REPORT

Feasibility of the PGS Plastic Collection Concept

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Feasibility of the PGS Plastic Collection Concept

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Sammendrag / Summary

Petroleum Geo-Services ASA (PGS) has developed a plastic collection concept to mobilise the available fleet capacity to combat the problem of marine plastic pollution. This desktop review evaluates the potential and feasibility of PGS' proposed novel concept for collecting pelagic plastic waste in the North Atlantic. The review found that knowledge on the spatial and temporal distribution of macroplastics in the surface ocean is scarce, particularly for the North Atlantic. Existing studies suggest that pelagic microplastic densities are too low for surface plastic collection to be efficient, but densities may be higher in certain areas and/ or seasons, or during flush-out events. Floating plastic densities are likely to be higher close to the coast, particularly in rivers and river mouths, but this is also where impact on marine life of the clean-up technology may be the greatest. Organisms may be affected directly through physical interaction with the clean-up technology, or indirectly for example if floating habitats are removed with the plastics.

To evaluate the efficiency of the plastic collection concept, there is a need for field data on the spatial and temporal distribution of macro-plastic. The type of plastics should also to be recorded as it can identify the sources of the litter and the potential for recycling of recovered litter. Knowledge on the spatial and temporal distribution of marine life is also needed in order to reduce undesirable interactions. It is recommended that these knowledge gaps are filled before investing in further development of technology to collect plastic litter at sea as this knowledge is fundamental to how and where to implement clean-up technologies.

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PREFACE

This report was produced on behalf of PGS by SALT. The aim of the report was to evaluate the potential and feasibility of a pelagic marine plastic collection concept developed by PGS.

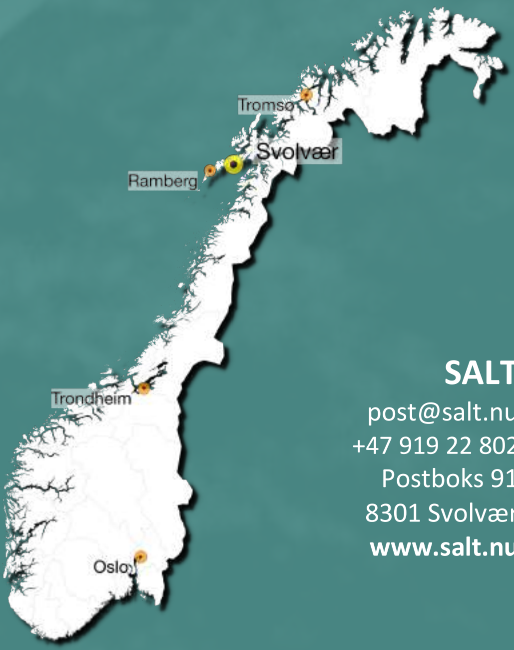
SALT is very grateful for the opportunity to research and write this report. A special thanks is also extended to Dr. Marcus Eriksen at the 5 Gyres Institute for invaluable feedback on a draft of the report.

Tromsø, 27.08.18

Jannike Falk-Andersson

Prosjektleder, SALT

Main chapters



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Summary and recommendations

PGS has developed a concept for collection of plastic waste at and near the sea surface by combining a bubble curtain with a boom arrangement and collection unit. This desktop study assesses key aspects of implementing such a technology in the North Atlantic. This includes an evaluation of knowledge on the spatial and temporal distribution of plastic in the ocean to determine the availability of plastic in the ocean for the clean-up technology, the feasibility of the bubble plume lifting marine plastic debris to the surface, the likely collection efficiency of the technology and the potential negative impacts of the cleaning technology on marine life. Legal considerations and the opportunities for marine plastics to enter a circular economy through recycling are also discussed.

A review of synthesis and modelling studies identified the Gulf of Mexico and the Caribbean Sea as areas where plastic could be available seasonally in high densities due to likely high flows of input from runoff and rivers during wet seasons. Other potential river hotspots were off the Amazon basin outlet in Brazil, in Guatemala/Honduras, as well as Costa Rica and off the coast of Nigeria. Clean-ups are likely to be the most efficient in rivers and possibly in- or close to river mouths. A lack of field studies on the spatial and temporal distribution of pelagic plastic waste makes it impossible to determine the availability of plastics in the ocean and thereby the efficiency of the proposed clean-up technology. Larger plastic particles are likely to be the target of the technology, and while there are no field studies on the horizontal distribution of macroplastics, it is likely that majority of the larger plastic fragments will be found at or near the sea surface. The few studies documenting pelagic macroplastics in the North Atlantic, suggests that collection efficiency will be low.

While it is more likely that high concentrations of larger plastic particles will be found close to the coast, this is also where the potential negative impact on marine organisms of the clean-up technology is likely to be high. Furthermore, since the operations will be within national economic zones, permissions from local authorities to operate will be needed.

Studies on the spatial and temporal distribution of floating marine plastics in the identified focus areas, as well as retention time, should be conducted to evaluate the potential availability of plastic litter. The amount and type of plastics available need to be established to investigate recycling opportunities. While air bubbles have been developed in zooplankton and pelagic fisheries, there are no studies on the use of this technology to lift plastic items. Laboratory and field studies on the ability of the bubble curtain to lift relevant macroplastic items to the surface should also be conducted.

Ecological impacts were evaluated using the Gulf of Mexico as a case study. The clean-up technology may have a negative impact on marine life and floating habitat through capture or encounter with marine life. Of particular concern are commercial and vulnerable species, that may be affected at different life stages, as well as Saragassum mats (floating brown macroalgae) that are considered essential fish habitat. The impact of the air curtain on plankton should be evaluated and bycatch of all species, including organic debris, should be monitored. It may be possible to limit negative environmental impacts by accounting for seasonal variations and dial migrations of marine organisms in the area, as well as scouting for biological activity at the surface.

Data on marine litter in general, and surface macro litter specifically, is scarce. Vessels can contribute to filling these knowledge gaps by monitoring marine litter during operations.

Key recommendations for pilot studies

All information collected should be open-access as this is a field with large knowledge gaps and it is only through sharing knowledge a better understanding of the state of marine plastic pollution, its impacts and solutions can be achieved.

Filling the knowledge gaps on the spatial and temporal distribution of ocean plastics, as well as marine life the clean-up technology may interact with, is vital to evaluating the efficiency of collecting pelagic ocean plastics and prevent negative impacts on the ecosystem through undesirable interactions. It is recommended that these knowledge gaps are filled before investing in further development of technology to collect plastic litter at sea as this knowledge is fundamental to how and where to implement clean-up technologies.

The following section lists the type of studies that should be conducted to evaluate the feasibility of implementing the clean-up technology proposed by PGS.

Lab experiments and small-scale experiments

Before initiating a pilot testing, some laboratory experiments, or possibly highly controlled field testing, are recommended to improve the understanding of the behaviour of plastics encountering the air curtain.

1. While there are some differences between stationary bubble plumes in current and towed plumes in quiescent water, a flow chamber to simulate tow is still likely the best place to start as this allows trials to run continuously for some time. Following this, further targeted trials can be conducted where the plume is towed across long tanks in short bursts.
2. Trials needs done with plastic items of different types and sizes to determine how size and buoyancy influences entrainment and thus the effectiveness of the air curtain in lifting plastics.
3. Trials also needs done to determine how long raised items remain at the surface. This is critical to determining the maximum distance behind the air curtain the collection boom can be towed.
4. Conduct trials with the collection boom to determine the angle of the skirts at different tow/current speeds.

During pilot testing, but before embarking on the sailing route (i.e., when considerable modifications to the setup are still readily feasible), we recommend conducting small-scale tests near port to improve understanding of the physical characteristics of the air curtain.

1. Tow the air curtain (without the collection booms) for a short distance at the target tow speed and film, using both underwater and aerial drones, to determine (1) the continuity of the air curtain, (2) the vertical angle of the plume, (3) the horizontal shape of the air curtain while towed, and (4) the distance behind the air hose which the plume surfaces.
2. Repeat the above trial, this time to measure upwelling flow generated by the air curtain. Use dye as in Grimaldo et al. (2011).
3. Trials should also be done to test the practical aspects of sampling and monitoring during operations. For example, sampling nets could be suspended from the vessel both in front of and behind the clean-up device as illustrated in Fig. 1. Vertical sampling nets in advance of the air curtain, regularly spaced between the air curtain and the collection boom, and behind the boom would allow field testing of: (1) the effectiveness of the air curtain in concentrating particles (and potential bycatch) at the surface, (2) the location of plastics and organisms concentrated in front of- or behind where the air curtain surfaces, (3) the duration for which plastics and organisms remain concentrated at the surface, and (4) the fate of plastics and organisms after hitting the collection booms. If successfully arranged, such a setup could be used at intervals or throughout operations during the pilot study sailing route.
4. Trials should be done to determine the rapidity by which the booms and collection net can be reliably reeled in or otherwise disabled; same for the air supply hoses and bubble curtain. This knowledge is critical to being able to minimise catastrophic bycatch if e.g., essential habitat such as Sargassum mats or aggregations of whales are encountered as it indicates the distance ahead of the vessel which must be monitored for these.

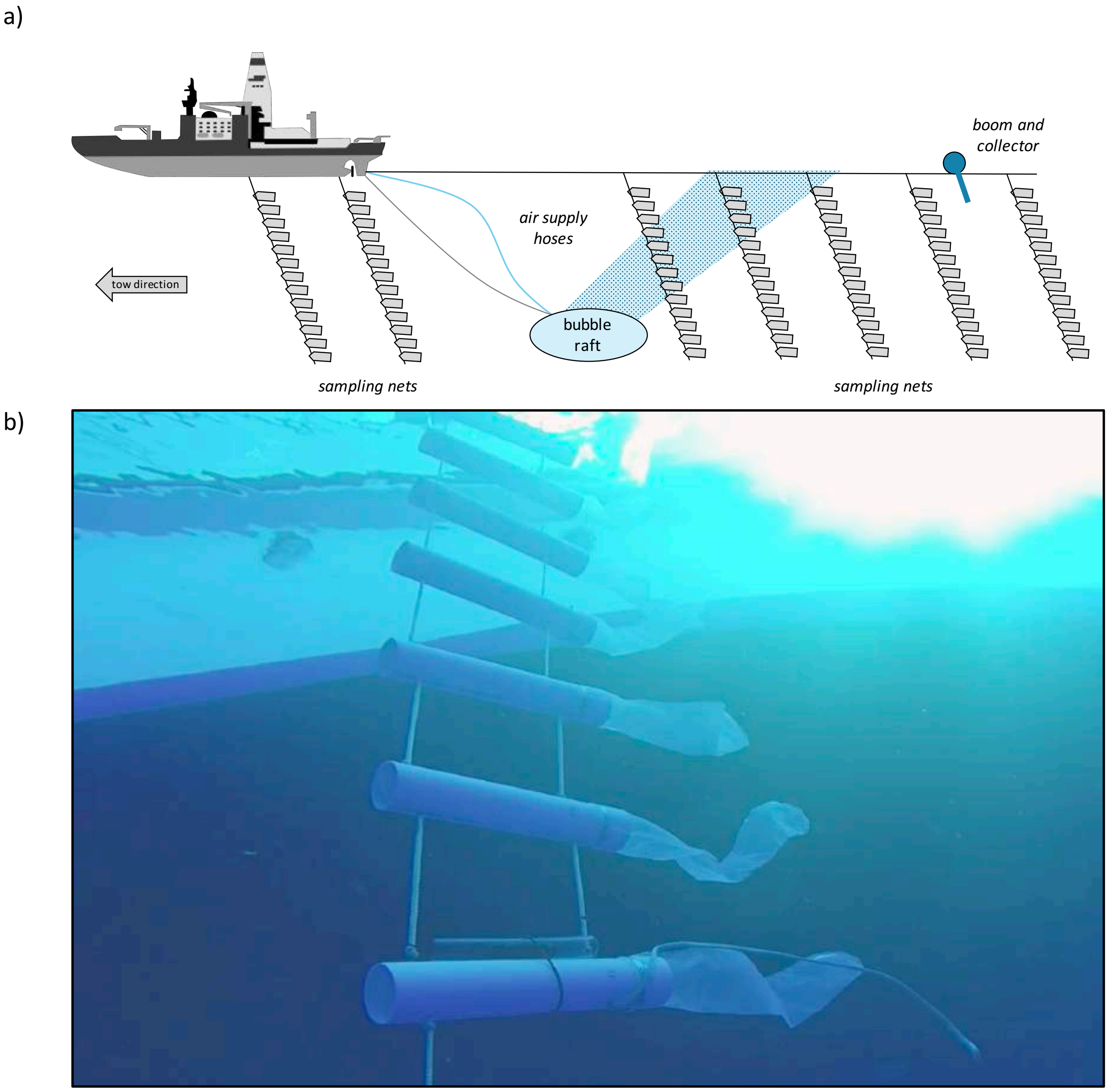


Figure 1. (a) Conceptual drawing of sampling design to monitor the behaviour and fate of plastics and small organisms encountered (redrawn from Grimaldo et al. (2011)). (b) Illustration of vertical sampling nets (picture by Marcus Eriksen, 5 gyres institute, pers. com.). Note that this set-up will only capture smaller organisms and smaller plastic pieces.

Field experiments along the sailing route

Apart from using visual surveys, field experiments will require permission from the respective countries where the studies will take place.

During the pilot study itself, sampling to monitor bycatch and testing of best practices to avoid it must be conducted.

1. Regular analyses of organic content in the collection net must be conducted to identify both quantity and taxa of bycatch. Note that this will require a small laboratory or work space on board with microscopes, as well as staff with the ability to key organisms.
2. Regular analyses of the contents of vertical samplings nets in different positions.

3. Regular monitoring with cameras to observe behaviour and fate of organisms (and plastics) encountered.
4. Skills training and development of best practises with bridge staff to identify "hazards" (e.g., Sargassum mats, aggregations of whales or other large animals).
5. Based on all of the above, guidelines should be developed for when operations should be paused. These guidelines should be developed by a marine biologist.

The efficiency of the clean-up technology and the possibility to recycle the litter depends on the amount and type of plastic litter available for clean-up. Since the clean-up technology is targeting meso- and macro-plastic, the pilot study should focus on quantifying these size categories.

1. Sampling should be done in a gradient from rivers to river outlets, to coastal and offshore locations.
2. Visual surveys can be used to identify and quantify surface plastics. Methods for ship-based observation of floating litter are described in Appendix 1.
3. Net sampling without using the bubble plume is needed in order to estimate how much plastic is floating in the surface ocean and therefore potentially available for the clean-up technology. The mesh size of the net should be the same as the one PGS will use in the collector unit of the clean-up technology. To capture mesoplastic particles the mesh size should not exceed about 5 mm.
4. Knowledge of the vertical distribution of litter is important to determine how deep the bubble curtain should be deployed and the degree to which collection below surface will generate more litter. The depth of the sampling should be determined based on the technical feasibility of how deep the bubble curtain of the clean-up technology can be deployed. Multi-level net tows, such as those conducted by Reisser et al (2015), should be used to determine the vertical distribution of the litter. However, the bubble plume should not be used during these tests as this could affect the vertical distribution of items in the water column. If a sampling technology such as that illustrated in Figure 1 is developed, then the sampling nets in front of the clean-up technology could capture the sample needed for analysis. Note that a net at the surface is also needed to cover the surface water items.

To provide information relevant for up-stream solutions to prevent plastic pollution, the recovered litter should be source identified. Furthermore, knowledge of the weight and quality of the plastics will give information on the amount of plastic available for clean-ups and the possibility for recycling of the plastics.

1. For each plastic item recovered the source, weight, type of plastic, degree of degradation and cleanliness should be recorded. The OSPAR monitoring protocol (OSPAR 2010), which focuses on the source of plastics, can be extended and modified to document the relevant information. The indices on degree of degradation and cleanliness should be developed in dialogue with relevant companies that recycle marine plastics.

At what time plastic pollution may be in particularly high concentrations and how long time it remains at these concentrations is relevant to determine if clean-ups could be more efficient at specific times of the year and how quickly the clean-up technology has to be deployed to catch the litter before it is flushed out to sea.

1. Year-round monitoring and close monitoring of large plastic pollution events should be conducted. Monitoring during wet-season should be given priority.
2. If a larger plastic pollution event takes place during the pilot survey period, these should be monitored to document the evolution of the event from first detection to it is almost impossible to detect.

Key terminology

Marine litter: *«any persistent, manufactured or processed solid material discarded, disposed of or abandoned in the marine and coastal environment. Marine litter consists of items that have been made or used by people and deliberately discarded into the sea or rivers or on beaches; brought indirectly to the sea with rivers, sewage, storm water or winds; accidentally lost, including material lost at sea in bad weather (fishing gear, cargo); or deliberately left by people on beaches and shores»* (UNEP 2005).

Marine debris: has been used as a synonym to marine litter, but could also include detached natural fragments as well as pieces of litter.

Marine plastic debris/marine plastic litter/marine plastic pollution/marine plastics: refers to the plastic fraction of marine litter.

Waste: *«any substance or object which the holder discards or intends or is required to discard»* (EU 2008).

There are many definitions describing the size fractions of plastic. **Generally, particles < 5 mm are defined as microplastics and macroplastics are > 5 mm**. The definitions used in this report are generally as follows:

- **Nanoplastic**: < 100 µm (Koelmans, Besseling, and Shim 2015)
- **Small microplastics**: 0.33-1.00 mm (Eriksen et al. 2014)
- **Large microplastics**: 1.01-4.75 mm (Eriksen et al. 2014)
- **Mesoplastic**: 4.76-200 mm (Eriksen et al. 2014)
- **Macroplastic**: > 200 mm (Eriksen et al. 2014)

BACKGROUND AND AIM OF THE REVIEW

Petroleum Geo-Services ASA (PGS) has developed a plastic collection concept to mobilise the available fleet capacity to combat the problem of marine plastic pollution. The incident of a stranded beaked whale in Norway in 2017 that died due to consuming plastic bags, as well as other widespread media attention related to the growing plastic pollution problem, has inspired PGS to evaluate how their technology can contribute to being a part of the solution.

PGS has developed a concept for collection of plastic waste at sea by combining an air bubble curtain with a boom arrangement and collection unit. This desktop review will enable PGS to better understand the potential and feasibility of a proposed novel concept for collecting plastic waste at sea. In particular, the review will answer the following questions:

1. Can a bubble plume conceivably lift marine plastic debris to the surface?
2. Assuming that all plastic debris in the upper 40 m of the water column is successfully collected, what is the likely collection efficiency (tons per day and year) and in what areas would the potential be highest (e.g. North-Pacific, Mediterranean etc.)?
3. What are the potential negative impacts of the cleaning technology on marine life, in particular zooplankton?

The focus area is the Atlantic Ocean, north of equator, hereafter referred to as the North Atlantic. Plastic will be the litter type in focus of this study as this is the main contributor to marine debris and because the properties of plastic makes it a material of particular concern.

This report evaluates the impact of the cleaning technology on the marine ecosystem. It does not include a cost-benefit analysis of implementing the technology, neither with respect to operational costs and the economy in recycling of marine plastics, nor environmental impacts beyond the local impact on marine life of implementing the technology.

IDENTIFICATION OF AREAS WHERE IMPLEMENTATION OF THE CLEAN-UP TECHNOLOGY MAY BE THE MOST EFFICIENT

This section discusses the potential efficiency of the concept. The air curtain system of PGS' plastic collection concept is meant to lift plastic from 30-40 meters depth. Efficient collection of marine plastic in the water column is dependent on the concentration of plastic particles within the size range that the technology is able to capture. Previously proposed clean-up technologies are unlikely to be able to collect smaller particles less than 1 cm (Plastic and Ocean Platform 2018; Slat et al. 2014). The PGS technology is also likely to target larger items. It is therefore assumed that the system will be able to collect meso- and macroplastics, which are particles larger than 5 mm. The concentration of plastic particles varies in the water column, as well as between areas and in time, for example due to seasonal fluctuations in rainfall or extreme weather events. There are also legal considerations to be made when considering which areas are suitable for implementing the clean-up technology.

