A Global Data and Information Platform to Monitor Marine Litter and Inform Action

Emily Smail[1,2,3], Jillian Campbell[4], Daniel Takaki[2,5], Audrey Hasson[2,6], René Garello[2,7], Anne Bowser[8], Dany Ghafari[4], Hans-Peter Plag[2,9], Samy Djavidnia[2,10], José Moutinho[11], Ghada El Serafy[12,13], Alessandra Giorgetti[14], Matteo Vinci[14], Maria Eugenia Molina Jack[14], Kate Larkin[15], Dawn J. Wright[16], Francois Galgani[17], Konstantinos Topouzelis[18], Stewart Bernard[19], Guido Colangeli[20], Leah Mupas Segui[2,3],Linwood Pendleton[21,22,23], Caroline Kamu[4], Marta Ottogali[4], Llorenç Milà i Canals[4], Morgan Simpson[24], Armando Marino[24], Imanol Zabaleta[25], Malcolm Heron[27], Eric P. Chassignet[28]

[1]University of Maryland Earth System Science Interdisciplinary Center, College Park, MD, USA

[2]GEO Blue Planet, College Park, Maryland, USA

[3]NOAA/NESDIS/SOCD, College Park, Maryland, USA

[4]UN Environment Programme (UNEP), Nairobi, Kenya

[5]NOAA/NOS/Office of Response and Restoration, Silver Spring, MD

[6]Mercator Ocean International, Toulouse, France

[7]IMT Atlantique, France

[8]Woodrow Wilson International Center for Scholars

[9]Department of Ocean, Earth and Atmospheric Sciences and Mitigation and Adaptation Research Institute, Old Dominion University, Norfolk, VA, USA

[10]European Maritime Safety Agency, Lisbon, Portugal

[11]AIR Centre (Atlantic International Research Centre), Portugal

[12]Deltares, Delft, The Netherlands

[13]Technical University of Delft, The Netherlands

[14]Istituto Nazionale di Oceanografia e di Geofisica Sperimentale - OGS, Trieste, Italy

[15]EMODNET, Oostende, Belgium

[16]Environmental Systems Research Institute (Esri), | Redlands, CA, USA

[17]IFREMER, Bastia, France

[18]Department of Marine Sciences, University of the Aegean, Greece

[19]CSIR, Cape Town, South Africa

[20]EO Ground Segment Infrastructure and Operations Management Division, Directorate of Earth Observation Programmes, Frascati (RM) Italy[14]

[21]Ocean Knowledge Action Network

[22]Ocean Data Foundation and REV Ocean, Oslo, Norway

[23]IUEM/LABEXMER, Brest, France

[24]Global Change Institute, University of Queensland, Brisbane, Australia

[25]The University of Stirling Biological and Environmental Services, Stirling, UK

[26]RWA Group, Zürich, Switzerland

[27]James Cook University, Townsville, Australia

[28]Center for Ocean-Atmospheric Prediction Studies, Florida State University, Tallahassee, FL, USA

Disclaimer

The scientific results and conclusions, as well as any views or opinions expressed herein, are those of the authors and do not necessarily reflect the views of the NOAA or the US Government.

Funding

The work was in part supported by the NOAA/NESDIS Center for Satellite Applications and Research (STAR) and the EU4OceanObs Action funded through the Partnership Instrument managed by the European Commission's Service for Foreign Policy Instruments and implemented by Mercator Ocean International.

Introduction

Marine litter consists of any persistent, manufactured or processed solid material discarded, disposed of or abandoned in the marine and coastal environment. All of the world's oceans and seas contain marine litter, even in remote areas far from human contact. This is due to the transboundary nature of litter and to ocean dynamics. Increasing amounts of discarded solid waste, paired with the slow degradation of most items, have led to a gradual increase in marine litter found at sea, on the sea floor and on coastal shores. This has become an economic, environmental and aesthetic problem, as well as a threat to human health, and poses a complex and multi-dimensional challenge[1].

