J, Murphy MB, Thompson RC. 2020 Evaluating scenarios toward zero plastic pollution. *Science* 369, 1455-61. (https://doi.org/10.1126/science.aba9475)

26 Lavers JL, Hutton I, & Bond AL. (2018). Ingestion of marine debris by wedge-tailed shearwaters (Ardenna pacifica) on Lord Howe Island, Australia during 2005–2018. *Marine pollution bulletin*, 133, 616-621. ()https://doi.org/10.1016/j.marpolbul.2018.06.023

27 Codina-García M, Militão T, Moreno J, & González-Solís J. (2013). Plastic debris in Mediterranean seabirds. *Marine pollution bulletin*, 77(1-2), 220-226.(https://doi.org/10.1016/j.marpolbul.2013.10.002)

28 Lavers JL, Hutton I & Bond AL. (2018). Ingestion of marine debris by wedge-tailed shearwaters (Ardenna pacifica) on Lord Howe Island, Australia during 2005–2018. *Marine pollution bulletin*, 133, 616-621. ()https://doi.org/10.1016/j.marpolbul.2018.06.023

29 https://doi.org/10.1016/j.envpol.2011.06.008 https://doi.org/10.1016/j.envpol.2011.06.008

30 Fossi, M C, Baini, M, Panti, C, & Baulch, S. (2018). Impacts of marine litter on cetaceans: a focus on plastic pollution. In *Marine mammal ecotoxicology* (pp. 147-184). Academic Press.

31 Gall SC, & Thompson RC. 2015. The impact of debris on marine life. *Marine pollution bulletin*, 92(1-2), 170-179. (https://doi.org/10.1016/j.marpolbul.2014.12.041)

32 Cole M, Lindeque P, Fileman E, Halsband C, Goodhead R, Moger J, Galloway TS. Microplastic ingestion by zooplankton. 2013 *Environmental science & technology* 47.12, 6646-6655. (https://doi.org/10.1021/es400663f)

33 Bucci K, Tulio M, Rochman CM. 2020 What is known and unknown about the effects of plastic pollution: A meta- analysis and systematic review. *Ecological Applications* 30.2, e02044.

34 Thushari GG, Senevirathna JD. Plastic pollution in the marine environment. Heliyon 6, e04709.(doi.org/10.1016/j.heliyon.2020.e04709)

35 Gregory MR. Environmental implications of plastic debris in marine settings--entanglement, ingestion, smothering, hangers-on, hitch-hiking and alien invasions. Philos Trans R Soc Lond B Biol Sci. 2009 Jul 27;364(1526):2013-25. (doi: 10.1098/rstb.2008.0265).

36 Oehlmann Jörg, Schulte-Oehlmann Ulrike, Kloas Werner, Jagnytsch Oana, Lutz Ilka, Kusk Kresten O, Wollenberger Leah, Santos Eduarda M, Paull Gregory C, Van Look Katrien JW and Tyler Charles R.2009. A critical analysis of the biological impacts of plasticizers on wildlife *Phil. Trans. R. Soc. B* 364 2047–2062 (doi.org/10.1098/rstb.2008.0242)

37 Haram LE, Carlton JT, Centurioni L, Coong H, Cornwell B, Crowley M, Egger M, Hafner J, Hormann V, Lebreton L, Maximenko N, McCuller M, Murray C, Par J, Shcherbina A, Wright C, Ruiz GM. 2023. Extent and reproduction of coastal species on plastic debris in the North Pacific Subtropical Gyre. *Nat Ecol Evol* 7, 687–697. (https://doi.org/10.1038/s41559-023-01997-y)

38 Haram LE, Carlton JT, Centurioni L, Coong H, Cornwell B, Crowley M, Egger M, Hafner,J, Hormann V, Lebreton L, Maximenko,N, McCuller M, Murray C, Par J, Shcherbina A, Wright C, Ruiz GM. 2023. Extent and reproduction of coastal species on plastic debris in the North Pacific Subtropical Gyre. *Nat Ecol Evol* 7, 687–697. (https://doi.org/10.1038/s41559-023-01997-y)