Spatial distribution of marine plastic debris in the ocean

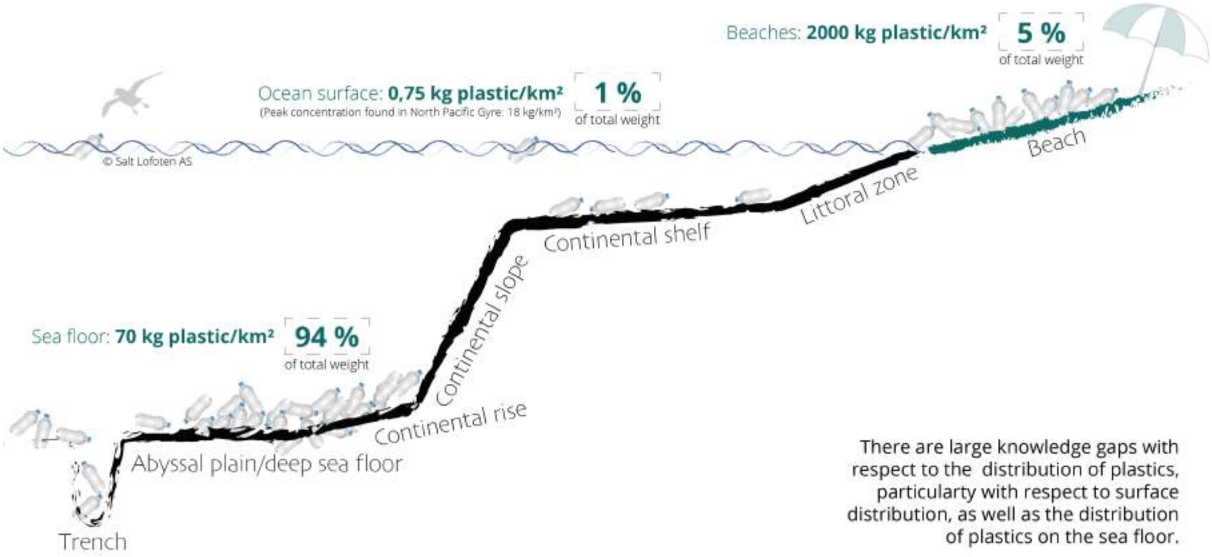
An estimated 5.25 trillion plastic particles weighing 268 940 tons are floating in the world's oceans. About 233 400 tons are larger plastics items and 35 540 tons are microplastic particles (Eriksen et al. 2014). Floating debris is transported by currents and wind at the sea surface, before they either sink to the seafloor, are washed up on the shore or degrade over time (Galgani, Hanke, and Maes 2015). Biofouling and leaching of additives may increase the density of plastics that otherwise would have a lower density than seawater, thereby causing them to sink (op. cit.). Data sets on floating ocean plastics is sparse. The few data sets that exist have therefore been coupled with dispersal models to predict the level of marine plastic pollution globally (Lebreton et al. 2018).

This section will first look at synthesis and modelling studies of marine litter in and into the oceans to identify which areas could be suitable for clean-ups at sea. This will be followed by a review of the data available from field studies, with a focus on the areas identified as having the largest potential for these clean-ups.

Synthesis- and modelling studies of marine litter input to the ocean

The majority of marine plastic pollution is at the sea floor (94%) with an estimated 70 kg of plastics per km^2 on the sea bed (Eunomia 2016). The concentration on the beaches, where 5% of the plastic pollution is found, is estimated to 2 000 kg per km^2. About 1% is floating at or on the surface, with a global average estimate of less than 1 kg per km^2 (Figure 2). The highest concentrations of surface plastics are in mid-ocean locations with the highest recorded concentration being in the North Pacific Gyre at 18 kg per km^2, however, the average concentration of plastic across all oceans is 0.74 kg per km^2 (op. cit). The 1% floating at or on the surface is the target of the proposed cleaning technology.

To evaluate if and how cleaning of surface litter in the oceans can be implemented efficiently we need to know what the distribution of the 1% of the plastic that is floating in the ocean is, and what proportion of this is of a size that will be collected by the clean-up technology. It is also worth noting that the calculations by Eunomia (2016) of the relative distribution of marine plastics is the stock of the plastics, not the flow. Thus, the distribution of the flow of plastics into the ocean, the density of this plastic, as well as the retention time in the water column where it will be available to be collected are important factors to evaluate.

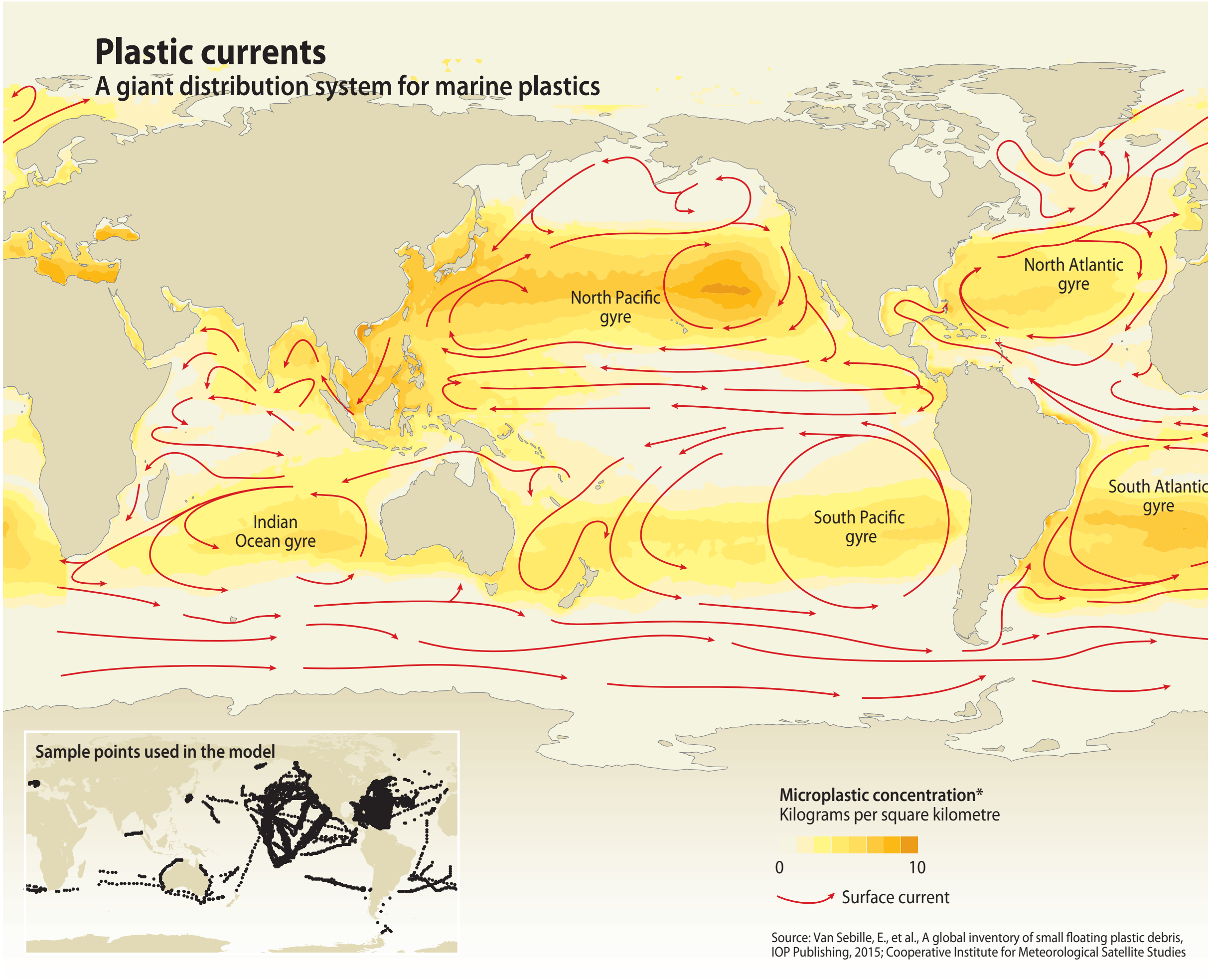


There are large knowledge gaps with respect to the distribution of plastics, particularty with respect to surface distribution, as well as the distribution of plastics on the sea floor.

Figure 2. Plastic pollution in the ocean showing the relative distribution of marine plastic pollution and the average density on beaches, on and at the sea surface and at the sea floor (modified from Eunomia (2016)).

Figure 3 illustrates the five large circular currents that dominate the world oceans, as well as the dispersal of floating plastic debris. The currents around the gyres are mainly driven by wind (David K. A. Barnes et al. 2009; UNEP and GRID-Arendal 2016). At the centre of the gyres, the water sinks to depths of a few hundred meters, but the plastic is too buoyant and is trapped in the converging current (Van Sebille, England and Froyland 2012; UNEP and GRID-Arendal 2016). In these areas, there is a high concentration of plastic particles between 1-5 mm (Plastic and Ocean Platform 2018). The plastic can reach average concentrations of up to 10 kg per km^2 in certain areas, such as off the coast in the East Asian and in the North Pacific gyre. In the North Atlantic gyre, plastic concentrations have been recorded to be up to 8 kg per km^2 (Figure 4) (Cózar et al. 2015).

The Ocean Cleanup project has been criticized for focusing on cleaning the North Pacific gyre, when removal of plastics can be done more efficiently from near the coastline. This because it is not the amount of plastic, but the flux that determines how much plastic can be removed in a given period (Sherman and van Sebille 2016). Furthermore, by focusing clean-up efforts close to the source of the pollution, plastics can be removed before they pass through areas of high ecosystem impact. This would reduce the harm done by the plastics (op. cit.). Information from Jambeck et al. (2015) on the amount of mismanaged waste in a country that can enter the oceans, was used to model where microplastic would be most efficiently collected (Sherman and van Sebille 2016). Coastal areas in East Asia and the Eastern Mediterranean Sea were identified as areas where removal would be the most efficient. They also identified locations in the South Atlantic Gyre, as well as the Black Sea and the Southern Bight.



Source: Van Sebille, E., et al., A global inventory of small floating plastic debris, IOP Publishing, 2015; Cooperative Institute for Meteorological Satellite Studies

Figure 3. Micropastic concentration in the world oceans, illustrating the five garbage patches. (Illustration: UNEP and GRID-Arendal 2016)

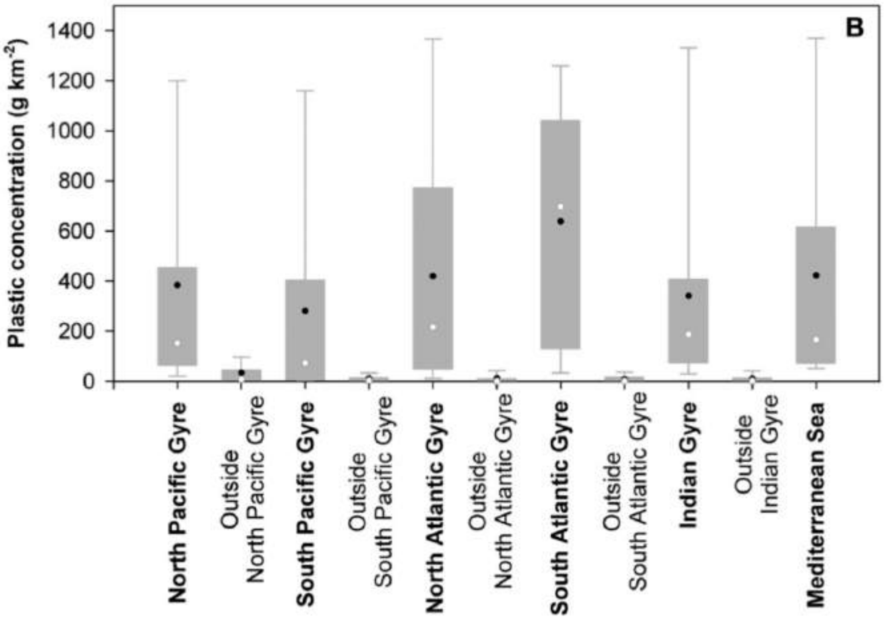


Fig 3. Ranges of surface plastic concentrations measured in the Mediterranean Sea, and reported for the open ocean. A) Frequency distribution of the measurements of plastic concentrations in the Mediterranean Sea (*n* = 72) and in the global ocean (*n* = 1760). Mediterranean measurements (blue line) are from the present study and ref. [20, 21]; ocean measurements (red line), including the five plastic accumulations in the subtropical gyres, were compiled from ref. [1–5, 10, 11]. All these data are mapped in Fig. 2. Size limits of the bins, shown in the horizontal axis, followed a 2.5-log series of plastic concentration (in g km^{2}). B) Surface plastic concentrations measured in the Mediterranean Sea, and reported for the inner accumulation zone of the five subtropical gyres (dark gray areas in Fig. 2) [1–5]. Ranges of concentrations outside the convergence zone of each subtropical gyre (white areas in Fig. 2) are also shown for comparative purposes. The boundaries of the boxes indicate the 25th and 75th percentiles, the whiskers above and below the boxes indicate the 95th and 5th percentiles, and the black and white dots mark mean and median respectively. All data in this analysis include correction by wind effect.

Figure 4. Plastic concentrations measured in open ocean surface waters and the Mediterranean Sea (Adopted from Cozar et al., 2015).

The majority of studies on the distribution of floating plastics have focused on microplastics. Knowledge on the density and location of the larger plastic items is important as these fractions will be more available to the clean-up technology than microplastic. Eriksen et al (2014) looked at the global distribution of different size groups of plastic particles. They estimated that in terms of weight the world's marine floating plastic pollution comprises 75% macroplastic (>200 mm), 11% mesoplastic (4.75-200 mm), and 11 and 3% in two microplastic size classes, respectively. In the North Atlantic, high density areas in terms of numbers of microplastics (10 000-100 000 pieces km^{-2}) and mesoplastics (1 000 pieces km^{-2}) are the North Atlantic gyre, the Gulf of Mexico and the Mediterranean Sea. Also in terms of weight, the pattern is similar, with high concentrations in the North Atlantic Gyre and the Mediterranean. While the number of macro- and meso plastic particles are smaller in these areas compared to the smaller fractions, the total weight of the larger particles is much higher. The highest weight density of macroplastics in the North Atlantic is estimated to be in the western part of the North Atlantic Gyre and the Mediterranean south of Italy (Figure 5a and 5b).

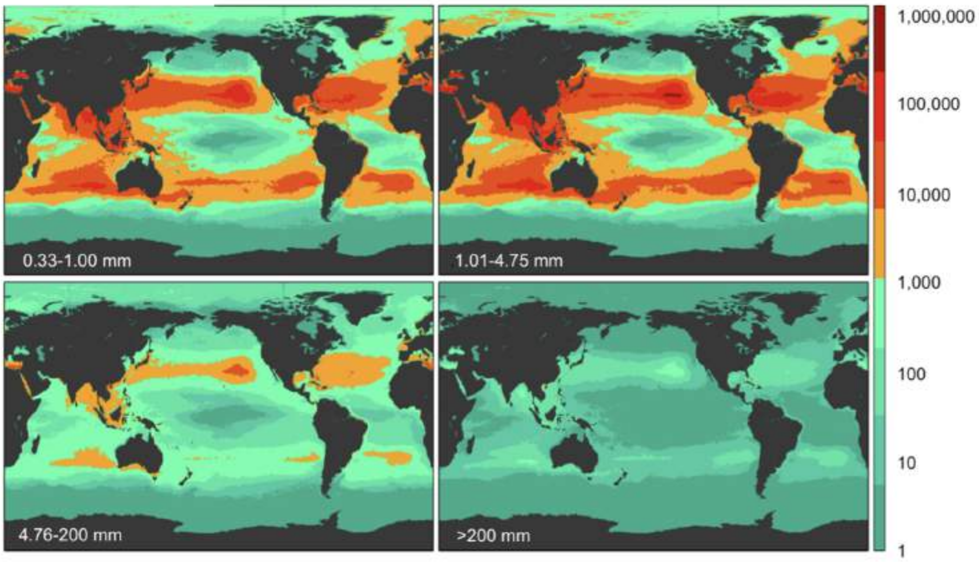


Figure 5a. Model results for global count density in four size classes. Model prediction of global count density (pieces km^{-2}; see colour bar) for small microplastics, large microplastics, mesoplastics and macroplastics. (Adopted from Eriksen et al 2014).

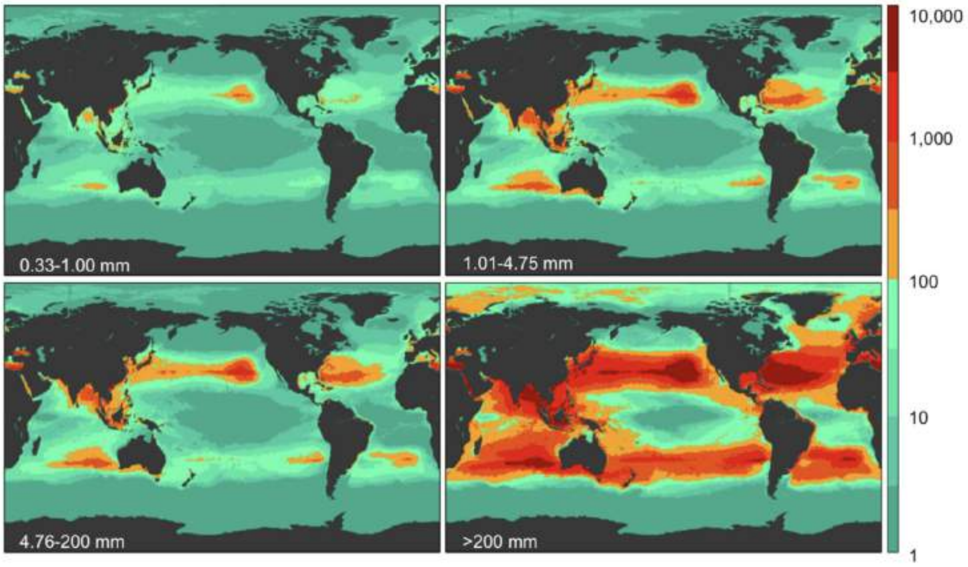


Figure 5b. Model results for global weight density in four size classes. Model prediction of global weight density (g km-2; see colour bar) for small microplastics, large microplastics, mesoplastics and macroplastics. The majority of global weight is from the largest size class. (Adopted from Eriksen et al 2014).

Jambeck et al (2015) estimated the mass of land-based plastic waste entering the ocean using data on solid waste, population density and economic status. Population size and the quality of the waste management systems were assumed to be the most important factors determining the contribution of a country to marine plastic pollution. In the North Atlantic the countries contributing the most to plastic waste were estimated to be North America, Brazil, Nigeria, Senegal, Morocco, Western Sahara and Algeria (Figure 6).

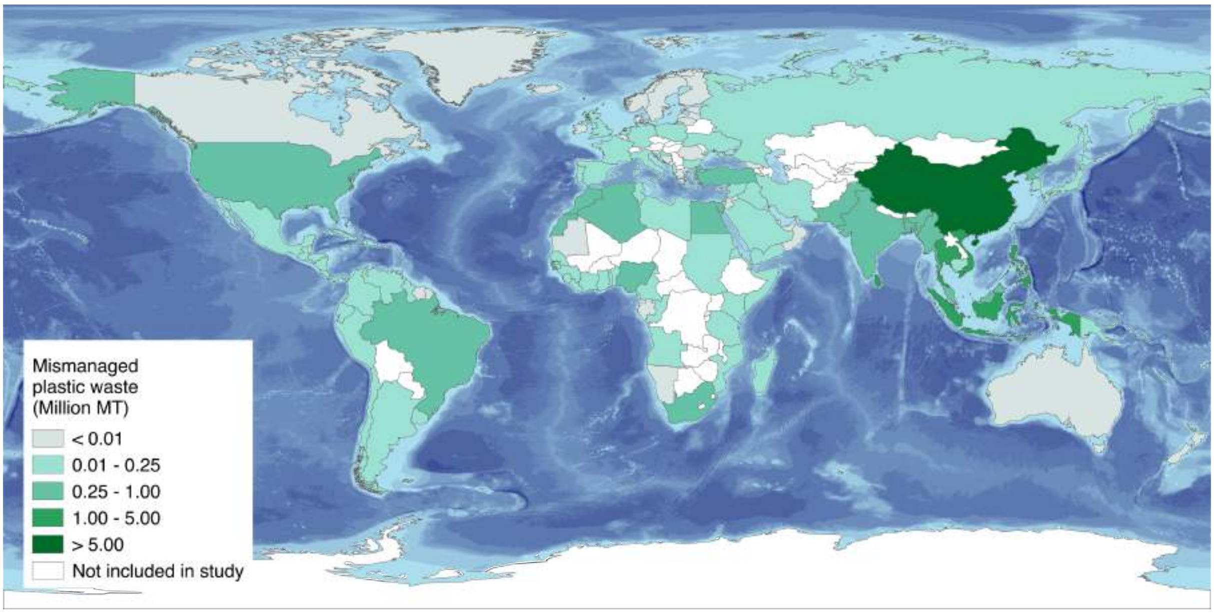
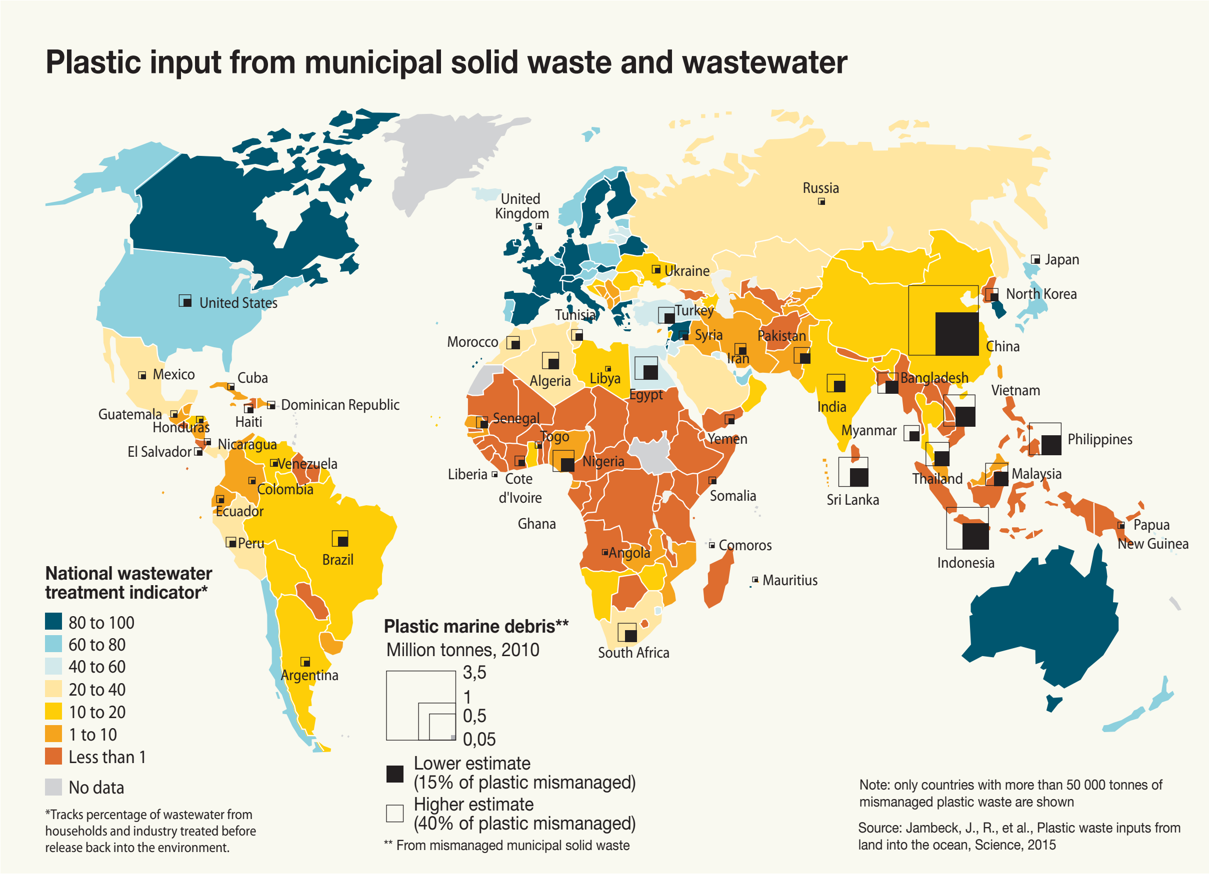


Figure 6. A global map illustrating the estimated mass of mismanaged plastic waste (millions of tons) generated in 2010 by populations living within 50km of the coast (Adapted from Jambeck et al, 2015).