Marine plastics are of particular interest since plastic production has increased more than 22-fold in the last 50 years, while the global recycling rate of plastics was only an estimated 9 per cent in 2015 (Geyer, Jambeck, and Law 2017). The rise in plastic production and its associated mismanaged waste are a growing threat to marine environments: an estimated 5-13 million tons of plastic from land-based sources reach marine environments annually (Jambeck *et al*., 2015).

In Sustainable Development Goal (SDG) 14, Target 14.1, the consistent need to monitor and report marine litter is recognized: “by 2025, prevent and significantly reduce marine pollution of all kinds (…)”. This target provides a deadline for progress in reducing marine litter and is further informed by SDG 14.1.1b on plastic debris. The UN Environment Programme (UNEP) has suggested four core subindicators for SDG 14.1.1b:

1) Plastic debris washed/deposited on beaches or shorelines (beach litter)

2) Floating plastic debris and debris in the water column

3) Plastic debris on the seafloor/seabed

4) Plastic ingested by biota (e.g. sea birds) (optional).

The topic of marine plastics is also addressed in at least four UN Environment Assembly (UNEA) resolutions (including UNEA-1 in 2014, UNEA-2 in 2016, UNEA-3 in 2017 and UNEA-4 in 2019). However, large gaps in knowledge prevent us from understanding the full extent of the presence of marine litter and microplastics. Reliable figures to quantify the volume of plastics entering the ocean are lacking, as are information on the accumulated volume of plastics in the marine environment, detailed maps of source and sink locations of plastics, and basic data on global microplastics. A wide range of existing data stemming from remote sensing, from citizen science and from in situ monitoring must therefore be used. And yet, much of the research in this field is still in the early stages with only data related to beach litter available in many regions (UN Environment Programme [UNEP] 2018b). Similarly, despite a growing interest for monitoring through remote sensing, citizen science and in situ data collection, non-comparable monitoring approaches in each of these areas limit the development of indicators and of spatial and temporal assessments (Galgani, Hanke and Maes 2015).

[1] https://www.unep.org/explore-topics/oceans-seas/what-we-do/working-regional-seas/marine-litter

While standardizing the methods used to monitor marine litter will greatly improve understanding, integrated and comparable data will also be needed to develop and report the indicators. Much of the data on marine litter is contained in peer-reviewed journals, databases hosted by non-governmental organizations (NGOs) and through government authorities. As suggested by Galgani *et al*. (2015) and Maximenko *et al.* (2019), a joint international database would facilitate the collection of data on marine litter indicators and improve standardization and comparability levels. Policy decisions on marine litter reduction and studies on the efficacy of mitigation efforts would also be strengthened.

In 2019, the UNEA called for the creation of a marine litter platform in resolution UNEP/EA.4/Res.6 operative paragraph 3 (UNEP 2019).

> "to strengthen coordination and cooperation by establishing, subject to the availability of resources and building on existing initiatives, a multi-stakeholder platform within the United Nations Environment Programme to take immediate action towards the long-term elimination, through a life-cycle approach, of discharges of litter and microplastics into the oceans".

The result was the creation of a data and information platform known as the Global Partnership on Marine Litter (GPML) Digital Platform[2]. The GPML Digital Platform is a multi-stakeholder platform that partly relies on open-source technologies and approaches. It compiles and crowdsources a variety of resources, while also integrating data and connecting stakeholders for them to guide and coordinate actions on ad hoc and regularly bases. This is achieved through three clusters of technical components designed to enable knowledge exchange, to connect stakeholders, and to share data through a data hub. While each component can function as a stand-alone platform, the conceptual architecture supports interlinkages between the different components to ensure a user-friendly experience. For instance, users will be able to search across technical components to access a wide range of materials in order to support stakeholders' needs: there will be a range of published scientific research, information on technical innovations, and public outreach materials.