39 Krause S *et al.* 2021 Gathering at the top? Environmental controls of microplastic uptake and biomagnification in aquatic food webs. *Environmental Pollution* 268, 115750. (https://doi.org/10.1016/j.envpol.2020.115750)

40 Browne MA, UnderwoodAJ, Chapman MG, Williams R, Thompson RC, & van Franeker JA. 2015. Linking effects of anthropogenic debris to ecological impacts. *Proceedings of the Royal Society B: Biological Sciences*, 282(1807), 20142929. (https://doi.org/10.1098/rspb.2014.2929)

41 The Royal Society. 2019 Microplastics in freshwater and soil. See https://royalsociety.org/-/media/policy/projects/microplastics/microplastics-report-executive-summary.pdf (accessed 31 October 2023).

42 Leone G *et al.* 2023 A comprehensive assessment of plastic remediation technologies. *Environment International*, 107854. (https://doi.org/10.1016/j.envint.2023.107854)

43 OECD Global Plastic Outlook. See https://www.oecd-ilibrary.org/environment/data/global-plastic-outlook_c0821f81-en
(accessed 11 March 2024).

44 Brouwer R *et al.* Assessing the performance of marine plastics cleanup technologies in Europe and North America. *Ocean & Coastal Management* 238, 106555. (https://doi.org/10.1016/j.ocecoaman.2023.106555)

45 See https://www.science.org/doi/10.1126/science.abb0354

46 Onink V, Jongedijk CE, Hoffman MJ, van Sebille E, Laufkotter C. 2021. *Environ. Res. Lett.* 16 doi 10.1088/1748-9326/abecbd

47 OECD Global Plastic Outlook https://www.oecd-ilibrary.org/environment/data/global-plastic-outlook_c0821f81-en - (accessed 11 March 2024).

48 See https://news.sky.com/story/why-beach-cleans-matter-as-new-research-gives-scientists-hope-for-polluted-oceans-12962030
(accessed 11 March 2024).

49 Wyles KJ, Pahl S, Holland M & Thompson RC. 2017. Can Beach Cleans Do More Than Clean-Up Litter? Comparing Beach Cleans to Other Coastal Activities. *Environment and Behavior*, 49(5), 509- 535. https://doi.org/10.1177/0013916516649412

50 Preventing Plastic Pollution. 2023 Reducing and Removing the Legacy of Plastic Pollution. See https://preventingplasticpollution.com/wp-content/uploads/2023/03/Reducing-and-removing-the-legacy-of-plastic-pollution-1.pdf (accessed 1 November 2023).

51 OSPAR. Beach Litter Monitoring. See https://oap.ospar.org/en/ospar-assessments/committee-assessments/human-activities/marine-litter/beach-litter-monitoring/ (accessed 1 November 2023).

52 Brouwer R *et al.* Assessing the performance of marine plastics cleanup technologies in Europe and North America. *Ocean & Coastal Management* 238, 106555. (https://doi.org/10.1016/j.ocecoaman.2023.106555)

53 Preventing Plastic Pollution. 2023 Reducing and Removing the Legacy of Plastic Pollution. See https://preventingplasticpollution.com/wp-content/uploads/2023/03/Reducing-and-removing-the-legacy-of-plastic-pollution-1.pdf (accessed 1 November 2023).

54 Burt AJ, Raguain J, Sanchez C, Brice J, Fleischer-Dogley F, Goldberg R, Talma S, Syposz M, Mahony J, Letori J, Quanz C, Ramkalawan S, Francourt C, Capricieuse I, Antao A, Belle K, Zillhardt T, Moumou J, Roseline M, Bonne J, Marie R, Constance E, Suleman J, Turnbull LA. 2020. The costs of removing the unsanctioned import of marine plastic litter to small island states. *Nat Sci Rep*. 10;10(1):14458. doi: 10.1038/s41598-020-71444-6.