Europe, USA and Canada have high rates of wastewater treatment from households and industry, while in countries further south bordering the Atlantic Ocean, less than 20% of the wastewater is treated (Figure 7a). Still, the expected input of plastic waste into the sea from the USA is relatively high. When looking at the sources of plastic, storm water runoff carrying litter from urbanised areas is believed to be a major source of marine litter in the US, particularly into the Gulf of Mexico as indicated by the blue circle in Figure 7b (impervious surface in watersheds). In Brazil at the outlet of the Amazon river, storm water runoff is also identified as a major source of plastics into the sea. While coastal inputs of plastics in general are lower in the Atlantic Ocean compared to the Pacific and Indian oceans, coastal inputs from Nigeria is high. This is reflected in a high estimated proportion of plastic waste being mismanaged in Nigeria. Also, in Senegal a high proportion of the plastic waste produced is mismanaged (Figure 7c). Shipping is believed to be a major source of marine litter in the North Atlantic, as in other areas of major shipping routes (UNEP and GRID-Arendal 2016) (Figure 7b).

Countries bordering the North Atlantic where poor solid waste management is believed to contribute significantly to marine plastic pollution are Morocco, Senegal, Nigeria and Brazil. Mexico and countries bordering the Caribbean Sea are also believed to contribute to marine plastic pollution through poor municipal solid waste management (Figure 7a).

The proportion of plastic waste that is mismanaged is high in some Island states in the Caribbean such as Cuba, Haiti, the Dominican Republic, Honduras, El Salvador and Nicaragua. Other African countries in the North Atlantic in addition to Senegal and Nigeria also have high rates of mismanagement of plastic waste, such as Morocco and Cote d'Ivoire ria (Figure 7c). While other areas in the North Atlantic have a lower rate of mismanagement, the production of plastic waste is relatively high. This could result in countries such as Brazil representing a relatively high input source of plastic waste, although the proportion of plastic waste mismanaged is lower than in other countries.



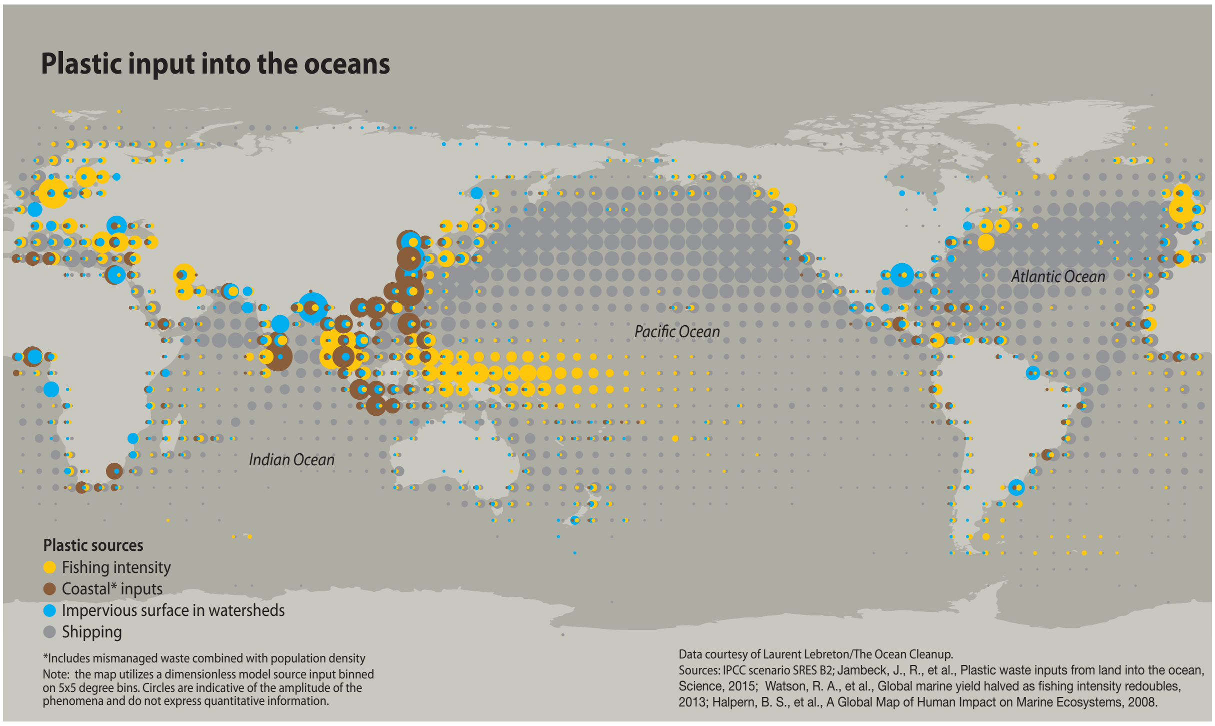
*Tracks percentage of wastewater from households and industry treated before release back into the environment.

** From mismanaged municipal solid waste

Note: only countries with more than 50 000 tonnes of mismanaged plastic waste are shown

Source: Jambeck, J., R., et al., Plastic waste inputs from land into the ocean, Science, 2015

Figure 7a. Illustration of plastic input from municipal solid waste and wastewater (Illustration: UNEP and GRID-Arendal 2016).



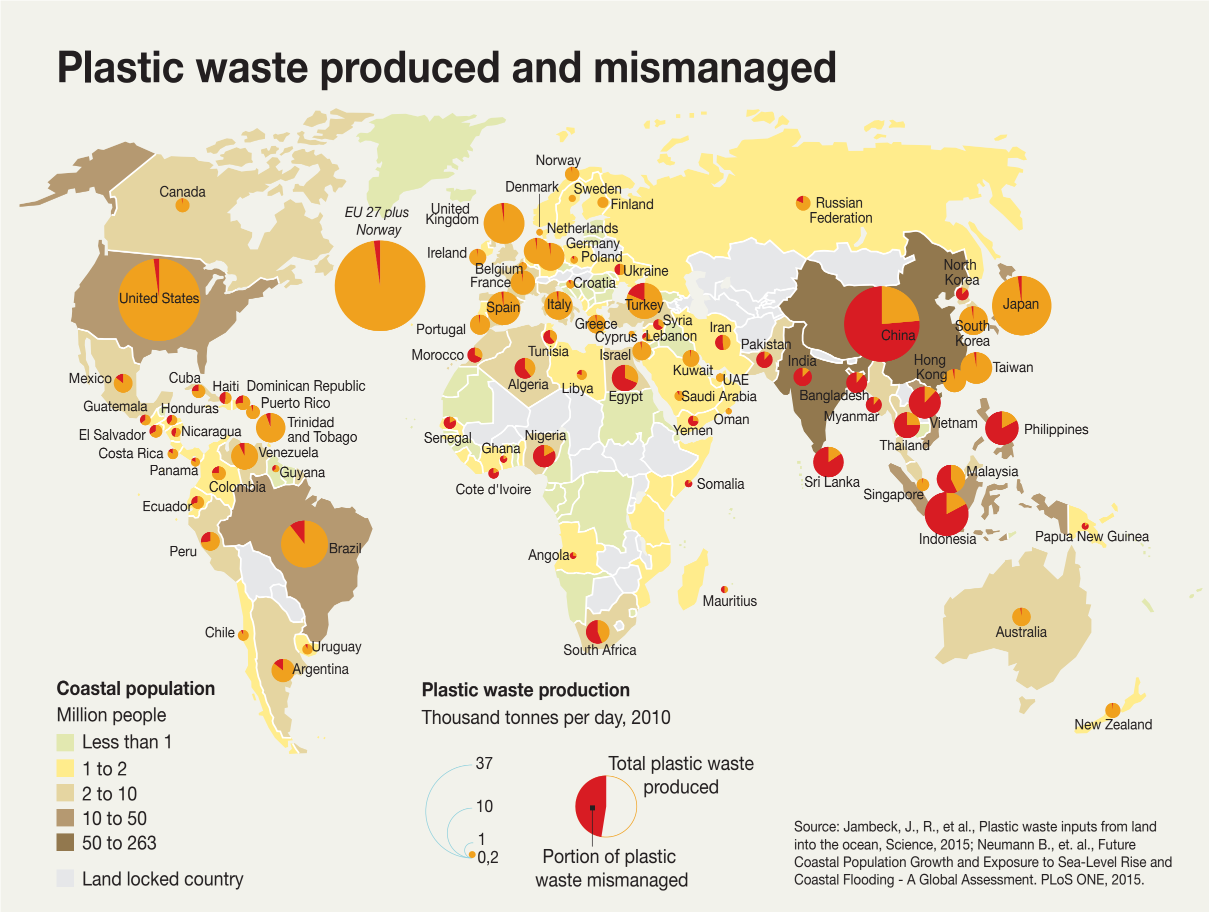
*Includes mismanaged waste combined with population density

Note: the map utilizes a dimensionless model source input binned on 5x5 degree bins. Circles are indicative of the amplitude of the phenomena and do not express quantitative information.

Data courtesy of Laurent Lebreton/The Ocean Cleanup.

Sources: IPCC scenario SRES B2; Jambeck, J., R., et al., Plastic waste inputs from land into the ocean, Science, 2015; Watson, R. A., et al., Global marine yield halved as fishing intensity redoubles, 2013; Halpern, B. S., et al., A Global Map of Human Impact on Marine Ecosystems, 2008.

Figure 7b. Plastic input into the oceans by different type of sources (Illustration: UNEP and GRID-Arendal 2016).



Plastic waste produced and mismanaged

Source: Jambeck, J., R., et al., Plastic waste inputs from land into the ocean, Science, 2015; Neumann B., et. al., Future Coastal Population Growth and Exposure to Sea-Level Rise and Coastal Flooding - A Global Assessment. PLoS ONE, 2015.

Figure 7c. Regional variations in total amount of plastic waste produced compared to the proportion of plastic waste mismanaged (Illustration: UNEP and GRID-Arendal 2016)

Due to the near-neutral buoyancy of a large proportion of the plastics, rivers transport plastics efficiently downstream to the ocean (UNEP and GRID-Arendal 2016; David K. A. Barnes et al. 2009; Kooi et al. 2018). High flow rate and strong bottom currents make large rivers an important source of plastic litter into the sea. In smaller rivers, that have weaker currents, waste is typically found in zones adjacent to or in estuaries and often coincide with fronts (David K. A. Barnes et al. 2009). Lebreton et al (2017) estimated the global contribution that inland populations have on marine plastic pollution through river-systems (Figure 7d). Factors believed to be important determinants for river-based plastic inputs to the oceans that were included in the model was population density, rates of mismanaged plastic waste production, monthly catchment runoff as well as the presence of artificial barriers that would act as particle sinks (Lebreton et al. 2017).

Lebreton et al. (2017) calculated that the annual global input of plastic from rivers into the oceans is between 1.15-2.41 million tonnes and regarded this a conservative estimate. 86% of the riverine input to the oceans originates from Asian rivers, 7,8% from Africa, 4.8% from South America, 0.95% from Central and North America, 0,28% from Europe and 0.02% from the Australia-Pacific region. Among the world's most polluting rivers, some of them empty into the Atlantic. This includes the Cross catchment (Nigeria/ Cameroon, midpoint estimate of 40 300 t plastic yr^{-1}), the Amazon catchment (Brazil, midpoint input estimate of 39 800 t plastic yr^{-1}) and the Imo and Kwa Ibo catchment (Nigeria, estimates of 21 500 and 11 900 t yr^{-1}, respectively). The Magdalena River in Columbia also contributes significantly, with an estimated contribution of 16 700 tonnes per year to the Gulf of Mexico (Lebreton et al. 2017).

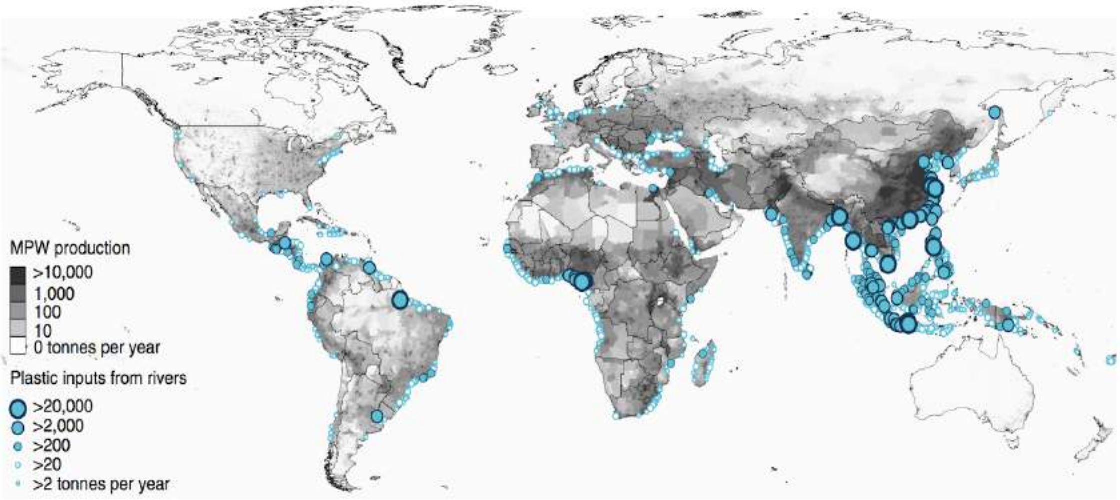


Figure 7d. Mass of Annual River plastic flowing into the oceans in tonnes. River contributions are derived from individual characteristics such as population density (in inhab km^{-2}), mismanaged plastic waste (MPW), production per country (in kg inhab^{-1}d^{-1}) and monthly average runoff (in mm d^{-1}). The model is calibrated against river plastic concentration measurements from Europe, Asia, North and South America. (Adopted from Lebreton et al. 2017)

In addition to the flow of plastics into the oceans, information on seasons of plastic releases could potentially improve the cost-effectiveness of clean-up efforts in the sea surface. On a global scale, Lebreton et al (2017) estimated that 74.5% of the total river plastic input occurs between May and October, with a peak in August and a low in January. The seasonal findings in the global model was driven by the East Asian monsoon affecting inputs from Chinese rivers. Peaks in river plastic inputs were seen for African, North and Central American rivers between June and October, and between November to May for European, South American and Australia-Pacific rivers (Lebreton et al. 2017).

Residence time for different types litter on the sea surface is still poorly known. Macro litter is likely to sink to the sea bottom, be washed ashore or fragment into smaller particles (Arcangeli et al. 2017). Based on a lack of presence of single-use soft plastics, such as plastic bags and styrofoam cups, beyond 500 miles offshore, it is likely that this type of plastics also sink out, gets shredded, UV degraded or are ingested as microplastic shortly after leaving the coast (Marcus Eriksen, 5 gyres institute, pers.com). Thus, litter at the sea surface indicates relatively recent discards of plastics into the marine environment (Arcangeli et al. 2017). Deep submarine extensions of rivers can transport plastics away from the coast and deposit the litter on the seabed in accumulation zones of high sedimentation (David K. A. Barnes et al. 2009). That can explain why continental shelves often have lower concentrations of litter, as the litter has been washed offshore by currents associated with river plumes (op. cit.). High discharge events, for example due to heavy rainfall, can transport debris far offshore from the river mouth. Furthermore, waves, large tides and currents along the coast may efficiently disperse the debris (UNEP and GRID-Arendal 2016). In estuaries, the residence time and transport of plastics is expected to be affected by stratification processes, wind and tidal currents. The latter are typically strongest between high and low tides (Kukulka T. et al. 2012; Sadri and Thompson 2014). Thus, while large rivers are an important source of marine litter, the litter may not necessarily be available for clean-ups close to the coast as the litter may quickly be flushed out to sea. Furthermore, natural materials, such as plants, wood and algae, may also be washed out together with the plastics making separation time consuming. Sampling after an historically high rainfall in Los Angeles, for example, resulted in the net being filled up with large amounts of algae, making separation and quantification of plastic debris difficult (Charles J. Moore, Lattin, and Zellers 2011).

Big storms (hurricanes, flooding), loss of containers or shipwrecking represent events where large amounts of marine debris may enter the ocean within a short time. Cleaning shortly after such events will be more efficient than at a later state when the litter has been carried off-shore and/ or has been spread out, sunk or torn into smaller pieces. The 2011 earthquake that triggered a massive tsunami in Japan, for example, swept an estimated 5 million tons of debris from the land and coastal systems into the ocean. It is believed that 70% of this sank close to the shore, while the rest floated into the North Pacific (Murray et al. 2015; Bagulayan et al. 2012). Modelling and observational studies of the faith of this debris, illustrates how the debris spread over large areas over time, entering ecologically important productive areas (Bagulayan et al. 2012). However, while some of the litter may be available for the proposed clean-up technology, the litter items may be too big for this technology. It may also damage the technology. Debris from the 2011 tsunami event included large items, such as fishing boats and docks (Bagulayan et al. 2012; Murray et al. 2015).

Recommendations of areas for pilot study

Based on the combined insights from the global analysis on plastic input to the North Atlantic, hotspot areas could be the Gulf of Mexico (scores relatively high on plastic waste available to enter the ocean and input from impervious surface in watershed) and the Caribbean Sea (scores high on major river inputs due to input from Columbia and Venezuela). Such enclosed and semi-enclosed seas typically have high densities of plastics, but variability in plastic densities is also high (David K. A. Barnes et al. 2009). Cost-effectiveness of cleaning could be higher in areas with major river inputs during wet season. Other river hotspots in the North Atlantic are found off the Amazon basin outlet in Brazil, in Guatemala/Honduras, as well as Costa-Rica. Nigeria also scores high on mismanaged plastic waste available to enter the ocean and major river inputs (Figure 8), but safety issues makes this a difficult area to operate in.