The goal of the data hub is to offer a coordinated point of entry for stakeholders to find data and information across the full plastic life cycle, from source to fate. The GPML Digital Platform data hub will contain two interlinked platforms: a data catalogue, including a metadata repository and an Application Programme Interface (API) management system, and a Geographic Information Systems (GIS) portal. Like the broader GPML Digital Platform, the data hub will follow a multi-year, phased release. In the early phases, UNEP and GPML partners will curate the data sets selected for the GPML Digital Platform. Over time, a range of data providers will be encouraged to submit relevant data and information for review and eventual publication in the data hub. In some cases, data may be directly hosted by the GPML Digital Platform. In other cases, the GPML Digital Platform's data catalogue and API management system will enable access to resources hosted by other UNEP platforms, such as the World Environment Situation Room (WESR), and resources maintained by a range of external partners.

[2] https://digital.gpmarinelitter.org/

This White Paper seeks to provide a scientific and technical foundation for the implementation of the GPML Digital Platform, particularly the data hub. Its primary focus is marine litter monitoring. This being only one part of the picture, an introductory list of additional topics is subsequently presented. While necessarily limited in scope, this White Paper provides important scientific and technical groundwork for the GPML Digital Platform. It also serves a range of stakeholders in the research, policy and education communities who view marine litter as an entry point towards understanding and addressing the plastic pollution life cycle. This paper is organized as follows:

Section One provides a summary of existing and developing monitoring technologies for marine litter.

Section Two provides a summary of existing marine litter databases and major published data sets.

Section Three explores indicators for marine litter monitoring.

Section Four explores life cycle indicators for plastic litter and linkages with other monitoring initiatives across the plastics value chain.

Section Five provides a summary of the relevant current and emerging platforms.

Section Six outlines the proposed features of a global platform to monitor marine litter and to inform action. Next steps and required resources are presented, and insights into aspirational future developments are disclosed.

1. Monitoring Technologies

Marine litter monitoring must be routine and standardized for long-term changes in pollution to be understood and for effective mitigation strategies to be developed. Due to marine litter's diverse nature, sources and impacts, a variety of monitoring technologies and methods are required. Recent efforts to compile information on ongoing procedures and on recommendations for global, standardized monitoring methodologies include: the Joint Group of Experts on the Environmental Aspects of Marine Environmental Protection (GESAMP) Guidelines for the monitoring and assessment of plastic litter and microplastics in the ocean (Joint Group of Experts on the Environmental Aspects of Marine Environmental Protection [GESAMP] 2019), and the Global Manual on Measuring SDG 14.1.1, SDG 14.2.1 and SDG 14.5.1 (UNEP 2021) (UN Environment Programme, 2021). Alongside partners such as Ocean Conservancy, UNEP is also working on developing harmonized monitoring methodologies in an effort to use citizen science to collect beach litter data for SDG reporting and other assessment processes.

Existing marine litter monitoring technologies must be understood before implementing and further developing new monitoring approaches. These technologies, and the ways in which they are used to collect the data needed for a global view of marine litter, are described in this section. Eleven of them are presented, falling under three main categories:

- In situ technologies: they rely on existing measuring techniques but require complex sampling. Sampling methods are very diverse (trawls, booms, pumps, etc.) and add a layer of complication to the monitoring of marine debris. In situ observations are vital to ground truth remote sensing and simulated products.
- Remote sensing technologies: they provide global surface observations but are limited by spatial resolution and revisit time (temporal resolution). Specific developments are needed for the detection of marine debris.
- Simulated products: they give access to continuous estimations of marine debris in the four dimensions but rely on the representation of physical processes.

For an overview of the observing system technologies required to develop a future integrated marine debris observing system, see Maximenko *et al.* (2019).

In this paper, technologies are grouped based on their applicability in relation to the size categories prescribed in the GESAMP 2019 methodology (Table 1.1). In addition, technology readiness levels (Table 1.2) are assigned based on the National Oceanic and Atmospheric Administration (NOAA) policy on research and on the development of transitions aimed at prioritising the standardization and the integration of data. Readiness levels are defined by the NOAA as "a systematic project metric/measurement system that supports assessments of the maturity of research and development projects from research to operation, application, commercial product or service, or other use and allows the consistent comparison of maturity between different types of research and development projects" (National Oceanic and Atmospheric Administration [NOAA] 2017).