55 https://resource.co/article/innovative-seabin-collects-waste-harbours-first-its-kind-uk-12327 - accessed on 14 November 2023

56 Hansard. Plastic Pollution in the Ocean: Volume 732: debated on Thursday 18 May 2023. See https://hansard.parliament.uk/Commons/2023-05-18/debates/E1937B7F-1B85-4593-B57D-6A3C4BBD5520/PlasticPollutionInTheOcean?highlight=ocean%20clean%20up#contribution-F462E33B-3F3C-4D8E-BC07-D4734DF83172 (accessed 1 November 2023).

57 See https://preventingplasticpollution.com/wp-content/uploads/2023/03/Reducing-and-removing-the-legacy-of-plastic-pollution-1.pdf (accessed on 14 November 2023).

58 CSA. The Ocean Cleanup Environmental Impact Assessment. See https://assets.theoceancleanup.com/app/uploads/2019/04/TOC_EIA_2018.pdf (accessed 2 November 2023).

59 See https://theoceancleanup.com/updates/system-002-and-marine-life-prevention-and-mitigation/ (accessed on 15 April 2024).

60 Cordier M, Uehara T. 2019. How much innovation is needed to protect the ocean from plastic contamination? *Science of the total environment*. 20;670:789-99. (https://doi.org/10.1016/j.scitotenv.2019.03.258)

61 Parker-Jurd FN, Smith NS, Gibson L, Nuojua S, Thompson RC. 2022 Evaluating the performance of the 'Seabin'–A fixed point mechanical litter removal device for sheltered waters. *Marine Pollution Bulletin* 184, 114199. (https://doi.org/10.1016/j.marpolbul.2022.114199)

62 Parker-Jurd FN, Smith NS, Gibson L, Nuojua S, Thompson RC. 2022 Evaluating the performance of the 'Seabin'–A fixed point mechanical litter removal device for sheltered waters. Marine Pollution Bulletin 184, 114199. (https://doi.org/10.1016/j.marpolbul.2022.114199)

63 Lebreton L *et al.* 2022 Industrialised fishing nations largely contribute to floating plastic pollution in the North Pacific subtropical gyre. *Sci Rep* 12, 12666. (https://doi.org/10.1038/s41598-022-16529-0)

64 Vogt-Vincent NS, Burt AJ, Kaplan DM, Mitarai S, Turnbull LA, Johnson HL. 2023 Sources of marine debris for Seychelles and other remote islands in the western Indian Ocean. *Marine Pollution Bulletin* 187, 114497. (https://doi.org/10.1016/j.marpolbul.2022.114497)

65 Velis CA, Cook E. 2021 Mismanagement of plastic waste through open burning with emphasis on the global south: a systematic review of risks to occupational and public health. *Environmental Science & Technology* 55.11, 7186-207. (https://doi.org/10.1016/j.marpolbul.2017.04.006)

66 See https://fishingforlitter.org/ (accessed on 20 March, 2024).

67 See https://fishingforlitter.org/ (accessed on 20 March, 2024).

68 See https://fishingforlitter.org/ (accessed on 20 March, 2024).

69 Ronkay F, Molnar B, Gere D, CziganyT. 2021. Plastic waste from marine environment: Demonstration of possible routes for recycling by different manufacturing technologies. *Waste Management*. 119,101-110, (https://doi.org/10.1016/j.wasman.2020.09.029.)

70 See https://www.econyl.com/magazine/econyl-news/net-works/ - (accessed on 20 March 2024).

71 See https://fishingforlitter.org/ (accessed on 20 March 2024).

72 Wyles KJ, Pahl S, Holland M, Thompson RC. 2017 Can beach cleans do more than clean-up litter? *Environment and Behavior* 49.5, 509-535. (https://doi.org/10.1177/001391651664941)

73 Preventing Plastic Pollution. 2023 Reducing and Removing the Legacy of Plastic Pollution. See https://preventingplasticpollution.com/wp-content/uploads/2023/03/Reducing-and-removing-the-legacy-of-plastic-pollution-1.pdf (accessed 1 November 2023).