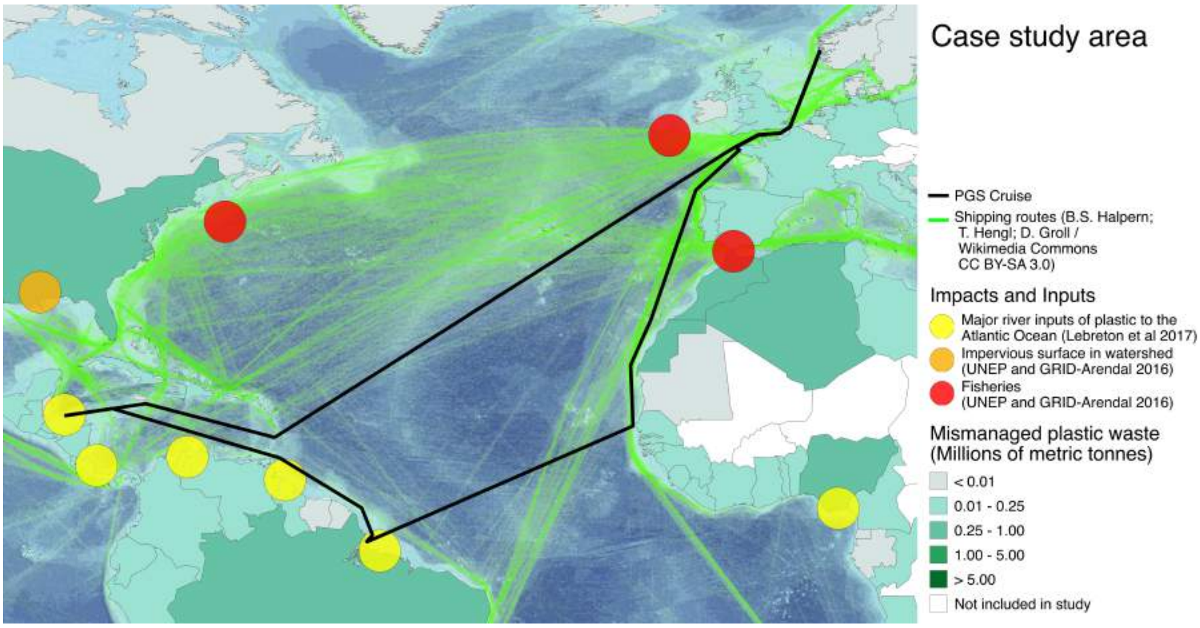


Figure 8. Map of the proposed case study areas illustrating the estimated mass of mismanaged plastic waste the North Atlantic (Adapted from Jambeck et al, 2015) and areas of major inputs according to source. The sailing route proposed by PGS is shown in black line.

The Gulf of Mexico will be used as the main case study[1] to illustrate factors that should be considered when evaluating if and how clean-up technologies could be implemented. After a short description of the main meteorological characteristics of the Gulf of Mexico and the Caribbean Sea, data from sampling of litter in the North Atlantic region will be reviewed, with a focus on the case study areas and meso- and macro- litter.

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[1] The proposed sailing route was provided quite late in the project period. To have the time to review the ecological aspects of the cleaning technology, the Gulf of Mexico was chosen as the main case study area at an earlier stage in the project period. While the ecological characteristics of the two systems may differ, it is believed that the main issues to consider will be accounted for.

OVERVIEW OF THE CARIBBEAN SEA AND THE GULF OF MEXICO

Figure 9 shows maps of the major river and- current systems in the Gulf of Mexico and the north-western part of the Caribbean Sea. The circulation system in the Caribbean Sea is dominated by the South Equatorial Current that flows Across the Atlantic from major upwelling areas off the south-western coast of Africa, and along the north-eastern South America into the Caribbean Sea, exiting into the Gulf of Mexico via the Yucatan Channel (CARSEA 2007). In addition to direct river discharge from surrounding continental rivers, the Sea is strongly affected by the seasonality of the discharge from the Amazon and Orinoco rivers, as well as the Guianas (op. cit.). These river systems, in addition to the Magdalena, bring fresh water and sediments out to the coast and the outflow is carried north- and westwards.

The Gulf of Mexico is a semi-enclosed coastal sea whose ecosystem is heavily influenced by the flow of freshwater from the Mississippi River (NOAA 2018). The Mississippi is the main source of freshwater, sediments and nutrients within the gulf, and is one of the ten largest rivers in the world (Bianchi et al. 2010; Androulidakis, Kourafalou, and Schiller 2015). The Loop Current, flowing northwards into the Gulf of Mexico between Cuba and the Yucatan Peninsula before exiting through the Florida Straits in the east, dominate the surface currents in the gulf in the upper 200 meters of the water column (Love et al. 2013).

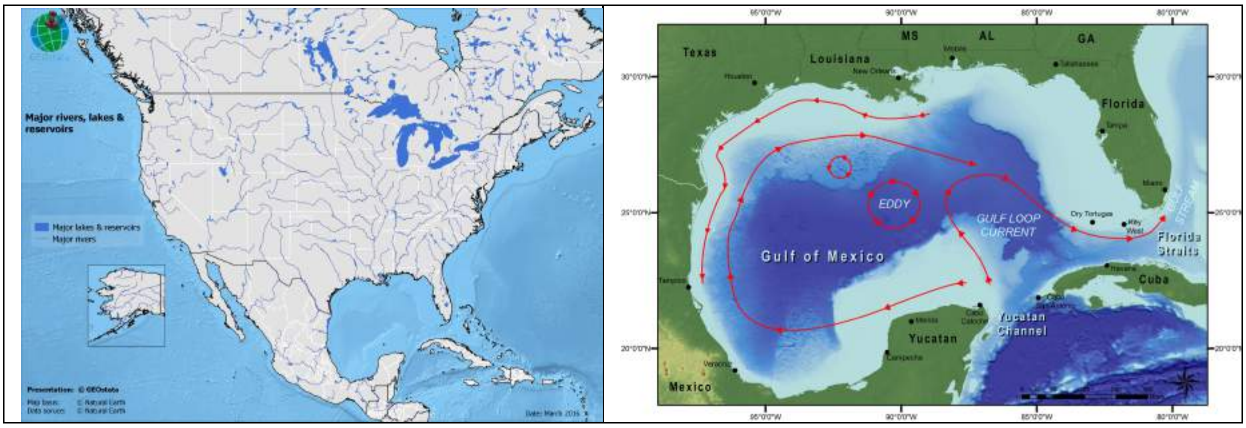

Figure 9. Major rivers in North and Central America (from Geostata.com[2]) and current systems in the Caribbean Sea and Gulf of Mexico (from NOAA[3])

In the summer months, the water column in the Gulf of Mexico is stratified. In the southern gulf, there is a thermocline (boundary between vertically separated warmer and cooler water) at approximately 20 m depth, which recedes to 70 m in winter (Espinosa-Fuentes and Flores-Coto 2004; Espinosa-Fuentes et al. 2009). From spring to fall there is a halocline (boundary between fresh/brackish water and seawater) from 15-30 m depth (Espinosa-Fuentes and Flores-Coto 2004). Stratification is also prominent during the summer in the northern Gulf of Mexico. The considerable freshwater input from the Mississippi watershed results in a distinct halocline sufficient to prevent oxygen exchange between surface and deeper layers, resulting in seasonal hypoxia below the stratification (Bianchi et al. 2010). There is considerably less stratification of the water column during winter months, but high winds may make operations during this time challenging as winds of 50-70

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[2] http://geostata.com/major-rivers-and-lakes-of-the-world/

[3] https://oceanexplorer.noaa.gov/okeanos/explorations/ex1711/logs/dec1/welcome.html

knots are common from November through February; average wind speed for the remainder of the year is 8 knots (M. L. Espinosa-Fuentes and Flores-Coto 2004).

Historical data illustrates that this area is frequently visited by hurricanes (Figure Y). Hurricane season in the Gulf of Mexico and the Caribbean runs from June through November and can bring torrential rains, storms surges and strong winds. The peak hurricane season in the Atlantic Basin is from mid-August to late October (Ocean Conservancy 2013; CARSEA 2007).

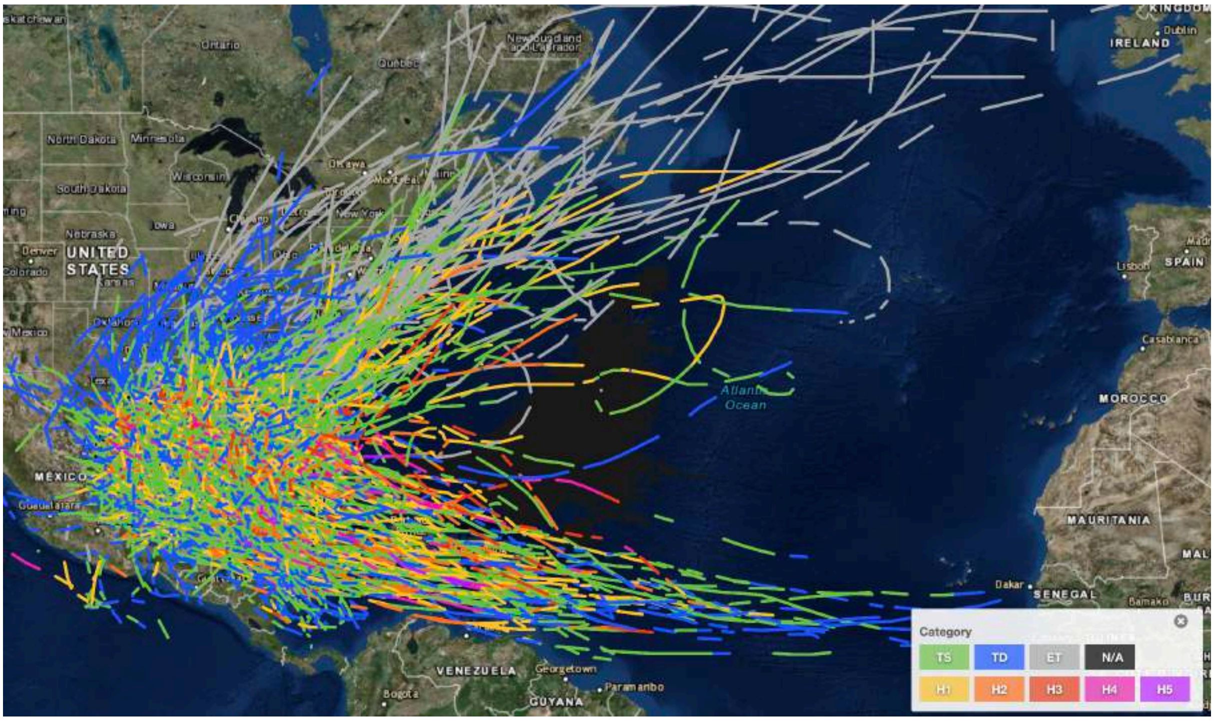

Figure 10. Historical hurricane data showing tropical storm (TS), tropical depression (TD) and hurricanes (H1-5) in the north-western Atlantic. Map made using https://coast.noaa.gov/hurricanes/

SURFACE MARINE LITTER IN THE NORTH ATLANTIC

This section investigates the availability of data on surface litter, with a focus on pelagic macrolitter that is the target of the clean-up technology. Most data on plastic particles on the ocean surface have been collected using trawl nets initially developed for sampling of plankton. As the nets generally have a mesh size of 0.33 or 0.20 mm, they don't collect smaller fragments. Additionally, researchers have focused on microplastics that are between 1-5 mm. Thus, while they may have captured larger fragments, this has often been discarded from the data set (see for example Gago et al. (2015)). Also of relevance to this project is a lack of data on plastic concentration in the water column (Plastic and Ocean Platform 2018; Eriksen et al. 2014; Lebreton et al. 2018).

Availability of data

The most reliable data sets available are those from scientific publications. Litterbase (http://litterbase.awi.de/) is a data base giving an overview of the scientific studies conducted to date in global maps and figures. It also provides links to the original scientific papers. Figure 11 shows that the number of macro-plastic samples taken in surface waters in low in the areas identified as having the largest potential testing out the clean-up technology. The highest resolution of samples is in the Mediterranean Sea.

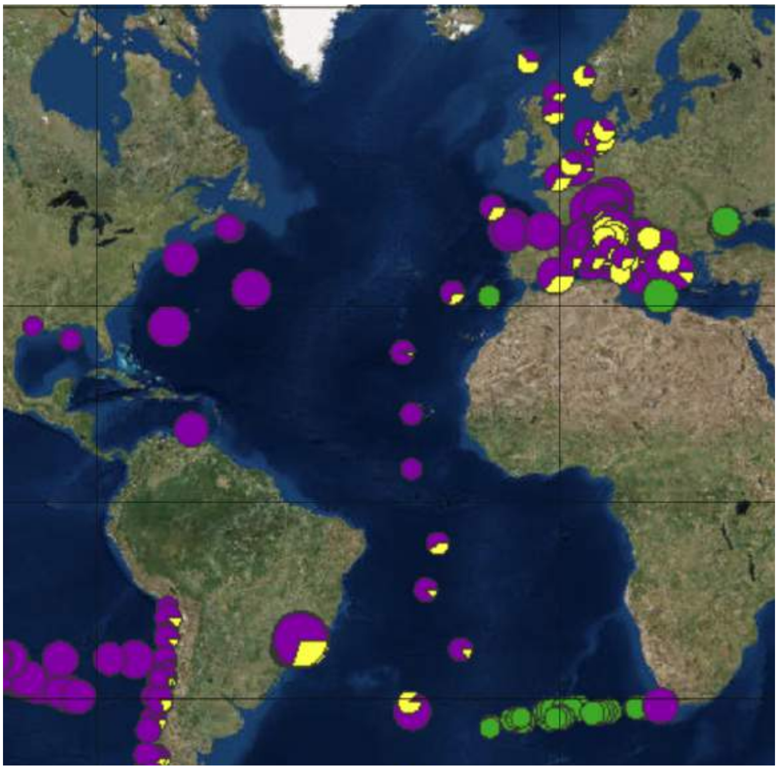

Figure 11: Macro-plastic samples taken in the surface waters (litterbase.awi.de). Above the Arctic Circle, outside the frame of the picture, there is only one station on the west-coast of Svalbard[4]. (Purple: plastic, Yellow: other, Green: N/A).

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[4] Joint Norwegian-Russian ecosystem surveys in the Barents Sea have documented sea surface marine debris in the Barents Sea, but this area is outside the focus area of this report.

There are initiatives to collect information from marine litter clean-ups conducted by volunteers around the world. The image from ArcGIS Clean up our World[5] (Figure 12) gives an overview of the data available in the database for the study area. Data points from Lebreton et al. (2017) were indicated on the map, but since these were based on modelled inputs, they were excluded. Thus, there are no field data available to confirm the modelled river inputs to sea in this area (see Lebreton et al. (2017) for list of observational studies on global river plastic inputs, of which only 2 studies recorded macro litter). Figure 12 illustrates that information from volunteer clean-ups cannot provide sufficient field observations to evaluate the availability of pelagic macrolitter in the case study areas.

If this information were to be used to say something about the relative amount of litter in the region, it is important to keep in mind that the methods used by the different organizations may not be the same. Furthermore, the type of area cleaned are mostly beaches, with only a few reports from under water clean-ups, fresh- and salt water and land. Registration of beach litter is an established indicator of marine litter used in management, and the only indicator saying something about the source of the litter. Thus, such registrations provide important information to implement preventive measures (Busch 2015; Nelms et al. 2016). However, since the main purpose of collecting information on beach litter is source identification, the number of items of different types of litter are typically recorded, while the mass of this litter is not. The data will therefore not say anything about the amount of litter that was recorded.

If data on beach litter was to be used to get an impression of the amount of litter in the surface in pilot case-study regions, the data would have to be standardised and organized according to type of habitat. Data are not easily downloadable from the home pages of the different organisations collecting data, and the data format in the ArcGIS database is not in a format that allows for easy downloading and analysis. To the best of our knowledge little is known about the relationship between beach litter concentrations in an area and the concentrations of plastics in the surrounding sea surfaces.

While there may be some observations of litter along rivers, these are unlikely to be time series showing seasonal variations. If the concentration of litter is only high enough for efficient collection during river flush-out events, the seasonality of these events should be confirmed through observations. It is therefore recommended to do field surveys to evaluate the optimal areas and timing for implementing the clean-up technology.

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[5] http://www.arcgis.com/home/webmap/viewer.html?webmap=fa88085bed764cd68b5da32fac81bd1c&extent=-180,-46.7786,66.0916,70.6813

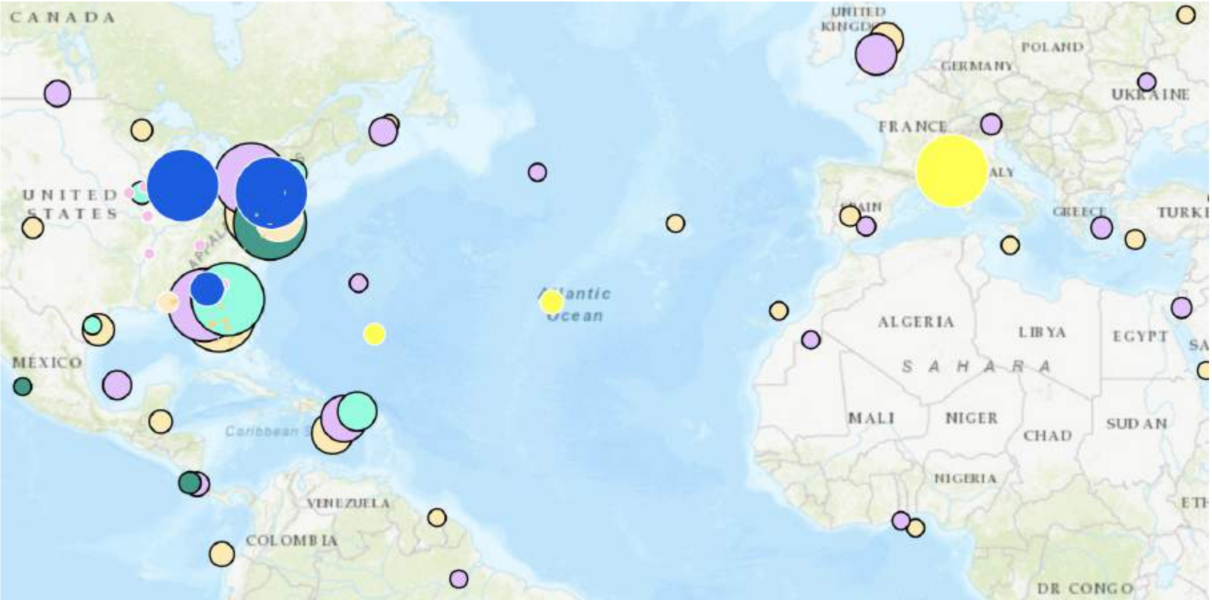

Figure 12. Availability of data from volunteer registrations. NOAA (light orange with line and green circles), Ocean Conservancy[6] (purple circles), data collected by Ocean Conservancy's Clean Swell app[7] (orange dots), 5 Gyres[8] (yellow circles), Marine Debris tracker[9] (light green) and Coastal Clean-up Day (light orange) are both organized by Ocean Conservancy. Organisations with a particular focus on river clean-ups are: the American Rivers Clean-up (blue circles) and Living Lands and Waters[10] (small pink circles with a white line) with data points along the Mississippi river and one in north-east Florida.

Description of existing data on surface marine macro litter

While there are large knowledge gaps with respect to the availability of floating marine litter for clean-up, existing literature gives some useful insights into the challenges of implementing such technology and knowledge gaps needed to be filled to evaluate its feasibility.

Synthesis studies have found that there are large spatial variability in observations of floating marine litter concentrations (Eriksen et al. 2014), which is likely due to differences in source pathways and litter accumulation areas. Due to differences in reporting, data sets are often not comparable. Estimates of the mass of litter typically has to be calculated based on the number of items recorded per surface area. Furthermore, as already concluded for the North Atlantic, the monitoring of floating litter that is being done is scarce (Galgani, Hanke, and Maes 2015).

A recent field study of plastic in the Great Pacific Garbage Patch, estimated that around 79 thousand tonnes of plastics are floating inside an area of 1.6 million km^2 (Lebreton et al. 2018). This is four to sixteen times higher than reported previously. This is explained by more robust methods to quantify larger debris. Most data on buoyant ocean plastics have been collected by small sea surface trawls, which could underestimate the presence of rarer, but larger objects such as bottles, buoys and fishing nets. A study combining net tow data with vessel-based visual surface found that, although dominating in numbers, small particles (<4.75 mm) only represented 13% of the surface plastics (Eriksen et al. 2014)[11]. Lebreton et al (2018) used surface trawl samples, including a mega-trawl, and

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[6] https://oceanconservancy.org/trash-free-seas/international-coastal-cleanup/

[7] https://oceanconservancy.org/trash-free-seas/international-coastal-cleanup/cleanswell/

[8] https://www.5gyres.org/

[9] http://www.marinedebris.engr.uga.edu/

[10] Livinglandsandwaters.org

[11] None of the field locations were in the focus areas of this report.

two aerial surveys collecting aerial imagery to measure the amount of plastic in the Great Pacific Garbage Patch. They found that the plastic mass within this area is dominated by litter items larger than 5 cm, out of which 46% was fishing nets. While microplastics accounted for 94% of the number of pieces, they only made up 8% of the total mass (op. cit.). No such extensive studies of surface plastics have been conducted in the focus areas of this report.

Western North Atlantic and the Caribbean Sea

The primary source of information for this analysis are scientifically published data as these are the most reliable in terms of the method applied and because data is available from the publications. Litterbase was used to identify the number of publications available on macro-plastics in the surface waters of the North Atlantic from 1990-2018. Some of the papers were found to not report on macro litter in surface waters in the North Atlantic and were excluded from the review. Only four scientific publications on surface macroplastic were found for this region (Table 1).

Law et al (2010) analysed plastic content in surface plankton net trawls collected from 1986-2008 in the western North Atlantic and the Caribbean Sea. Their paper does not report on the distribution of the different size particles in the area[12], but analysis of a subset of samples suggested that 88% of the plastic pieces had a dimension less than 10mm. The highest litter density recorded in one tow was 580 000 pieces km^{-2}. They found the lowest concentrations closer to land, such as along the Florida coast and the Florida Keys, in the Gulf of Maine and near the Caribbean islands. The average plastic concentration measured in the Caribbean Sea was 1414 pieces km^{-2} and in the Gulf of Maine 1534 pieces km^{-2}. The highest concentrations were found in the North Atlantic subtropical gyre. Studies using surface drifters and modelling suggest that the plastic may have originated in the subtropical western North Atlantic. Their study also confirmed other plastic concentration studies with respect to high variability in observed plastic concentration between years.