Table 1.1. Size categories for routine marine litter monitoring (GESAMP 2019)

Size Category	Size Range
Mega	> 1 m

Macro	25 mm - 1 m
Meso	5-25 mm
Micro	<5 mm

Table 1.2. Technology readiness levels (NOAA 2017)

Readiness Level	Readiness Level Defined
1	Basic research and/or development principles observed and reported
2	Formulation of a concept for operations, application, commercialization or other uses for societal benefits
3	Proof-of-concept (established viability)
4	Validation of a system, process, product, service or tool in a laboratory or in another experimental environment
5	Validation of a system, process, product, service or tool in a relevant environment
6	Validation of a system, process, service, or tool in a relevant environment (demonstrated potential)
7	Demonstrated prototype in an operational or other relevant environment (functionally demonstrated in a pseudo real world environment)
8	System, process, product, service, or tool completed and “mission qualified” through testing and demonstrated in an operational or other relevant end-to-end environment (demonstrated functionality)
9	System, process, product, service or tool approved for deployment and use in decision making (transition complete)

1.1 Human Observers

Visual human observation is the most widespread and technically simplistic way of collecting marine litter data. Human observers monitor beach/shoreline litter, floating litter, water column litter, seabed/seafloor litter, marine litter ingestion/entanglement and sources of marine litter. Human observation is most appropriate for macro- and mega-litter based on what is consistently visible to the naked eye (GESAMP 2019).

Protocols and guidelines to monitor beach/shoreline litter through visual observation vary widely depending on the organization (Arctic Council 2015; Cheshire *et al*. 2009; European Commission Joint Research Council 2013; Northwest Pacific Action Plan Special Monitoring and Coastal Environmental Assessment Regional Activity Centre [NOWPAP CEARAC] 2007; Opfer, Arthur, and Lippiatt, 2012; UN Environment Programme 2016b). The analysis of beach/shoreline litter is typically done through visual transects and by counting items collected during beach cleanups. Some organizations employ mobile applications (such as citizen science applications) to facilitate data entry and reporting. These include: the NOAA Marine Debris Tracker App[3], the European

[3] https://marinedebris.noaa.gov/partnerships/marine-debris-tracker

Environment Agency's Marine LitterWatch App[4], and the Ocean Conservancy's Clean Swell App[5].

Offshore floating litter are typically monitored by human observers from ships during transects. While different methods are used, an important one consists of visually surveying floating marine litter from ships; it has been practiced for almost fifty years (GESAMP 2019). These observations are generally limited to mega- and macrolitter. For the human observation of water column litter and for the analysis of mesolitter, materials must be collected with net tows. Observers sort items by type and size and analyse them by count and/or weight (GESAMP 2019; Lebreton *et al*. 2018).

In shallow waters, SCUBA divers can monitor and collect marine litter by conducting underwater visual surveys. Distance and transect sampling are commonly used to measure marine litter density (Buckland, 2001; Galgani, Hanke, Werner and De Vrees, 2013; Spengler and Costa 2008). This method is limited in its water depth to 20-30 metres at most. It requires SCUBA equipment, skilled observers, and is most appropriate for macrolitter and larger items. In addition to professional surveyors, recreational divers also play a role in surveys. For example, PADI AWARE's Dive Against Debris programme[6] encourages divers to collect and report marine litter found underwater. Divers are asked to collect and observe at the same locations to provide further data validation (GESAMP 2019).