74 See https://www.sevencleanseas.com(accessed on 16 November 2023).

75 Leone G, Moulaert I, Devriese LI, Sandra M, Pauwels I, Goethals PL & Catarino AI. (2023). A comprehensive assessment of plastic remediation technologies. *Environment International*, 173, 107854. .(https://doi.org/10.1016/j.envint.2023.107854)

76 Hardesty BD *et al.* 2017 Using numerical model simulations to improve the understanding of micro-plastic distribution and pathways in the marine environment. *Frontiers in marine science* 4, 30. (https://doi.org/10.3389/fmars.2017.00030)

77 Clark JR *et al.* Marine microplastic debris: a targeted plan for understanding and quantifying interactions with marine life. *Frontiers in Ecology and the Environment* 14.6, 317-324. (https://doi.org/10.1002/fee.1297)

78 See https://whc.unesco.org/en/marine-programme/ (accessed on 6 March 2024).

79 See https://www.gov.uk/guidance/marine-protected-areas-mpas (accessed on 6 March 2024).

80 Lithner D, Larsson Å & Dave G. (2011). Environmental and health hazard ranking and assessment of plastic polymers based on chemical composition. *Science of the total environment*, 409(18), 3309-3324. (https://doi.org/10.1016/j.scitotenv.2011.04.038)

81 OECD Global Plastic Outlook. See https://www.oecd-ilibrary.org/environment/data/global-plastic-outlook_c0821f81-en - (accessed 11 March 2024).

82 OECD Global Plastic Outlook. See https://www.oecd-ilibrary.org/environment/data/global-plastic-outlook_c0821f81-en - (accessed 11 March 2024).

83 See https://oceanservice.noaa.gov/facts/gyre.html (accessed 9 April 2024).

84 Lebreton LC, Van Der Zwet J, Damsteeg JW, Slat B, Andrady A, Reisser J. 2017 River plastic emissions to the world's oceans. *Nature communications* 8.1, 15611. (https://doi.org/10.1038/ncomms15611)

85 Van Sebille E *et al.* 2015 A global inventory of small floating plastic debris. *Environmental Research Letters* 10.12, 124006. (https://doi.org/10.1088/1748-9326/10/12/124006)

86 Sherman P, Van Sebille E. 2016 Modeling marine surface microplastic transport to assess optimal removal locations. *Environmental Research Letters* 11, 014006. (https://doi.org/10.1088/1748-9326/11/1/014006)

87 Maximenko N *et al.* 2019 Toward the integrated marine debris observing system. *Frontiers in marine science* 6, 447. (https://doi.org/10.3389/fmars.2019.00447)

88 Van Sebille E *et al*. The physical oceanography of the transport of floating marine debris. *Environmental Research Letters* 15.2, 023003.

89 Kaandorp ML, Lobelle D, Kehl C, Dijkstra HA, van Sebille E. Global mass of buoyant marine plastics dominated by large long-lived debris. *Nature Geoscience* 16, 689–694.

90 Vogt-Vincent NS, Burt AJ, Kaplan DM, Mitarai S, Turnbull LA, Johnson HL. 2023 Sources of marine debris for Seychelles and other remote islands in the western Indian Ocean. *Marine Pollution Bulletin* 187, 114497. (https://doi.org/10.1016/j.marpolbul.2022.114497)

91 Jambeck JR *et al.* 2015 Plastic waste inputs from land into the ocean. *Science* 347.6223, 768-771.

92 Lebreton LC, Van Der Zwet J, Damsteeg JW, Slat B, Andrady A, Reisser J. 2017 River plastic emissions to the world's oceans. *Nature communications* 8.1, 15611. (https://doi.org/10.1038/ncomms15611)