An aerial survey in the Gulf of Mexico in 1997 found that plastic was abundant all seasons, with densities ranging from 0.97 (winter) to 2.4 (summer) pieces km^{-2} (Lecke-Mitchell and Mullin 1997). Between 0-10 debris items per km^2 was found when doing ship-based surveys of floating debris in the Atlantic in 2001 and 2002. Plastic, kelp and wood made up the majority of the items, with plastic being the most abundant. There was a decrease in items found from the tropics to poles, with the highest densities in equatorial waters of 3 items per km^2 (Barnes and Milner 2005). Their study did not sufficiently sample the west-Atlantic and the tropics.

One study sampled litter on the surface of a touristic beach, Cartagena de Indias, in Colombia using nets deployed from the beach. The highest average density of floating solid waste recorded in these near-beach samplings was around 3 g/m^3. The other samples had a density of around 1 g/m^3. The average density of solid waste increased after rainfall and rough seas. The latter could have transported plastics from shallow waters disposal sites towards the beach (Diaz-Mendoza et al. 2014). The study does not report the time of year of these events.

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[12] When looking into the original data file available through www.marine-geo.org, only the number of pieces per km^2 was available.

Table 1. Summary of surface water macroplastic studies in the western North Atlantic and the Caribbean Sea.

Publication	Area	Method	Finding
Law et al. 2010	Western North Atlantic Ocean and Caribbean Sea	Surface plankton net	On average 1414-1534 pieces km^{-2}, mostly micro plastics.
Lecke-Mitchell and Mullin 1997	Gulf of Mexico	Aerial survey	Average 1 piece km^{-2}
Barnes and Milner 2005	Transect from UK to Antarctica along the south-eastern coast of South America	Ship observation	Average 3 items per km^2 in equatorial waters
Diaz-Mendoza et al 2014	Cartagena de Indias, Colombia	Specially designed nets deployed from the beach	Average 1- 3 g/m^3 depending on season

A video from November 2017[13] documents huge areas of plastic litter floating off the Honduran island of Roatan in the Caribbean. An area 2-5 miles wide had trash lines that were up to 30 meter wide. The images show that the debris consists both of plastics and organic debris, including large logs and seaweed. This suggests that the litter reached the sea due to a flooding event. A news story from United News International[14] proposed that the litter may have originated in the Motagua river in Guatemala. No documentation could be found on how frequent such plastic pollution events are.

Other sampling in the North Atlantic along the sailing route

Gago et al (2015) sampled plastic particles off the north-western coast of Spain. The average concentration of microplastic particles was 0.176 pieces m^{-2} in the last year of the study, with a mean weight of 0.0192 mg m^{-2}. However, while both macro and micro-plastic pollution was recorded, only concentrations of plastic pieces up to 20 mm in size were reported in their paper. Larger items, such as bottles and bags, were discarded (Gago, Henry, and Galgani 2015). The highest mesoplastic concentrations (pieces between 5 and 20 mm) were recorded to 0.007 particles per m^2 (op. cit.). Sá et al (2016) recorded floating marine debris in offshore continental Portuguese waters and recorded an average of 2.98 items km^{-2}. The majority of the items were plastics.

In the North Sea, there are few studies on surface macro-plastic distribution. Barnes and Milner (2005), recorded 0.63-0.68 items m^{-1} at one station in the English Channel. In a review by Galgani et al (2015), the reported average number of debris items > 2 cm recorded using ship-based visual surveys were 32 km^{-2} in the German Bight, 25 m^{-2} at the White Bank, 28 m^{-2} around the Helgoland islands and 39 m^{-2} items in the East Frisian part of the German Bight. Over 70% of the items were plastics. Offshore regions had higher concentrations of debris than coastal waters.

Existing data on plastics from rivers

There are few freshwater studies on plastic contamination and existing studies differ in the methodology used. As for marine surveys, there are large variations in plastic concentrations

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[13] https://cv-insight.com/en/facebook/video_ranking/30660366

[14] https://www.youtube.com/watch?v=YJqLxBI9CRM

reported for rivers and most studies have focused on microplastics (Wagner et al. 2014; Kooi et al. 2018; Lebreton et al. 2017). Large seasonal variations in the amount of plastics in rivers has been documented through field studies. This has been attributed to weather events impacting runoff (thus dry and wet weather) (Charles J. Moore, Lattin, and Zellers 2011; Diaz-Mendoza et al. 2014; Yonkos et al. 2014; Rech et al. 2015). Rech et al. (2015) demonstrated large variations in litter in Chilean river surface waters also within season, with no litter registered only one week after litter had been recorded. Correlation between microplastic concentrations and population densities as well as urban development (Yonkos et al. 2014), and between micro-plastic concentration and litter deposition on the riversides (Rech et al. 2015) have also been documented.

The river where surface sampling has showed the highest microplastic concentrations in the world, is the Chinese Yangtze River mouth with 4137 particles m^{-3} (Zhao et al. 2014). European studies have estimated the importance of rivers in transporting plastics to the Black Sea, the North Sea and the Mediterranean Sea. The Rhine was estimated to transport between 20-30 tonnes of plastic litter into the North Sea annually (van der Wal et al. 2015). The review by Lebreton et al (2017) did not identify any other field measurements of plastic in rivers within the focus areas of this report.

Distribution of plastic in the water column

The proposed cleaning technology will use air bubbles to lift plastic particles to the surface. The vertical distribution of the plastic in the upper part of the water column is therefore important to determine how deep the technology has to operate to capture the majority of the macroplastics in the surface waters. Plastics collected using surface nets are mostly fragments of polyethylene and polypropylene, that originates from packaging and fishing gear. About 62% of all plastic produced annually are made of these substances. They are also less dense than seawater and are therefore more likely to float, until they are washed ashore or sink due to biofouling and leaching of additives (Galgani, Hanke, and Maes 2015; Reisser et al. 2015).

Stratification and mixing processes between fresh- and salt water, as well as in the upper ocean layer, affect both the horizontal and vertical positions of buoyant items (Kukulka T. et al. 2012; Sadri and Thompson 2014; Isobe et al. 2014). Millimeter-sized fragments of plastics of low- and high-density polyethylene, polypropylene and foam polystyrene are abundant in the surface open ocean. These particles are less dense than surface seawater and will therefore be subject to mixing in the ocean surface boundary layer. Surface and subsurface net tows at 5, 10 and 20 meters, combined with modelling of these particles, predicted that the decrease in plastic concentration will be the largest over the first metres of the water column (Kukulka et al. 2012).

A 5-meter depth profile study as part of the Ocean Cleanup project measured the vertical distribution of buoyant plastic pieces 0.5-207mm in length in the North Atlantic Gyre. The study confirmed that plastic concentrations drop exponentially with water depth (Reisser et al. 2015). Median values were 1.69 pieces m^{-3} and 1.60 mg m^{-3} at the surface. Both numbers- and mass of plastic pieces at the surface decreased with increasing Beufort number (wind speed). Smaller plastic pieces were more susceptible to vertical transport due to their lower rise velocities. This resulted in median mass being relatively lower at deeper depths, compared to the number of plastic items. For example, median mass was 13.3 times lower at 0.5-1 m compared to at 0-0.5 m, while it was only 6.5 times lower in terms of number of plastic particles. While the model by Kukulka et al (2012) predicts that all plastics would be at the surface at the calmest sea state condition, Reisser et al. (2015) observed some particles submerged below 0.5m of the water surface. The Ocean Cleanup project has been criticised for their pilot study not measuring plastic below 5 meters as plastic has been documented to mix below this depth (Martini 2014).

Keeping in mind the limited number of studies, the existing studies on smaller plastic items suggest that the upper few metres have the highest plastic concentrations. However, larger plastic items closer to the coast that have been washed out with rivers may have a different vertical distribution.

Visual images from major washouts[15] seem to support that these items are floating in the upper water surface, with the higher concentrations at the surface. This needs to be verified by field studies. At the same time, the whales that have been found stranded dead with plastic in their stomach (a sperm whale on the coast of Spain[16] and a goose beaked whale on the west coast of Norway) can dive to considerable depths, beyond 1000 meters. It is not known where in the water column the whales may have ingested the plastic.

Recommendations based on data availability of surface litter

It can be assumed that the density of plastic will be higher during the wet-season in the Gulf of Mexico and the Caribbean. However, a lack of data on the density of larger plastic particles in the North Atlantic in general, and the focus study areas in particular, makes it difficult to estimate the likely collection efficiency of the device and recommend where the pilot study should take place. Field studies documenting annual variations in plastic pollution at the sea surface, particularly in connection with areas with river run-off, the vertical distribution of larger plastic items and retention time before being washed ashore, are recommended. An ad-hoc approach could also be taken, where close dialogue with local NGOs could give information on plastic discharge events during the time the vessel with the clean-up technology is in the area. However, there are uncertainties related to such discharge events taking place within the time window the vessel will be in the area.

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[15] https://www.nst.com.my/world/2018/03/342982/watch-diver-films-shocking-underwater-video-balis-plastic-garbage-wasteland

https://cv-insight.com/en/facebook/video_ranking/30660366

[16] https://www.independent.co.uk/environment/plastic-pollution-killed-sperm-whale-dead-spain-beach-bags-blue-planet-a8293446.html

DESCRIPTION OF THE PLASTIC COLLECTION CONCEPT

PGS has proposed a concept whereby a single vessel tows a boom arrangement with a collection bag in a similar manner to commercial trawling- or oil spill response operations. Plastic debris floating on the surface will be collected in the bag and sent ashore for further processing and disposal.

To enable removal of plastics suspended below the surface, it has been proposed to generate a bubble curtain by releasing compressed air from a perforated hose extended between the deflectors at 30-40 m depth. Suspended plastics may potentially be brought to the surface either directly by flotation or indirectly with the resulting upwelling.

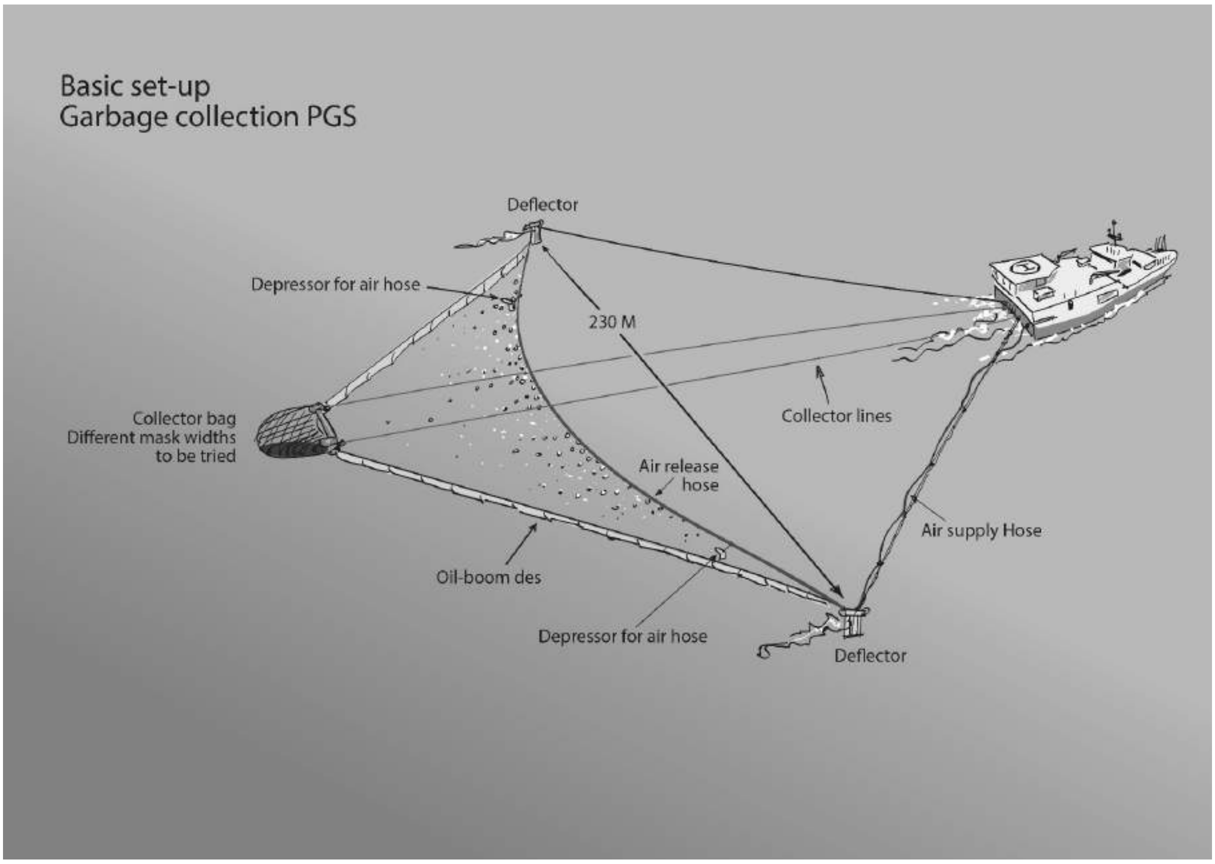

Figure 13. Illustration of the plastic collection concept.

Vessel

Seismic vessels are particularly suited for the task as they have a large towing capacity combined with a large compressor capacity capable of generating a bubble curtain. Seismic vessels are also equipped with deflectors and winches necessary to deploy and operate such a boom arrangement.

Furthermore, there is accommodation space for approximately 30 persons additional to the maritime crew and ample deck space, workshops and office space. This enables addition of scientific components to a pilot study where interested scientists can join the vessel and set up laboratories on-board to do studies of their choice related to plastic pollution during a cruise.

The vessel used for such operations may be one PGS’s Ramform vessels or associated seismic vessels. Regardless, the vessel will have oil booms, a collector, sensors and an air curtain system.

Oil booms

For collecting the floating litter, modified oil-booms will be used. Oil booms is an already well-developed technology, and has been widely tested for oil-spill operations in Norway and abroad. Exact design for this project will be determined later based on modelling of tow forces and the capacity of the winches that will be chosen. The initial parameters are as follows:

- The boom flotation will have a diameter of 1 meter, weight 3 kg/meter.
- It will be equipped with skirts approximately 1 meter deep, weight 4 kg/meter.
- The skirts will be weighted down by chain, weight 10kg/meter.
- The length of the booms will be 3 x 100 meter, 300 meter in total.
- The resulting opening will be approximately 230 meter.
- The front of the oil booms is connected to the deflectors with a rope. By adjusting the length of this rope one can ensure that the air bubbles from the air seepage hose will reach the surface prior to the booms arriving at a point based on around 2 knots towing speed.

Collector

The collector will be towed approximately 200 m behind the air curtain and consist of two parts:

- Main frame that is connected to the oil-booms, shaped like an upside-down U
    - The upper part will have facilities for mounting a radio unit connected to various sensors that will be mounted to monitor the content entering the net.
    - The side parts will have the connection to the oil booms' pulling points for the collector lines
- The collector net consisting of a frame with a cod end (net) attached
    - The opening (i.e. the frame) net will be 1.7 m deep and 10 m wide
    - The cod end will be 15 m long.
    - Different mesh sizes will be tested
    - Pulley ropes will be connected to the upper corners of the frame; these can be used to pull the cod end forward to the stern of the vessel without retrieving the rest of the system (see: https://youtu.be/GC5k5zYqNc8)
    - The cod end will be emptied on-board and organic materials disposed of (method to be decided)
    - Plastics will be sorted and catalogued

Sensors

Various sensors to count and quantify materials entering the collector will be tried out.

- Standard wide-angle underwater camera
- Hyper spectral camera (e.g., https://ecotone.com/)
- Scantrol deep vision (e.g., https://www.deepvision.no/)
- Scanners to determine type of plastics and organic materials

Air curtain system

Compressor

- The seismic vessels are equipped with ample compressor capacity and this will be used for the tests.
- Reduction valves will be used to reduce the present operation pressures of 137 bar down 1.5 to 3 bars.

Air release system

- A supply hose will be mounted along one of the main towing ropes.
- At the deflector area there will be a depth rope attached to a weight/depressor.
- Here it will be connected to a seepage hose that will go across the tow to the other side where it ends at a weight/depressor.
    - The seepage hose will be around 10 to 15 mm in diameter.
    - There will be one test using a garden water seepage hose. PGS have tested this type on another project several years ago where the aim was to make an air curtain over the standard seismic source (see: https://www.youtube.com/watch?v=0yYmM7hdZZw)
    - PEH hoses with holes will also be brought along for testing.
        - With this hose it will be considered running test with a sparging system that will ensure smaller bubbles in the water.
        - This means that in this case we will pump water with air already injected into the hose.
- For the towing arrangement proposed it looks like the most sensible depth of the air seepage hose is around 10 meters. This can easily be adjusted.
- Due to drag the air-hose will end up in a slight U-shape in the horizontal plane. It will be balanced to be fairly even in the vertical plane.

FEASIBILITY OF USING BUBBLE PLUMES TO LIFT MARINE DEBRIS

The concept PGS has developed for collection of plastic waste at sea includes a bubble curtain that will be used to get plastic to the surface before it is lead into the collector bag. This section discusses the feasibility of using bubble plumes to lift marine plastic debris to the surface from a depth of 20-40 meters[17] where the air curtain will be released. There are relatively few data available to indicate how successful a bubble plume is in lifting marine debris and concentrating it at the surface. This review therefore focuses primarily on what is known about the general dynamics of bubble plumes, and the potential implications and outstanding questions with respect to PGS' proposed scheme.

To our knowledge, there is only one other project currently seeking to use air curtains to concentrate marine debris: "The Great Bubble Barrier" (http://thegreatbubblebarrier.com). This is a technology employed in relatively calm rivers. A curtain of air bubbles is generated using a perforated rubber tube placed on the riverbed. Floating debris is then carried by upwelling generated by the bubble barrier, bringing the waste to the surface. The air curtain is placed at an angle downstream, and intercepted plastics are pushed to the riverbanks by the current, making it accessible for collection. The system filters floating material from 5mm to 1m in size. Indoor-testing of a pilot estimates that the barrier captures 70-80% of top-surface floating plastic and 50% of underwater plastics. Due to limited budgets, they have focussed on technology development. What type and size of plastic litter the bubbles lift have not been in focus. However, the system has only been tested very briefly in the field, and the results are not available to the public.

Consequently, there are relatively few concrete data available with which to predict the success of using a towed bubble plume to concentrate plastics. However, general research on bubble plumes give some indications and identifies important research questions. Concentrating macroplastics is the key objective; microplastics are of much less interest given that collecting such small particles will likely be impossible with a boom and collection net setup (Slat et al. 2014). The bubble curtain's ability to raise macroplastics is therefore paramount.

Mechanisms by which bubble plumes lift suspended objects

There are two mechanisms by which a bubble plume or curtain can lift objects in the water column: (1) upwelling, and (2) attachment (Grimaldo et al. 2011). Upwelling occurs as the bubble plume transfers momentum to the surrounding water, thus also transporting deeper water towards the surface, including objects entrained in this water (Leifer et al. 2009; Grimaldo et al. 2011). Objects can also be lifted directly by the bubble plume as individual bubbles attach to objects, adding positive buoyancy and lift (Grimaldo et al. 2011).

Plastics suspended in the water column above or near the depth of the bubble curtain are likely to be entrained in upwelling and lifted higher in the water column. The extent to which this occurs, however, will probably depend on several factors. Firstly, the strength of the upwelling flow will depend on the characteristics of the bubble plume. Greater density of bubbles results in more upwelling (Leifer et al. 2009). Larger bubbles rise more rapidly than do smaller bubbles (Leifer et al. 2009), and greater velocity of the curtain presumably means more momentum to transfer to surrounding waters and stronger upwelling. In a current, however, the upwelling flow is reduced on the upcurrent side (Leifer et al. 2009), which means upwelling may also be reduced in front of a towed bubble curtain. Secondly, entrainment will likely vary with both particle size and buoyancy.

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[17] The first descriptions of the proposed clean-up technology provided by PGS to SALT described air release systems at 40 meters depth. This was later changed to 10 meters depth.

Objects with greater negative buoyancy, such as larger and heavier objects, will presumably have a higher threshold for entrainment (i.e., require more energy to sustain lift). Thirdly, if used in an area with strong stratification of the water column, the bubble curtain will need to be sufficiently strong for upwelling to penetrate the boundary between water layers.