The visual reporting of abandoned, lost or otherwise discarded fishing gear is also an important part of monitoring entanglement and entanglement risk. The observational methodology when monitoring entanglement is overall straightforward. Reports should include the size, location, impacted species or habitat, and the type of litter (GESAMP 2019). Networks known for reporting entanglement and litter with entanglement risks include the NOAA SOS Whale Network[7] and the International Association of Geophysical Contractors Marine Debris and Ghost Net Initiative[8]. In a study on pollution incidents reported by observers aboard fishing vessels in the Western and Central Pacific Ocean, 71-80 per cent of reported incidents were documented as waste dumped overboard, and only 13 -17 per cent as abandoned, lost or dumped fishing gear depending on the type of vessel (Richardson *et al*. 2017). Essential information on the types and amounts of pollution caused by shipping could be generated by an increase in observers collecting data aboard fishing vessels and other boats. Using navigation logs to report on-board pollution incidents is seen as an appropriate method that could be deployed through an expanded, cross-fleet observer programme that would be quality-controlled and consistent with Global Information Systems.

The human observation of marine litter sources includes the monitoring of floating riverine inputs to the ocean and the reporting of leakages from waste sites. In Europe, the human observation of floating macrolitter on the river surface is a method used by the Riverine Litter Observation

---

[4] https://play.google.com/store/apps/details?id=com.litterwatch&hl=en_US

[5] https://www.coastalcleanupdata.org/#download

[6] https://www.diveagainstdebris.org/

[7] https://www.westcoast.fisheries.noaa.gov/protected_species/marine_mammals/disentanglement_network.html

[8] https://www.iagc.org/ghost-net-contact-form.html

Network[9]. Surface water speed and turbulence (González-Fernández and Hanke 2017) constitute challenges when conducting visual observations of floating litter in riverine environments. An accumulation of litter in aquatic vegetation (Schreyers *et al*. 2021; van Emmerik *et al*. 2019) is also a problem. Human observers conduct terrestrial litter surveys of inland, riverine and coastal areas to establish and estimate links between land-based waste management and waste losses into the marine environment (Schuyler *et al*. 2018).

Data collected by human observers have been tested and used extensively for analysis in regions including the North-East Atlantic, the Baltic Sea and the United States (European Commission Joint Research Commission 2013; Hardesty *et al*. 2017; OSPAR Commission 2017).However, since standardized global protocols/processes for the collection of data using human observations have not yet been implemented, we assigned human observers a general readiness level of seven, though select observational methodologies and data types may achieve higher readiness levels (as an example, citizen science data collected through beach cleanup campaigns are being used in SDG reporting at global and regional levels).

Readiness Level: Human Observers

7: Demonstrated prototype in an operational or other relevant environment (functionally demonstrated in a pseudo real world environment)

1.2 Microscopy

Microscopy is used to analyse meso- and microlitter. Its applications pertain to the monitoring of beach/shoreline litter, floating litter, water column litter, seabed/seafloor litter, marine litter ingestion, and sources of marine litter. Sample collection for beach/shoreline litter is typically done by collecting sediment with a spoon, spoon trowel or sediment core and passing the sample through various sieves depending on the size class of interest (GESAMP 2019). Floating/water column samples require filtration, either after the samples are collected, or by using in situ filtration equipment (Choy *et al*. 2019; GESAMP 2019). Samples to study plastic ingestion are generally drawn from dead organisms or from items associated with live animals, such as regurgitated pellets, scat and nesting materials (GESAMP 2019). In addition, submersible microscopes (holographic (4deep) or cytometric) can autonomously measure microplastics in typical outflow areas. The use of digital holographic microscopy, paired with ongoing advancements in deep learning techniques, can provide new opportunities for the use of coherent imaging systems in many fields, including for the study of microplastic pollution (Rivenson, Wu and Ozcan 2019).

Microplastics are often subject to microscopic analysis. Sample preparation methods and analysis vary widely depending on the sample type (water sample, sediment sample, ingested sample) and microscopy type (light microscopy, electron microscopy, etc.). Prior to analysis, microplastics typically undergo a chemical digestion process to remove all organic matter from samples.