93 Schmidt C, Krauth T, Wagner S. 2017 Export of plastic debris by rivers into the sea. *Environmental science & technology* 51.21, 12246-12253. (https://doi.org/10.1021/acs.est.7b02368)

94 Lau WW, Shiran Y, Bailey RM, Cook E, Stuchtey MR, Koskella J, Velis CA, Godfrey L, Boucher J, Murphy MB, Thompson RC. 2020 Evaluating scenarios toward zero plastic pollution. *Science* 369, 1455-61. (https://doi.org/10.1126/science.aba9475)

95 Drummond JD, Schneidewind U, Li A, Hoellein TJ, Krause S, Packman AI. 2022. Microplastic accumulation in riverbed sediment via hyporheic exchange from headwaters to mainstems. *Science Advances*. 8(2) (DOI: 10.1126/sciadv.abi9305)

96 Drummond J D, Nel H A, Packman AI, Krause S. 2020. Significance of Hyporheic Exchange for Predicting Microplastic Fate in Rivers. *Environmental Science & Technology Letters.* 7(10), 727-732. (DOI: 10.1021/acs.estlett.0c00595)

97 Hardesty BD *et al.* 2017 Using numerical model simulations to improve the understanding of micro-plastic distribution and pathways in the marine environment. *Frontiers in marine science* 4, 30. (https://doi.org/10.3389/fmars.2017.00030)

98 Vogt-Vincent NS, Burt AJ, Kaplan DM, Mitarai S, Turnbull LA, Johnson HL. 2023 Sources of marine debris for Seychelles and other remote islands in the western Indian Ocean. *Marine Pollution Bulletin* 187, 114497. (https://doi.org/10.1016/j.marpolbul.2022.114497)
See https://youtu.be/ma0wlFfA6dI (accessed 6 March 2024).

99 Martínez-Vicente V *et al.* Measuring marine plastic debris from space: Initial assessment of observation requirements. *Remote Sensing* 11.20, 2443. (https://doi.org/10.3390/rs11202443)

100 Watanabe JI, Shao Y, Miura N. 2019 Underwater and airborne monitoring of marine ecosystems and debris. *Journal of Applied Remote Sensing* 13.4, 044509. (https://doi.org/10.1117/1.JRS.13.044509)

101 Martin C, Zhang Q, Zhai D, Zhang X, Duarte CM. 2021 Enabling a large-scale assessment of litter along Saudi Arabian red sea shores by combining drones and machine learning. *Environmental Pollution* 277, 116730. (https://doi.org/10.1016/j.envpol.2021.116730)

102 Martin C, Zhang Q, Zhai D, Zhang X, Duarte CM. 2021 Enabling a large-scale assessment of litter along Saudi Arabian red sea shores by combining drones and machine learning. *Environmental Pollution* 277, 116730. (https://doi.org/10.1016/j.envpol.2021.116730)

103 Gonçalves G, Andriolo U, Gonçalves LM, Sobral P, Bessa F. 2022. Beach litter survey by drones: Mini-review and discussion of a potential standardization. *Environmental Pollution* 315,120370. (https://doi.org/10.1016/j.envpol.2022.120370)

104 Biermann L, Clewley D, Martinez-Vicente V, Topouzelis K. 2020 Finding plastic patches in coastal waters using optical satellite data. *Scientific reports* 10.1, 5364.

105 Veettil BK, Quan NH, Hauser LT, Van DD, Quang NX. 2022 Coastal and marine plastic litter monitoring using remote sensing: A review. *Estuarine, Coastal and Shelf Science* 279,108160. (https://doi.org/10.1016/j.ecss.2022.108160)

106 de Vries RV, Garaba SP & Royer SJ. 2023. Hyperspectral reflectance of pristine, ocean weathered and biofouled plastics from dry to wet and submerged state. *Earth System Science Data Discussions*, 1-29. (https://doi.org/10.5194/essd-15-5575-2023).