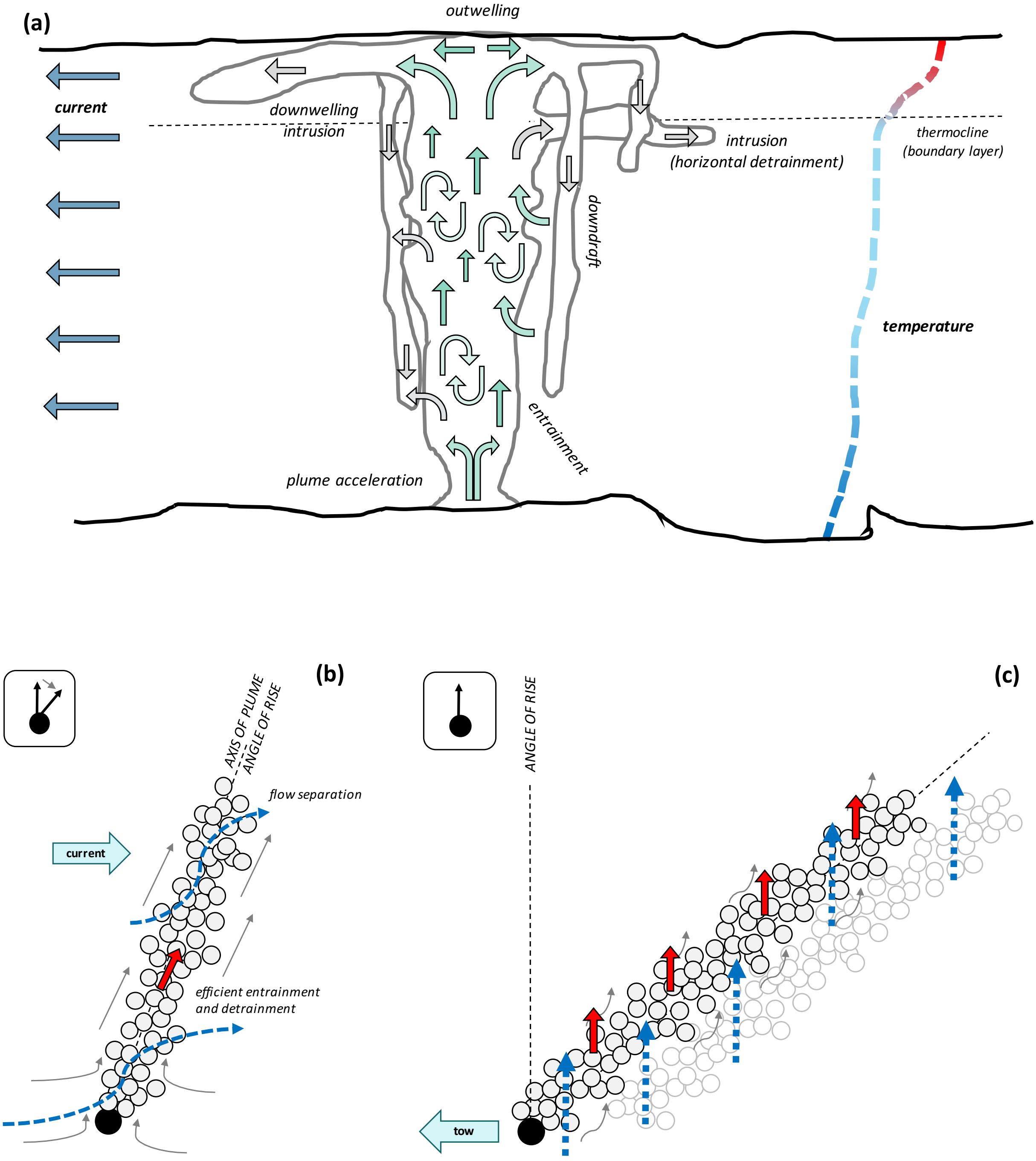

Figure 14. Illustrations showing the upwelling dynamics of a bubble plume. (a) A stationary bubble plume in a current. Redrawn from Leifer *et al.* (2009). Note the marked downwelling (downdraft) on the upstream side of the plume (on the right). Secondly, note the horizontal intrusion at the depth where water temperature begins to increase (*i.e.,* the transition and boundary between cooler deeper water and warmer surface water). (b-c) Contrast between (b) a fixed bubble source in a uniform horizontal current and (c) towed bubble source through quiescent water. Inset shows details of individual bubble motions. Red and black arrows pertain to bubbles and entrained water, respectively. Greyed bubbles represent plume several seconds earlier, and remnant, persistent fluid motions. Redrawn from Grimaldo *et al. (2011)*.

When the water column is stratified, there is a distinct boundary between layers of different densities. For example, when a warmer, less saline layer of water sits atop cooler, more saline deeper waters. Stratification is common during the spring and summer in temperate regions and may occur during the rainy season in the tropics (see Sprintall and Cronin (2009) for further explanations). Water density changes rapidly at the boundary between these layers, creating a barrier to upwelling. If the bubble plume is not strong enough to break this boundary, entrained objects will simply be deposited below the horizontal detrainment (i.e., the boundary) despite bubbles continuing to rise (Leifer et al. 2009; Grimaldo et al. 2011). In the latter case, the bubble curtain would not lift plastics from below this boundary; meaning there would be no uplifting of plastics from below this depth, limiting the effectiveness of the bubble curtain. Further research is needed to determine the necessary characteristics of the towed air curtain to sustain upwelling through stratification.

For plastics to be lifted through attachment, bubbles must first come into direct contact with plastics, stick to them rather than bounce off, and remain adhered long enough to cause upward movement. Smaller bubbles are more likely to attach to objects because of their slower rise velocities relative to larger bubbles (Grimaldo et al. 2011). Studies have been conducted on the possibility to lift Calanus (a type of zooplankton up to approximately 5 mm in body length) in order to increase their concentration and thereby the trawl catch, which would improve the harvesting efficiency in this fishery. To bring Calanus to the surface, bubbles need be smaller than 300 microns in diameter as bubbles 1 mm in diameter tend to displace Calanus in their wake rather than attach. However, smaller bubbles are less buoyant than larger bubbles, and an object therefore needs multiple bubbles to attach to achieve lift. Small bubbles successfully concentrating Calanus at the surface do not also concentrate larger organisms, such as small fish; the exception being jellyfish, which are raised ahead of the main bubble plume and thus removed from the trawl path (op. cit.). These observations suggest that controlling bubble size may allow for a degree of selectivity in the size of particles (and organisms) brought to the surface. If small bubbles (<300 microns) raise Calanus successfully, but not larger organisms, then larger bubbles (>1 mm) may provide the opposite selectivity and reduce zooplankton bycatch. It is also highly possible that small bubbles will be unsuccessful in rising macroplastics to the surface, just as they were unsuccessful in concentrating small fish and larger plankton at the surface in the study by Grimaldo et al. (2011).

Overall dynamics of the air curtain and entrained objects

Plastic bags share many characteristics with jellyfish (hence why sea turtles often mistake them for food; see e.g., Bugoni et al. (2001)), and may thus be affected similarly by the bubble curtain. Grimaldo et al. (2011) provide relatively few details regarding the behaviour of jellyfish in the plume, but the observation that larger bubbles rise ahead of the main plume, taking jellyfish with them, and depositing them out of the trawl path is potentially concerning. The reason this removes the jellyfish from the trawl path is not discussed, but presumably they are subsequently either displaced horizontally by the main plume, or they sink too rapidly following arrival at the surface to be captured by the trawl. If the latter is the case, this may prove problematic for PGS' concept given the long distance between the bubble curtain and the collection device. Proposed tow speeds are within the range of those used by Grimaldo et al. (2011), yet the distance between the sampling nets and the bubble curtain was only 25m when used by Grimaldo et al. (2011), compared to 200m proposed by PGS. How long objects remain concentrated at the surface before sinking back to original depths needs to be investigated.

It is also uncertain whether the proposed scheme will result in a sufficiently powerful and continuous bubble curtain. A towed bubble plume is fundamentally different from a stationary source plume; one key difference being that new bubbles are not released into the plume, but in front of it as the release hose moves forward (Figure 14). Consequently, in space, parcels of water will experience vertical advection in short pulses from the passing bubble sheet, and not as a sustained force (Grimaldo et al. 2011). On the down-tow side the “local” bubble pulses in a towed plume would therefore be restricted by upwelling flows driven by the bubble pulses that have already passed (Grimaldo et al. 2011). This likely results in greater overall upwelling than from a stationary plume. However, Grimaldo et al. (2011) used a series of rafts with sparger elements to generate a relatively homogeneous bubble plume (Figure 15), rather than the single line proposed by PGS, to achieve successful concentration of zooplankton at the surface. Grimaldo et al. (2011) also angled these rafts to maintain a 35 degree inclination towards the direction of travel while towed. The angle was carefully chosen to match bubble rise velocities in the plume whilst towed at approximately 1 knot to ensure that new bubbles were continuously injected into the rising bubble sheet. It is unlikely that the same can be accomplished by a single hose, particularly by one over which one can exert relatively little control. It may therefore be that PGS’ bubble curtain will not in effect be continuous. A single point source (i.e., one hose rather than multiple parallel ones) may not inject new bubbles continuously into the sheet.

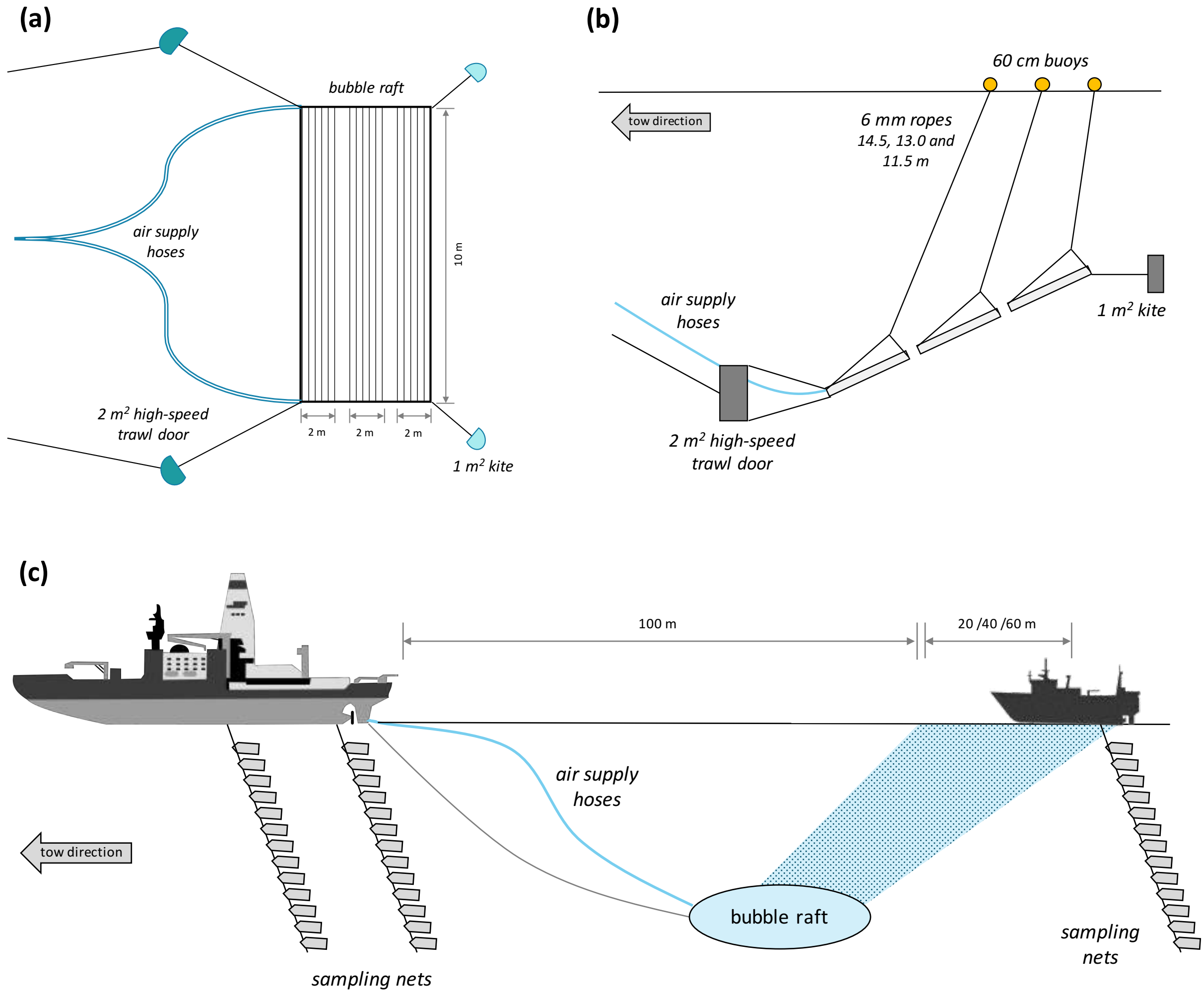

Figure 15. Illustrations showing the air curtain setup used by Grimaldo et al. (2011) to concentrate the zooplankton Calanus at the surface. The scale is an order of magnitude smaller than proposed in PGS’ scheme; however, the basic concept of using a towed air curtain to concentrate objects vertically distributed in the water column at the surface is the same. (a) Top view of raft with sparging elements comprised of 3 sub-raft elements and (b) side view of the same rafts. (c) Schematic of the complete setup with bubble raft and plankton net deployment. Redrawn from Grimaldo et al. (2011).

Consideration will also need to be given the collection boom skirts, their ballast, and their angle during tow. The skirts of The Ocean Cleanup boom array are estimated to surface at currents speeds over approximately 0.5 knots (Slat et al. 2014). Consequently, the skirts will float and not collect plastic at these current speeds. The proposed tow speed during PGS plastic collection of 1.5-2 knots is three to four times greater, and the efficacy of the collection booms in directing plastics to the collection net during tow needs to be investigated.

In summary, it is somewhat unclear how plastics will respond to the bubble curtain. The response is probably highly dependent on the physical characteristics of the plume, such as bubble size, rising velocity, homogeneity of the air curtain, amount of upwelling, etc. As much of this is unknown, however, combined with high variability in morphology and characteristics of plastic debris, considerable uncertainty remains. Field testing in a controlled and observable environment is required to determine what the characteristics of the plume are, and how these can be manipulated to create the desired effect on plastic debris. It also needs to be determined what is the more successful and selective mechanism by which to lift macroplastics - upwelling or attachment - and subsequently how to adjust the characteristics of the plume to maximise the preferred process.

Legal considerations

In areas outside of Norwegian waters, the selection of areas for the pilot study may be affected by regulations according to UNCLOS (United Nations Convention on the Law of the Sea). In the following we will look into a selection of the most relevant regulations of UNCLOS, pertaining to this project:

- UNCLOS gives Coastal States the rights to exercise sovereignty over their territorial sea which they have the right to establish its breadth up to a limit not to exceed 12 nautical miles (Part II, sections 1 and 2).
- Foreign vessels are allowed «innocent passage» through those waters, but «the carrying out of research or survey activities» is not in agreement with the term «innocent passage» (Part II, section 3).
- Coastal States have sovereign rights in a 200-nautical mile exclusive economic zone (EEZ) with respect to natural resources and certain economic activities, and exercise jurisdiction over marine science research and environmental protection (Part V, Article 56).
- Since the activity in this project may interfere with the wellbeing of marine organisms, the regulations on «Conservation of the living resources» (Article 61) and «Utilization of the living resources» (Article 62) may come into play.
- All States enjoy the traditional freedoms of navigation, overflight, scientific research and fishing on the high seas (Part VII, Articles 86 and 87); but they are also obliged to adopt, or cooperate with other States in adopting, measures to manage and conserve living resources (Part VII, Articles 118-120).
- The International Seabed Authority may carry out marine scientific research concerning the Area and its resources; Marine scientific research in the Area shall be carried out exclusively for peaceful purposes and for the benefit of mankind as a whole (Part XI, Article 143).
- Necessary measures shall be taken in accordance with this Convention with respect to activities in the Area to ensure effective protection for the marine environment from harmful effects which may arise from such activities (Part XI, Article 145).
- All marine scientific research in the EEZ and on the continental shelf is subject to the consent of the coastal State, but in most cases, they are obliged to grant consent to other States when the research is to be conducted for peaceful purposes and fulfils specified criteria (Part XIII, Article 246).

As a general rule, it will probably be possible to get a grant for a peaceful marine biological survey also within another country's EEZ, or even within their territorial waters, but it may be assumed that it will be easier to perform such a survey within Norwegian or international waters (Figure 16). This has to be taken into consideration when the final area for the pilot is decided. The areas identified as having the highest potential for a pilot study, are all within the EEZ of a country.

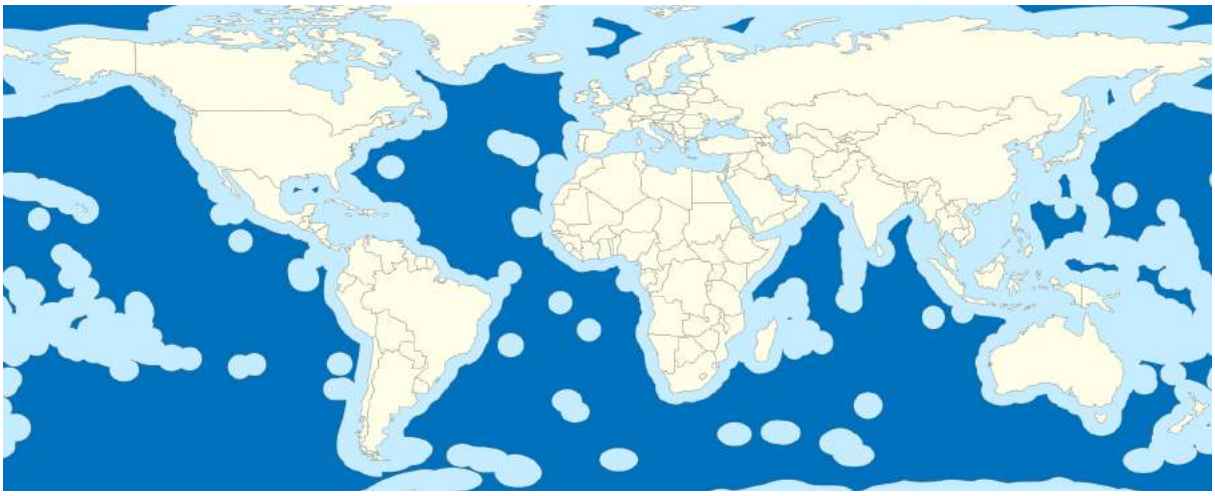

Figure 16. Areas outside of exclusive economic zones in bright blue (Wikimedia commons 2017).

POTENTIAL IMPACTS OF THE CLEANING TECHNOLOGY ON MARINE LIFE

The two main concerns with respect to potential impacts on marine life are bycatch and injury/mortality resulting from physical contact with equipment. There are currently few field data available quantifying impacts from pelagic plastic collection concepts and towed air curtains in general. Experiences from «The Great Bubble Barrier», which is a stationary riverine interception concept, and The Ocean Cleanup, which is an oceanic large-scale stationary boom array, provide some insight. Interpreting their claims is challenging, however, as these are not always backed by data or data made available. For example, according to «the Great Bubble Barrier» website[18], the concept will have several positive environmental effects, such as increased aeration of the water and reduced noise from shipping. However, there is no reference to documentation of these positive impacts, nor to literature on these types of impacts. Technology development has been the focus of the project and most results from the studies are internal memos. Two interns have produced reports in Dutch on impacts on fish and the feasibility of monitoring the effects of the Bubble Barrier (Zoet, Francis, pers. com.). The feasibility study for The Ocean Cleanup (Slat et al. 2014) was similarly focused on technological aspects, and vague on potential negative impacts on biota. Experiences from air curtain fisheries can provide some useful insights, and these results are generally well-backed by science.

Insights from application of air curtains

Bubble plumes and air curtains are sometimes used in lakes or smaller relatively closed marine systems, such as fjords, to aerate the water column and reduce toxic algal blooms (Milne 1970). An early example of such an application was in a Swedish lake where fish kills were occurring due to hypoxia, and aeration successfully raised the oxygen levels in the water by nearly 60% in three weeks (Milne 1970). A more recent example can be found in Arnafjord in western Norway where bubble curtains were tested as a means of mixing the water column to raise nutrients and stimulate the growth of non-toxic phytoplankton to cleanse mussels from the effects of toxic algal blooms (McClimans et al. 2010). Aeration can also be used to limit stratification of the water column in reservoirs (Milne 1970). “The Great Bubble Barrier” is expected to have similar positive impacts on the river system into which it is placed according to the project website. Such effects from the PGS air curtain will probably be more limited, however, as the aeration will not be sustained in any given area, but rather passing through.

A towed bubble curtain has already been demonstrated as an effective method of concentrating zooplankton at the surface in the context of a fishery (Grimaldo et al. 2011). Furthermore, in most cases the encounter rate will likely be greater for zooplankton than for plastics. Even in the Great Pacific Garbage Patch, the abundance of zooplankton is greater than that of plastics, including microplastics (Moore et al. 2001). Zooplankton, which includes the larval stages of fish and benthic invertebrates as well as jellyfish, caught in the collection boom towed behind the bubble curtain are likely to be killed. The Ocean Cleanup project seeks to place a large passive litter removal unit in the Great Pacific Garbage Patch, which will consist of a boom array and collection platform (see www.theoceancleanup.com for details). While the litter removal concept is quite different from the active scheme proposed by PGS, several of the inferences made in The Ocean Cleanup’s feasibility study regarding impacts on marine life remain highly relevant as the boom and skirts intercepting litter are likely to be of a similar design to that in PGS’ concept. The Ocean Cleanup feasibility makes two key conclusions regarding zooplankton: (1) The majority of zooplankton hitting the skirts will be deflected beneath them rather than brought to the surface and guided into the skimmer. (2) As the

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[18] http://thegreatbubblebarrier.com/en/

zooplankton are pushed against the skirts by currents they are likely to suffer injury and will most likely not survive (Slat et al. 2014). We can presume that zooplankton encountered during PGS' operations will suffer a similar fate.