[9] https://mcc.jrc.ec.europa.eu/main/dev.py?N=simple&O=394&titre_page=RIMMEL%2520observation%2520Network

Chemical digestion methods, along with their advantages and disadvantages, are broken down into three general categories: oxidative, acidic, alkaline/basic and enzymatic (Table 1.3).

Table 1.3. Advantages and disadvantages of extracting and purifying microplastics in organic matrices (GESAMP 2019)

Purification Method	Advantages	Disadvantages
Oxidative Digestion	• Inexpensive	• Temperature needs to be controlled • Several applications may be needed
Acid Digestion	• Rapid (24 hr)	• Can attack some polymers
Alkaline Digestion	• Effective • Minimal damage to most polymers	• Damages cellulose acetate
Enzymatic Digestion	• Effective • Minimal damage to most polymers	• Time-consuming (several days)

Methods to extract ingested litter from samples vary widely (Courtene-Jones *et al*. 2019; GESAMP 2019; van Franeker *et al*. 2011; Zhao, Zhu and Li 2016). A standardized approach is needed to ensure consistency.

Another challenge in the analysis of marine litter by microscopy is the potential for sample contamination. Meticulous procedures to avoid sample contamination are implemented in research studies, including: burning off contaminants from glassware, pre-filtering reagents using glass fibre filters, handling samples in laminar flow hoods, and analysing blanks to estimate potential contamination (GESAMP, 2019; Wesch *et al*., 2017; Zhao, Zhu and Li 2016).

Analysis by light microscopy typically consists of counting microplastics and characterizing their colour, shapes and sizes (Vandermeersch *et al*. 2015). Scanning electron microscopy can provide additional details regarding the surface texture of particles. However, due to the intensive processing and analysis it requires, it is only viable for small quantities of samples (GESAMP 2019). Overall, the various microscopic approaches have trade-offs in terms of precision and of the accuracy of material identification, with some methods potentially underestimating microplastics pollution due to false positives (Zarfl 2019). The protocols to cleanly and accurately collect, process and analyse samples for microscopy are being developed and implemented by individual research teams; global standardized protocols have not been implemented. We have therefore assigned a readiness level of four to light microscopy.

Readiness Level: Microscopy

4: Validation of a system, process, product, service or tool in a laboratory or in another experimental environment

1.3 Weighing

Techniques meant to calculate marine litter mass are frequently used for the analysis of macro, meso and microlitter, beach/shoreline litter, floating litter, water column litter, seabed/seafloor litter, marine litter ingestion/entanglement and sources of marine litter (Lebreton *et al*. 2018; Lebreton *et al*. 2017; NOAA Marine Debris Programme 2015). Mega-debris is difficult to weigh, compounded by the fact that it is heavily colonized by marine life, as in the case of fishing nets, and is critical to remove. Entangled sand or debris pose an additional challenge when attempting to weigh larger items accurately. Consistency when drying samples is also an issue (GESAMP 2019). Weighing sea floor debris is a mandatory form of assessment in some regional plans, but it presents limitations when the density of pieces is heterogeneous. Significant overestimations or underestimations can be made when there is a presence of Styrofoam, large pieces of trawl, wreck or containers. Weighing techniques for macro and mesolitter tend to be simple; they involve scales and drying ovens (Ryan *et al*. 2014).

Determining the accurate mass (or gravimetric analysis) of microplastics requires proper sorting, extraction and sample purification, as outlined in the light microscopy section. Consistency in mass measurements have shown to be satisfactory across labs when the same method is applied for analysis (NOAA Marine Debris Program 2015). A critical aspect to consider for mass calculation is that most methods for the analysis of microplastics include a density separation step where settled solids are discarded, and only floating solids are analysed (GESAMP 2019; NOAA Marine Debris Program 2015). Scanning electron microscopy images have shown extensive fouling on microplastics by microbial communities (Zettler, Mincer, and Amaral-Zettler 2013) which can cause plastic debris to sink (Andrady, 2011). It is therefore important to follow the proper steps prior to the analysis of the weight of microlitter to ensure that biofouling does not lead to an underestimate.