107 Leone G, Catarino AI, De Keukelaere L, Bossaer M, Knaeps E, Everaert G. 2023 Hyperspectral reflectance dataset of pristine, weathered, and biofouled plastics. *Earth Syst. Sci. Data* 15, 745–752. (https://doi.org/10.5194/essd-15-745-2023).

108 Watanabe JI, Shao Y, Miura N. 2019 Underwater and airborne monitoring of marine ecosystems and debris. *Journal of Applied Remote Sensing* 13.4, 044509. (https://doi.org/10.1117/1.JRS.13.044509)

109 Flores NY, Oswald SB, Leuven RS, Collas FP. 2022 Underwater macroplastic detection using imaging sonars. *Frontiers in Environmental Science* 10, 875917. (https://doi.org/10.3389/fenvs.2022.875917)

110 https://www.mcsuk.org/what-you-can-do/join-a-beach-clean/great-british-beach-clean/ - accessed on 8 November 2023

111 https://www.birmingham.ac.uk/research/water-sciences/projects/plastic-rivers.aspx - accessed on 15 November 2023

112 Nel HA, Sambrook Smith GH, Harmer R, Sykes R, Lynch I, Krause S. 2020. Citizen science reveals microplastic hotspots within tidal estuaries and the remote Scilly Islands, United Kingdom. *Marine Pollution Bulletin*. 161(Part B). 111776. (doi:10.1016/j.marpolbul.2020.111776)

113 Bangor University. Uk's Biggest Microplastic Citizen Science Project at Bangor University. See https://www.bangor.ac.uk/news/2021-03-04-uks-biggest-microplastic-citizen-science-project-at-bangor-university (accessed 1 November 2023).

114 Hardesty BD *et al.* 2017 Using numerical model simulations to improve the understanding of micro-plastic distribution and pathways in the marine environment. *Frontiers in marine science* 4, 30. (https://doi.org/10.3389/fmars.2017.00030)

115 OSPAR Commission. Marine Litter. See https://www.ospar.org/work-areas/eiha/marine-litter (accessed 1 November 2023).

116 CISRO. Marine pollution: sources, distribution and fate. See https://www.csiro.au/en/research/natural-environment/oceans/marine-debris (accessed 1 November 2023).

117 NOAA. Marine Debris Program. See https://marinedebris.noaa.gov/ (accessed 1 November 2023).

118 Van Sebille E *et al.* 2015 A global inventory of small floating plastic debris. *Environmental Research Letters* 10.12, 124006. (https://doi.org/10.1088/1748-9326/10/12/124006)

119 Barnes DK, Galgani F, Thompson RC, and Barlaz M. 2009. Accumulation and fragmentation of plastic debris in global environments. *Philos. Trans. R. Soc. Lond. B. Biol. Sci.* 364, 1985–1998. doi: 10.1098/rstb.2008.0205

120 Høiberg MA, Woods JS, Verones F. 2022 Global distribution of potential impact hotspots for marine plastic debris entanglement. *Ecological Indicators* 135,108509. (https://doi.org/10.1016/j.ecolind.2021.108509)

121 Everaert G, Van Cauwenberghe L, De Rijcke M, Koelmans AA, Mees J, Vandegehuchte M, Janssen CR. 2018 Risk assessment of microplastics in the ocean: Modelling approach and first conclusions. *Environmental pollution* 242, 1930-1938. (https://doi.org/10.1016/j.envpol.2018.07.069)

122 Breaking the Plastic Wave: A Comprehensive Assessment of Pathways Towards Stopping Ocean Plastic Pollution. The Pew Charitable Trusts and SYSTEMIQ. 2020. See https://www.pewtrusts.org/en/research-and-analysis/articles/2020/07/23/breaking-the-plastic-wave-top-findings (accessed on 20 March 2024).

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