Fish (non-larval stages) are likely to be scared by and herded by the bubble sheet. This response of schooling fish to bubble curtains is well documented. Humpback and killer whales, for example, are known to use bubble curtain spirals to corral fish during hunting, and concentrate schools at the surface (Similä and Ugarte 1993; Wiley et al. 2011). Bubble curtains have also been deployed in commercial fisheries (e.g., Smith (1961); Arimoto *et al. (1993)*). For example, bubble curtains have been used to steer herring towards passive fishing gear, a weir or stop-seine, in the Maine (USA) and New Brunswick (Canada) (Smith 1961). In this fishery, a single air hose is weighted to lay on the seafloor, creating a solid bubble curtain throughout the water column. The hose is a 12-20 mm diameter polyethylene pipe perforated with 400 micron holes, and may be deployed in different ways (Smith 1961). Often the hose is pulled along smooth bottom between two vessels, while at other times one end of the air curtain may be stationary and the other mobile. In both cases the air curtain herd the fish in front of it into an area accessible to a stop-seine (Smith 1961). The use of a bubble curtain has been deemed a highly successful method of guiding herring schools towards passive fishing gear. Smith (1961) noted, however, that when moving the bubble curtain, this needed to be done slowly, as if the fish were corralled too quickly they seem to panic and swim through the bubble curtain and escape; unfortunately, this critical speed was not quantified. Arimoto et al. (1993) conducted a series of laboratory and field tests of a similar concept of using bubble curtains throughout the water column to concentrate various small fishes (< 15cm total length) in passive fishing gears, and found the curtain to be an effective barrier at all tow speeds tested (up to approximately 0.5 knots). The authors also tested sequential stationary bubble curtains with varying progress speed, with the highest equivalent to approximately 1.5 knots towing speed, with similar success rates (Arimoto et al. 1993).

All the above observations of moving air curtains in the marine environment suggest that the bubble curtain used by PGS will likely be highly effective in herding fish encountered. Yet it remains possible that this will not result in major fish bycatch. Given the plume will be concave in the towing direction and angled vertically away from collection unit, fish may be primarily pushed in front of the bubble sheet and thus be displaced out of the trawl path. This assumption would need to be tested in the field. It is also possible that the bubble plume could concentrate pelagic fishes at the surface as the bubble sheet passes below and lead them into the collection unit, potentially causing massive bycatch. The ecological and economic consequences of such bycatch will depend on biomass caught and stock status. The depth of the bubble curtain (10-30 m) is fairly shallow, and many fishes, including pelagic species, will extend their distribution deeper in the water column. Combined with spatial heterogeneity in fish distribution, the number of fish encountered during operations will likely be highly variable. It is worth noting that in a river setting, "The Great Bubble Barrier" is based on the assumption that the air curtain will act as a barrier for plastics, while allowing fish to pass through. Their studies are not published, and thus cannot be evaluated, but the stark contradiction with proven air curtain fisheries in the marine environment may reflect fundamental differences in the way currents and fish behave in the marine versus a riverine environment.

Physical impact on marine life by the clean-up technology

Larger vertebrates may be hit, or become entangled in, and injured by the boom and collection unit if encountered. Animals that breathe air, such as marine mammals, turtles and seabirds use the sea surface for daily activities. These are also the organisms that show high rates of plastic ingestion and entanglement (Derraik 2002; Reisser et al. 2015), which could be linked to the relatively high concentration of plastic at the sea surface (Reisser et al. 2015). Slow-moving filter feeders, such as some species of sharks and whales, feed at the surface and may have limited ability to move out of the way of the vessel and collection booms. Northern right whales, for example, a critically endangered species, spends over 70% of its time in the top 10 m of the water column filter feeding on zooplankton (Baumgartner et al. 2017). This, combined with slow swim speeds while feeding, makes it highly susceptible to ship strikes and fishing gear entanglement (op. cit.), presumably also in a plastic collection boom. This risk may be substantially reduced by the slow tow speed of the array, however.

The Gulf of Mexico case study

The Gulf of Mexico is a highly productive region with continuous production cycles, and supports large commercial fisheries for various fishes and shrimps. Traditionally, fisheries in the northern Gulf of Mexico has accounted for one third of all US fisheries, the Gulf menhaden being the biggest in terms of volume, and shrimp the most valuable (Etzold and Christmas 1986).

Impacts on plankton

Plankton density and distribution varies in both daily and seasonal cycles, and thus the expected impact of litter removal operations will likely vary temporally as well. The Gulf of Mexico has relatively continuous production cycles and show less seasonality than more northern regions; nevertheless, ichthyoplankton (fish eggs and larvae) and other zooplankton tend to be more abundant in spring and summer than during fall and winter (Espinosa-Fuentes et al. 2009). Potential impacts on zooplankton are therefore likely greatest during spring and summer months, but cannot be disregarded during fall and winter months. With respects to vertical distribution of zooplankton, densities are greatest in the upper 18 m, with a max density at 6-12 m (Espinosa-Fuentes et al. 2009). Consequently, the use of an air curtain may drastically increase the amount of zooplankton affected compared to simply towing a surface collection unit as the zone with the greatest zooplankton abundance would be unaffected by the latter. Avoiding night-time operations may somewhat limit impacts on zooplankton as many species of ichthyoplankton and other zooplankton engage in diel migrations where they retreat to deeper and darker waters during the day and rise to the surface to feed at night under the cover of darkness (Espinosa-Fuentes et al. 2009). If the air curtain is towed at 10m depth, this may be above the majority of zooplankton during the day-time as they appear to concentrate somewhere between 45 and 18m depth during the day (Espinosa-Fuentes et al. 2009). If the air curtain is lowered to 30-40m depth, however, zooplankton in the Gulf of Mexico likely does not retreat deep enough during the day to avoid being impacted. Espinosa-Fuentes et al. (2009) did not observe higher densities during the daytime at 45-50 m depth in their study of vertical distribution of zooplankton, only reduced daytime densities above 18 m depth. They did not sample between 18 and 45m, so it is unclear exactly to what depth zooplankton retreats during the day, but the shift must occur in this depth rage. Thus, the amount of zooplankton impacted by litter removal during day and night will likely be similar as most will still be above the bubble release depth if this is placed lower in the water column.

Assuming a bubble release depth of 10m, an aperture of 230m, and a tow-speed of 2 knots, the volume of water affected by one hour of operations is approximately 12 million cubic meters. Based on the plankton tows conducted in the Bay of Champete in the southern Gulf of Mexico by Espinosa-Fuentes et al. (2009) in the mid-1990s, this means an average of over 50 million fish larvae and nearly 2 tons of other zooplankton may be affected during one hour of operations during the night, irrespective of time of year (although numbers will likely be above average during summer). During the day this may be reduced to 30 million tons of fish larvae and 1.4 tons of other zooplankton.

Jellyfish are also part of the plankton. Their density in the water column is highly spatially variable, but where densities are high, an hour of operations could concentrate over 12 litres of jellyfish (Martell-Hernández, Sánchez-Ramírez, and Ocaña-Luna 2014). Jellyfish distribution is highly dependent on water currents (op. cit.) and may therefore concentrate in the same area areas as floating plastics. Consistently high rates of jellyfish bycatch are therefore possible. Depending on the characteristics of the bubble plume used to lift them, however, they may be raised sufficiently quickly to be displaced out of the trawl path (Grimaldo et al. 2011). Although, to our knowledge, it is unknown whether the jellyfish (and other plankton) are likely to suffer injury in the upwelling flow and turbulence caused by the air curtain.

It is somewhat challenging to predict the consequences of such plankton mortality. The biomass of zooplankton potentially affected is high, particularly for sustained operations, and an increase in mortality of organisms making up the foundation of the food web is concerning. However, in the course of a week with 12-hr day operations, the area trawled would be equivalent to less than 0.01% of the total area of the Gulf of Mexico basin, and (if we assume uniform distribution of zooplankton) presumably the same proportion of the total zooplankton biomass. The underlying assumptions behind this conclusion are fundamentally flawed as zooplankton biomass is not uniformly distributed (e.g., Okolodkov (2003); Espinosa-Fuentes and Flores-Coto (2004); Espinosa-Fuentes et al. (2009)). Yet the total proportion of the zooplankton community affected likely remains relatively small unless local areas where zooplankton concentrate are targeted. Identifying where such areas are, and conversely which areas likely support less biomass, may be possible based on spatial and temporal patterns in temperature and salinity across the gulf if these are monitored or modelled in some way as oceanographic conditions impact horizontal zooplankton distribution (see e.g., Rooker et al. (2012); Cornic and Rooker (2018)). Avoiding areas and times known to have high concentrations of zooplankton is probably desirable (see Figure 17 for example of a map of spatial variation in mean phytoplankton distribution).

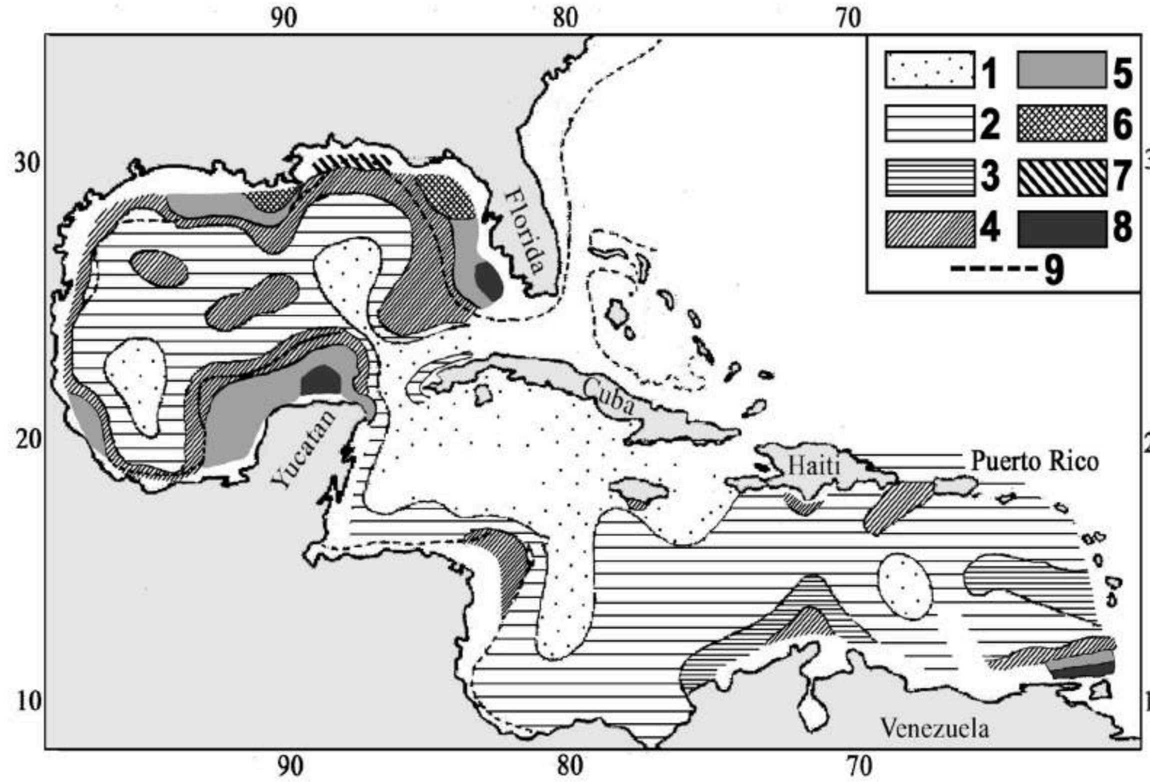

Figure 17. Averaged distribution of phytoplankton in the upper 100-m layer (mg/m^3), based on the 1962-1966 materials: 1 – 30-100; 2 – 50-150; 3 – 100-200; 4 - 100-300; 5 – 200-600; 6 – 200-1,000; 7 - 100-3,000; 8 – 300-1,000; 9 – shelf margin. Adopted from Okolodkov (2003).

The practical implications of large amounts of zooplankton potentially being caught in the collection unit should also be considered. The Ocean Cleanup estimates that the majority of zooplankton hitting their booms will be submerged below the skirts and not caught in the skimmer (Slat et al. 2014). The fate of zooplankton and smaller organisms hitting the skirts, and the amount which ends up as bycatch contaminating the targeted plastics, will need to investigated. If a significant portion of affected zooplankton is collected in the cod end, this may represent considerable contamination of the collected plastics.

Impacts on fish stocks

The zooplankton community includes ichthyoplankton, or fish larvae, and impacts on specific species may be of particular concern during times of year when these are spawning. The Gulf of Mexico is an important spawning ground for bluefin and various other tuna species (Richardson et al. 2016; Cornic et al. 2018). Tuna fisheries are of great economic value. The bluefin tuna alone supports an important international fishery, with what is believed to be only 1-2 stocks harvested across the North Atlantic by more than 20 nations (Richardson et al. 2016). Bluefin tuna stocks declined to historically low levels by the start of the 21st century, although the trend has been reversed in recent years following stricter management regulations (Richardson et al. 2016; Cornic et al. 2018). The bluefin tuna fishery is highly contentious and valuable (Richardson et al. 2016), and increased mortality of any life stage of the bluefin or other tuna species is not likely to be well received. Bluefin tuna spawn in the Gulf of Mexico from April to June, and several other tuna species spawn in June and July (Cornic et al. 2018). An hour of litter trawling in the northern Gulf of Mexico during June and July is likely to affect 7,000 to 18,000 tuna larvae based on larval tow data from Cornic et al. (2018). Note, however, that this estimate is based on the assumption that tuna larvae are present in the top one meter of the water column only (as per the sampling protocol in Cornic et al.(2018)), and may therefore be a considerable underestimate if tuna larvae have a greater vertical distribution, as the general ichthyoplankton community does (Espinosa-Fuentes et al. 2009). If we assume a uniform distribution of tuna larvae across Cornic et al.'s (2018) study area in the northern Gulf of Mexico, the number of tuna larvae affected by the litter trawl remains below 1% of the total abundance after a week of 12-hr/day operations during June and July. While this proportion seems very low, it should be interpreted with caution. It is very clear that the distribution of tuna larvae is not spatially uniform (Cornic et al. 2018), and the proportion of affected larvae could be essentially zero or very high depending on the specific location. Swordfish, which support multi-million-dollar fisheries, also spawn in the Gulf of Mexico and the Caribbean Sea year-round (Suca et al. 2018), presenting a similar, albeit less seasonal, scenario as for tuna.

The Gulf of Mexico is home to over a hundred pelagic fishes which could be encountered during plastic removal operations (Ward 2017). Over deep waters (> 200 m) in the oceanic zone, most fishes reach large body sizes with an average length of over 2m (op. cit.). Such large fish are unlikely to be caught in the collection unit in large numbers given its opening is not much larger than their body size and they have high swimming speed capabilities. However, they may sustain injury from impact with or entanglement in the booms and various lines, particularly if operations concentrate potential prey species and these mostly predatory fish aggregate to feed (see Slat (2014) for discussion of how The Ocean Cleanup boom may act as a Fish Aggregating Device). In more nearshore waters (< 200m), however, there are several smaller pelagic fishes that may be affected (Ward 2017). One of the most important commercial species is the menhaden (Vaughan, Levi, and Smith 1996). Menhaden are schooling pelagic fish feeding on plankton near the surface. They form large schools nearshore from April to November and may move further offshore in the winter. Menhaden is an important prey species for many larger fishes (op. cit.). Being surface schooling fish, there could be a high risk of encountering menhaden during plastic clean-up, although this risk is probably reduced in the summer months when they are most commonly found in shallow nearshore waters, typically estuaries, which may be inaccessible for operations due to insufficient depth.

Impacts on larger vertebrates

There are several larger vertebrates whose presence should be considered in terms of risk of ship strike and possible injury of and to the towed units, such as the endangered sperm whale (Farmer et al. 2018). Whale sharks are also present in the Gulf of Mexico as well as in the Caribbean Sea. In particular, whale sharks aggregate by the hundreds in their summer feeding area off the north-eastern Yucatan Peninsula, Mexico, where the Gulf of Mexico meets the Caribbean Sea. These sharks are filter feeders and quite docile near the surface, swimming slowly (Hueter, Tyminski, and de la Parra 2013) and may be vulnerable to ship strikes and entanglement. Loggerhead turtles are another endangered species present in the Gulf of Mexico where a small sub-population of fewer than 500 individuals reside (Hart et al. 2014). Sea turtles, which must surface to breathe, frequently suffer direct mortality in trawling gear (Wallace et al. 2008); an eventuality which should be considered for litter removal operations. Juvenile sea turtles of various species seek floating debris for shelter; primarily Sargassum macroalgae, but also plastic pieces (Witherington, Hirma, and Hardy 2012) and may therefore be at risk of capture along with plastic litter during collection.

Acoustic pingers may be used to deter marine mammals, such as sperm whales. Acoustic pingers are frequently deployed to reduce marine mammal bycatch in gillnet fisheries (e.g., Barlow and Cameron 2006; Cox et al. 2007). Such devices are highly unlikely to deter sharks or turtles, however. These do not have same acute sense of hearing and acoustic communication as marine mammals. Shark fisheries are among gillnet fisheries where acoustic pingers are used to reduce marine mammal bycatch (Barlow and Cameron 2006); if the pingers also deterred the sharks this measure would be counterproductive. In trawl fisheries, turtle bycatch is typically reduced with turtle exclusion devices. These are metal grates fitted to the neck of a trawl net, and which let the smaller target species, such as shrimp, pass through while preventing the turtles from entering the cod end and instead allow them to slide out an open flap in the net (Cox et al. 2007). Such a measure is likely not suitable for the plastic collection concept, however, as the turtle exclusion devices may also exclude large pieces of plastic.

Impacts on floating habitat

Sargassum are floating brown macroalgae ubiquitous in the Gulf of Mexico (Rooker, Turner, and Holt 2006). The macroalgae typically originate within the North Atlantic Gyre and are subsequently distributed by currents and wind (Wells and Rooker 2004). The Gulf of Mexico itself is also a key source of Sargassum (Gower and King 2011). Sargassum is a source of primary production in open waters and can accumulate in large mats (Rooker, Turner, and Holt 2006). Bacteria and various sessile invertebrates colonise the algae as substrate, and several species of fish, shrimp and crabs are believed to depend on the shelter of these mats during early life stages (Wells and Rooker 2004; Rooker, Turner, and Holt 2006). Aggregating by sargassum mats presumably offers juvenile fishes and invertebrates protection from predators (Rooker, Turner, and Holt 2006). Because of this, Sargassum mats are considered Essential Fish Habitat by the US Marine National Fisheries Service (Wells and Rooker 2004). Commercial fishes aggregating in Sargassum mats as juveniles include dolphinfish, yellowfin and blackfin tuna, king mackerel, and blue marlin (Rooker, Turner, and Holt 2006). Various species of sea turtles are also tightly associated with Sargassum, particularly as juveniles (Witherington, Hirma, and Hardy 2012). The catch-per-unit-effort of fish associated with Sargassum mats is greater offshore than nearshore (Wells and Rooker 2004). Sargassum is most abundant in the Gulf of Mexico from May through July, and more predominant in the northern part of the gulf. Sargassum moves passively with currents (Gower and King 2011). It is therefore quite possible that plastics and Sargassum will be transported in similar manners and aggregate in the same locations. Such positive correlations between plastic debris and Sargassum has been confirmed in the Gulf of Mexico, and juvenile sea turtles living in and feeding on Sargassum frequently ingest plastic (Witherington, Hirma, and Hardy 2012), and needs to be further investigated and considered accordingly. If plastics concentrate together with Sargassum mats it is clearly not desirable to also remove large volumes of Sargassum and the associated fishes and invertebrates.

Estimates of potential collection rates of pelagic plastics

While limited data make accurate predictions impossible, we can make some estimates on expected collection rates based on the data that are available. These estimates all have key limitations, and must be interpreted with these in mind.

Lecker-Mitchell and Mullin (1997) conducted aerial surveys in the Gulf of Mexico in the 1990s and recorded an average of 1 item km^{-2} from spring to fall and 2 items km^{-2} during winter. All items larger than about a cup were recorded. Assuming an operational speed of 1.5 knots and air curtain width of 500 m, these data suggest an hour of operations would recover 1-2 items from spring to fall, and 3 items during winter. The concentration of surface plastics may be somewhat higher in the region today than at the time of these data.

Barnes et al. (2005), sailed across the Atlantic, recording visual sightings of debris 10 cm and larger. If we consider the part of their course which overlaps with proposed PGS pilot sailing plan (0-50°N from the coast of Brazil, northeast to the north-western African coast, and north to the coast of Spain), they observed 0-10 items of litter km^{-2}. This suggests PGS may recover up to 14 items in an hour of operations in the most polluted areas along this route. For long stretches the recovery will likely be 0-4 items per hour. During the course of a week (7 days, 12-hr days) this equates to approximately 350 plastic pieces 10 cm or larger. It is worth noting that the observed density of floating plastics was considerably higher in the English Channel (10-100+ items km^{-2}), suggesting an hour of operations here could recover up to 140 items.

Both these studies covered surface plastics only, and real plastic recovery numbers may be higher if plastics lower in the water column are able to be raised and also collected. However, the catch rate may not increase much given the concentration of suspended plastics is likely lower than that of floating items. Data on vertical distribution of plastics in the top 5 m of the water column in the North Atlantic Gyre (Reisser et al. 2015), suggest an hour of surface tows would collect approximately 1.1 kg of plastics and that extending collection to recover plastics down to 5 m depth would recover only an addition 70 g. While these data are spatially limited, do not consider plastics suspended below 5 m depth, and rely on extrapolation of point samples, and are therefore likely subject to considerable error, they do clearly suggest that recovery rates of macroplastics are likely to be quite low. However, as discussed in Chapter 2, there may be events leading to higher concentrations of floating marine litter that could increase recovery rates.

When compared to the estimated bycatch rates listed in the previous sections, it does give a sense of the possibility of having greater bycatch than target plastics.

Summary of potential impact on marine life

This case study is not comprehensive, and there are likely many interactions not considered. Some of the considerations raised are generalisable to different regions, while others are more localised. What it does illustrate quite well, however, is the potentially complex and broad range of interactions that may occur, and some of the research that needs be done before commencing operations in an area.

RECYCLABILITY OF MARINE LITTER

A potential income stream to cover some of the costs related to clean-up of marine litter, could be to sell the recovered plastics to the recycling industry. While recognising that a well-functioning waste management and recycling industry should reduce plastic consumption and prevent littering in the first place, this section looks at the potential of marine litter to enter the circular economy, which could incentivise further clean-ups.

Recycling of plastic marine litter is relatively costly and time consuming as most of the plastics retrieved from the ocean are fouled and weathered to some extent and may contain persistent organic pollutants and other toxins. Most of the marine plastics must therefore be sorted and cleaned thoroughly before recycling. Furthermore, a large proportion of the plastics is not recyclable at all due to the above-mentioned factors. Plastics from rivers may have higher quality to plastics recovered further away from the source as it is cleaner, less biofouled and less degraded by UV radiation (Marcus Eriksen, 5 gyres institute, pers. com.). The recycling channels and technologies included in this study, with the exception of plastic-to-fuel recycling, have some restrictions when it comes to the size of the items and type of plastics, which is why it is up to the marine litter collectors to sort the marine waste prior to delivery. The identification of type of plastic can also be demanding, as the composition and quantity of additives may differ among plastic manufacturers (Plastic and Ocean Platform 2018). Due to the variation in quality of the materials, it is challenging to maintain a constant supply of marine plastics that can be recycled to new products. Some manufacturers have begun investing in the use of marine plastics in their products, creating some relatively robust recycling channels. Adidas is for example making running shoes and football jerseys from recycled PET bottles, and Proctor & Gamble are producing shampoo bottles made from up to 25 percent recycled marine plastic. These companies are cooperating with recycling companies and marine litter collectors, such as TerraCycle and Parley for the Oceans.

TerraCycle recycles rigid plastics and prefers HDPE and PET, and everything between 5 cm to items as large as big barrels, containers and fishing crates when it comes to the size of the plastic items. TerraCycle is able to rinse the plastics but cannot recycle very contaminated materials, and they work with marine litter collectors globally. Another recycling company working with rigid plastics is Envision Plastics, through a project called OceanBound Plastic. Envision Plastics operates in the U.S. and are the only plastic producer that has managed to produce food-grade post-consumer HDPE plastics. OceanBound focuses, however, on HDPE plastic at-risk of entering the oceans, i.e. plastic collected from areas that lack formal community-based waste collection, which are located within 50 km of a coast line. It is uncertain as to what degree OceanBound cooperates with marine litter collectors.

Parley for the Oceans (Parley) is an organisation that collects marine plastics from various areas, such as Hawaii, UK, Jamaica, Maldives, Australia, and Alaska. Parley works together with clean-up organisations such as Sustainable Coastlines Hawaii, Surfers Against Sewage and Gulf of Alaska Keeper. Envision recycles some of the marine plastics collected by Parley from these organisations. Parley accepts the following materials: HDPE nets, nylon 6 (PA6) nets, PP nets, fish boxes, monofilament nets, and ropes only if they are a part of nets/trawls. There is no size limit, nor specific degree of biofouling that is unacceptable. Parley is able to do light sorting and cleaning prior to processing, but the thumb rule is “the cleaner, the better”.

The Danish company Plastix Global recycles discarded fishing nets and trawls. They accept HDPE nets, Nylon 6 nets, PP nets, fish boxes, monofilament and ropes only if they are a part of nets or trawls. The Norwegian company Nofir also recycles discarded gear from fishing and fish farming on a global scale. Nofir accepts gill nets, purse seine nets, trawls and ropes that are under 20 percent contaminated.

Some companies have also begun converting plastics into fuels, such as the UK-based company Plastic Energy. Plastic Energy uses specifically end-of-life plastics as feedstock and accept all plastic materials. They use thermal anaerobic conversion to transform plastics into fuel that can even be used to fuel planes. Plastic Energy has two plants in Spain, and is expanding their business to the U.S., Caribbean, Central and Latin America. Plastic-to-fuel recycling is especially interesting when it comes to marine plastics that cannot be recycled into new plastic products.

There are various other smaller-scale recycling channels available in the North Atlantic region, and the number of companies working with marine plastic recycling is increasing. However, as recycling marine plastics is relatively costly and time consuming, the alternatives for especially long-term partnerships can be limited. If recyclability of the marine plastics is prioritized in the project, it is important to contact the individual recycling companies to check whether they operate in the area of interest and accept the type of plastics expected to be collected through the project. Another consideration to take is whether it is possible to cooperate with other marine litter collection projects in order to create a more secure supply of plastics to the recycling company, and to increase the chances to be able to arrange pick-ups from more isolated regions, i.e. regions that do not have local recycling options but require long-distance pick-up and delivery.

An overview of the recycling companies included in this study is found in Table 2 below.

Table 2: An overview of the recycling companies included in the study

Company	Type of plastic	Size	Contamination /Fouling accepted	Operational in
TerraCycle	- HDPE - PET	5 cm to containers, barrels, fish crates	Slightly contaminated	Global
Envision Plastics – OceanBound plastic	- HDPE	N/A	Slightly contaminated	United States
Parley for the Oceans	- HDPE nets - Nylon 6 nets - Fish boxes - Monofilament nets - Ropes as part of nets	No size limit	No specific degree of biofouling, "the cleaner, the better"	Global
Plastix Global – OceanIX	- HDPE nets - Nylon 6 nets - PP nets - fish boxes - monofilament - ropes if part of nets or trawls	N/A	N/A	Global
Nofir	- Gill nets - Purse seine nets - Trawls - Ropes	Ca. over 2 m	Max. 20% fouling	Global
Plastic Energy	All types of plastic	No size limit	No specific degree	Europe, Americas

CONCLUSIONS AND RECOMMENDATIONS

PGS is seeking support for a 2-3-month pilot survey and would like advice on what should be the focus for the pilot. This section summarises the main findings and point to some important knowledge gaps. It also gives advice on how the proposed pilot, as well as vessels in general, can contribute to filling the knowledge gaps related to plastic in the oceans. The focus will be on collection of surface data of macro litter as this will be directly relevant for any clean-ups at sea.

The potential- and the feasibility of the plastic collection concept

Knowledge on the spatial and temporal distribution of plastic in the surface ocean is scarce particularly for the North Atlantic and the proposed case study area where synthesis and modelling studies suggest that concentrations of marine plastic could be relatively high. It is therefore not possible to calculate the likely collection efficiency of the technology.

Densities of plastics in surface waters may be higher during wet-season in the Gulf of Mexico and the Caribbean due to more litter being carried to the coast with rivers during periods of high flow. To evaluate if the plastic collection concept will be efficient, we recommend surveying the areas identified as having the highest potential for clean-up. Priority should be given to the seasons when rivers are expected to carry the most litter to the coastline. The mass, plastic type and size of the items, variations in time and space, as well as vertical distribution should be documented. Documenting the type of plastic recovered, is important to evaluate the recycling potential of the litter. This can include using spectrometry identification of plastic type. How long the litter remain at densities high enough to be accessible for the clean-up technology, before being dispersed, sunk or washed off-shore, should also be recorded. If rivers are an important source of plastic pollution in the area, it may be better to focus cleaning efforts in the rivers, rather than capturing the litter further out from the coast. If events giving high concentrations of litter are unpredictable and the retention time is short, the clean-up operations will have to be available locally and on short notice. Furthermore, the ability of the proposed vessels to operate in these waters (e.g. how shallow they can go) should be evaluated in light of the results. Legal aspects also have to be clarified.

While there is limited knowledge on the vertical distribution of floating plastics, it is likely that the highest concentrations will be at the top of the surface. A bubble curtain to lift plastic particles may not be needed or would only need to be deployed at a few meters depth which may contain some floating plastics. Turbidity, stratification and wind may affect the vertical distribution of the litter, as well as the ability to operate the clean-up technology. The response of plastics to the bubble curtain is uncertain, but it is likely to depend on the physical characteristics of the plume. Laboratory studies should therefore be conducted to evaluate factors determining the mechanisms that successfully and selectively lift macroplastics to the surface. This includes experiments on the size and rising velocity of the bubbles and the homogeneity of the air curtain. This should be followed up by field testing. A potential first step in gaining an improved understanding of the characteristics of the air curtain could be deploying it for a short tow in home waters and using underwater drones to film the process from different angles. Such a relatively simple test may quickly answer some general questions concerning the behaviour of the curtain and help guide further research.

Factors to consider to mitigate potential impacts on marine life

While floating plastic densities are likely to be higher close to the coast, the impact on marine life of the clean-up technology may also be a bigger concern in these areas compared to in open oceans. While the relative impact on plankton may be small, plastic is expected to aggregate in the same areas as passively transported organisms, potentially exaggerating impacts. Furthermore, the Gulf of

Mexico is home to numerous marine organisms, some of which represent valuable fisheries or vulnerable species, as well as floating habitats.

Ecologically defensible operations will require extensive prior research into the local pelagic ecosystem of each region of the sailing plan. Based on this, key undesirable interactions, such as potential negative impacts on endangered species, should be highlighted, and prevention strategies developed to avoid negative environmental impacts. Prevention strategies could include identifying seasons where encounters are less likely and a strategy for scouting ahead of the ship's path to identify obvious biological activity at the surface, such as feeding whales, flocks of seabirds fishing (indicating the presence of fish schools), etc., in time to avoid them.

Testing of how the air curtain affect plankton and monitoring of zooplankton bycatch, as well as estimates of zooplankton hitting the booms and being swept under, should be conducted. Acceptable levels of zooplankton bycatch will also need to be considered, most likely independently for each new area (and/or season), for monitoring of mortality to be useful. The same applies to fish. Whether or not to operate in areas with substantial amount of floating organic debris, such as Sargassum mats which are defined as Essential Fish Habitat, needs careful deliberation to weigh potentially increased concentrations of plastics against the very great potential for high bycatch. In conclusion, there is real potential for negative impacts on marine life and this has to be weighed up against implementation of the clean-up technology. Given the relatively low estimates of plastic recovery rates based on existing date, there is considerable potential for bycatch to outweigh litter removal. At the same time, a number of them may be possible to limit or avoid.

Monitoring and data collection of marine plastic pollution

As identified through the review on data availability of marine plastic pollution in the focus regions, there is a need for field studies to estimate the amount of litter in the area, as well as its vertical, horizontal and seasonal distribution. Additionally, in order to evaluate the recyclability of the plastic collected, data on type of plastic should be collected.

The most cost-efficient solution to the marine plastic pollution problem is prevention (UNEP 2005). Source-identification and documentation of marine litter is an important tool to reduce the amount of plastic waste in the ocean. Collection of such data would therefore be an important contribution for decision makers to base their behaviour and policies, and for scientists to get a better understanding of marine plastic pollution dynamics. The UNEP/IOC Guidelines can be downloaded from the UNEP web-page[19] and provide detailed instructions on how to survey and monitor marine litter.

Visual observations of marine litter at the sea surface by ships, is a particularly useful and inexpensive way of monitoring accumulation and distribution of marine debris (Galgani, Hanke, and Maes 2015). Such observations can be made by any ship sailing on the ocean and can also be applied to large rivers. The floating litter trawl survey operational guidelines (pg 49) and the floating litter visual survey operational guidelines (pg 52) provide instructions on data collection that will be directly relevant to get information needed to evaluate the potential efficiency of the plastic collection technology. Existing observation schemes, such as NOAA, UNEP and Hellenic Marine Environment Protection, use different monitoring protocols (Galgani, Hanke, and Maes 2015). As part of the Marine Strategy Framework Directive, monitoring methods have been reviewed and general advice is given (Galgani et al. 2013), but there are no final protocols available. An example of detailed instructions on ship-based surveys of floating debris are given in Appendix 1 and is copied from Ryan (2014) and Arcangeli et al (2017). The latter protocol was set up based on Galgani et al. (2013) and developed in order for it to be simple and effectively used by any large research vessels. Some general advice on collecting data on surface macro-plastic is provided under.

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[19] http://wedocs.unep.org/handle/20.500.11822/13604

To detect high-density areas, the survey sites should be areas that are known to have high discharges of litter or that accumulate debris. This could be areas of major shipping lanes, close to rivers or urban development (Cheshire et al. 2009). However, collection of data at regular intervals throughout operations would give valuable information on surface litter densities throughout the ocean. It is important to record the size classes of debris items in order to get more accurate mass calculations from number of items recorded (Galgani, Hanke, and Maes 2015). One should also report and if possible try to recover particularly damaging litter, such as fishing nets that are known to keep fishing after being lost at sea causing death and suffering of a range of marine organisms.

Data collection using trawl has to be mindful of accidental bycatch of marine species and require specific equipment. Visual surveys can be done as part of normal operations (Cheshire et al. 2009). Relatively calm conditions are needed to avoid bias due to objects being mixed into the water column and to be able to spot items larger than 2.5 cm (Galgani et al. 2013). Current guidelines on floating litter generally do not include vertical sampling of litter. Subsurface samples of marine plastics are therefore scarce. Thus, inclusion of such sampling could be of great importance to better understand the distribution, concentration and dynamics of pelagic marine plastics. This includes sampling at different sea states to improve our understanding of vertical mixing of buoyant plastics (Reisser et al. 2015).

Reisser et al. (2015) sampled the upper 5 m of the North Atlantic accumulation zone using 12 multi-level net tows. They sampled at 0.5 m intervals using nets stacked vertically that each were 0.5 m height*0.3 m width and fitted with a 2.1 m long 150 µm mesh polyester nets. The top net was above the mean water line. Tow durations ranged from 55-60 minutes at a speed of 1-1.9 kn (op. cit.). Appendix 2 describes how the sample was treated after the nets were emptied. If only larger plastic items are the target of the sampling to get information on the vertical distribution of plastic items targeted by the clean-up technology, the documentation procedure could be simplified and the mesh size of the nets could be wider. Underwater video recordings could also give information on vertical distribution of larger plastic items.

Automatized approaches for monitoring are under development, using techniques such as digital imaging and recognition techniques for large-scale monitoring of litter (Galgani, Hanke, and Maes 2015). Thus, as these techniques are developed further, automated monitoring using videos attached to the ship or to drones could make the documentation of litter less demanding.

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APPENDIX 1

Description of ship-based observation of floating litter from Ryan (2014)

"Observations were conducted throughout daylight hours while the ship was underway. Only debris on one side of the bow was counted. Most observations were made from the bridge wing or from the deck above the bridge, 12–15 m above sea level and 50 m from the ship's bow, but some observations were made from the ship's bow (elevation 6 m) during calm conditions. Litter was mostly detected with the naked eye, but regular scans of waters away from the ship were made with 8 32 binoculars to detect more distant debris. Binoculars or images taken with a digital SLR camera with a 500 mm telephoto lens were used to identify litter items, but some submerged items could not be identified. Natural debris (mainly large seaweeds) and drifting biota (epipelagic jellyfish Physalia physalis and Velella velella, bubble raft shells Janthina spp. and buoy barnacles Dosima fascicularis) were also counted. day (mainly by one observer, but with assistants standing in for occasional short breaks), with location and environmental parameters (wind speed, direction, sea surface temperature, salinity) recorded from the ship's data logger at the start and end of each hour. Track length was calculated from the ship's positional record to measure the distance covered during observations. To compensate for the patchy nature of floating debris at sea, data were pooled into transects of roughly 50 km (2–3 h of transects), which sample 2.5 km2 of sea surface given an effective transect width of 50 m. This sample scale was deemed suitable to average out smallscale aggregations of floating debris associated with fronts and local convergence zones (Lebreton et al., 2012; Ryan, 2013). Density estimates per 50-km transect as well as environmental conditions were compared among regions using one-way ANOVA with posthoc Newman–Keuls range tests to assess which regions differed significantly. The size of items and their distance from the side of the ship were estimated following Ryan (2013). Distance from the ship was placed into one of seven categories: 0 = 0–10 m from the side of ship, 1 = 11–20 m, 2 = 21–30 m, 3 = 31–40 m, 4 = 41–50 m, 5 = 51–100 m, and 6 = >100 m. The size of each debris item was allocated to one of five size classes based on its longest dimension: a < 5 cm, b = 5–15 cm, c = 15–30 cm, d = 30–60 cm, and e > 60 cm. Minimum item size was approximately 1–2 cm. Litter items were placed into one of the following categories based on the type of material and likely use of the item. Plastic items were divided into packaging (bottles, tubs/cups, lids and lid-rings, bags, food. wrapping, polystyrene, and other packaging such as packing strips, etc.), fishery-related plastic articles (ropes and nets, floats, and other fishing gear such as fish trays), other plastic user items (designed for repeated use, unlike packaging, divided into three categories: buckets, shoes/gloves/hats, and other user items), and finally, other plastic pieces (mostly fragments of items that could not be identified, but some items too deep to see clearly also were placed into this category). Non-plastic items were divided into glass jars/bottles, light bulbs, tins/aerosols, cardboard/paper, and wood (worked timber). The incidence of encrusting biota on litter items was recorded. The effect of item size on detection distance was determined from the frequency of encounters in relation to distance from the ship" (Ryan, 2013).

Description of ship-based observation of floating litter from Arcangeli et al. (2017)

"Surveys were performed by the side of the navigation bridge (17–25 m high) with best visibility and in the vicinity of the bow in order to avoid the turbulence generated by the bow itself. The equipment consisted of: binoculars, GPS, range finder, digital camera, and recording data sheet. A dedicated handheld GPS was used for automatically recording the survey tracks at the finest resolution, marking the beginning/ending points and locations of floating objects. The observation was made by naked eye, and the binocular was used to confirm, when in doubt, the types of items. Only items bigger than 20 cm (longest dimension) were recorded. This size limit was chosen after the initial calibration during the testing phase. It comprises several common litter items (i.e. plastic drink bottles, gloves, shopping bags, tableware) and, most importantly, was the size that undoubtedly could be seen from the mean height of a ferry within the detection strip. Monitoring was carried out only in optimum weather conditions (≤2 of the Beaufort scale), in a range of speed 19–25 knots, and with a mean duration of 1.5 h to avoid fatigue of the observer. A fixed strip width (Thiel et al., 2003;

Pyle et al., 2008; Topcu et al., 2010) was defined at the beginning of the effort, from 25 m up to a maximum of 100 m (Shiomoto and Kameda, 2005) depending on sea state, glare, and speed, requiring that all items > 20 cm were surely sighted. The strip was estimated using a range finder and was regularly checked during the effort. The identification of a predetermined strip width and size classes was chosen as a best method given the spatial scale of the study, to simplify the data collection in order to reduce the risk of missing items and to concentrate on object characterization; density data were normalized taking into account the strip width (see Data analysis section). Identification and categorization of items was organized by material (Artificial polymer material, Glass, Processed wood, Metal, Textile, Paper, Rubber, Natural debris) and general names, according to the MSFD master list (Galgani et al. 2013)[20]. While not used in this present study for each item, source (land, sea, undefined) and buoyancy (positive, negative, neutral) were also recorded; details about the production sector, color, and object state (entire, fragment) were recorded when possible" (Arcangeli et al. 2017).

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[20] Can be downloaded from https://publications.europa.eu/en/publication-detail/-/publication/76da424f-8144-45c6-9c5b-78c6a5f69c5d/language-en

APPENDIX 2

Description of marine plastic sample treatment (Reisser et al. 2015)

The sample was transferred to a 150 µm sieve and stored frozen in aluminium bags for transportation. Samples were washed into clear plastic containers filled with filtered seawater. Floating macroscopic plastics were counted and characterised in gridded petri dishes for at least 1 hour per sample. The plastics were then washed with deionised water, transferred to aluminium dishes, dried at 60°C, and weighed. The frame dimensions and readings from a mechanical flowmeter was used to estimate the number/milligrams of plastics per m^3

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