We assigned a technology readiness level of three to weighing marine litter, as standardized approaches to removing sand, biofouling and water residue from samples have not been implemented, and as methods often vary widely or are not specifically reported.

Readiness Level: Weighing Litter

3: Proof-of-concept (established viability).

1.4 Spectroscopy

Particle discrimination – between organic and inorganic matter and between various types of plastics – can take place through spectroscopy, the analysis of absorption and light-scattering, due to the fact that these materials produce different spectral signals (Lenz *et al*. 2015). While waste management and recycling industries have utilized near-infrared spectroscopy to identify plastics since 1998, the use of spectroscopy to analyse marine litter is fairly recent (Choy *et al*. 2019; Yu *et al*. 2019; Zhu *et al*. 2019; Zulkifley *et al*. 2014).

Spectroscopy protocols for the study of microplastics in the marine environment centre on specific techniques, such as Fourier Transform Mass Spectroscopy (FTIR) and Laser Raman Spectroscopy (Choy *et al*. 2019; GESAMP 2019; Yu *et al*. 2019). New spectroscopic approaches, such as staining and semi- or fully-automated spectroscopic analyses, are currently under development and are being tested by several research groups (GESAMP 2019). As sample treatment and study methods for the identification of marine plastics by spectroscopy are still in their development and automation phases, we have assigned a readiness level of three to spectroscopy.

Readiness Level: Spectroscopy

3: Proof-of-concept (established viability).

1.5 Mass Spectrometry

Mass spectrometry measures the mass-to-charge ratio of ions in a sample, providing information on the sample's chemical composition. Mass spectrometry techniques used to study microplastic particles include thermal extraction and desorption gas chromatography mass spectrometry (TED-GC-MS) and pyrolysis gas chromatography mass spectrometry (Py-GCMS). These technologies require the thermal degradation of plastics, the separation of degradation products through chromatography, and the analysis of the products with mass spectrometry (Dumichen *et al*. 2017; GESAMP 2019). Polymers and chemicals associated with plastic samples can be identified through mass spectrometry (Kuhn *et al*. 2018). For example, inductively coupled plasma spectroscopy (ICP-MS) can identify metals associated with plastics, which then provides information on hazardous metals associated with microplastics (Kuhn *et al*. 2018). The application of mass spectrometry to the analysis of marine litter is still in the research and development phase; but since the technique has been widely implemented in many other fields, we assigned a readiness level of three to mass spectrometry.

Readiness Level: Mass Spectrometry

3: Proof-of-concept (established viability).

1.6 Visual Imagery and Video

Visual imagery is collected through ship-based cameras, unmanned aerial vehicles (UAVs), balloons, high altitude pseudo-satellites (HAPS), remotely piloted aircraft systems (RPAS), and satellites. Fixed-wing drones increase the distance and duration of drone flights while blimps offer longer stable flights. Model studies should guide the use of both drones and blimps as they present limitations in terms of timing and spatial coverage.

The use of small aircrafts, drones, UAVs, balloons, and satellites hold promise for the analysis of beach litter and sea surface litter. The advantages of aerial technologies include: images retrieved from hard-to-access areas, more rapid and complete coverage and high-resolution imagery. Aerial imagery can either be processed manually or automatically through machine learning tools that are currently in development (Deidun *et al*. 2018; Martin *et al*. 2018; Moy *et al*. 2018). The various aerial technologies have strengths and weaknesses based on cost and coverage. For example, UAVs provide ultra-high resolution images but some regions prohibit them from flying over people, thus limiting survey locations (Moy *et al*. 2018). Using ground measurements to corroborate results is important for these technologies to develop. Further tests are needed to understand the limitations and appropriate applications of aerial technologies for the monitoring of beach litter (Deidun *et al*. 2018; Moy *et al*. 2018).

An emerging approach to monitor floating marine litter consists of photographing marine litter using a camera that is fixed to a vessel's bow or mast. Observations can be multiplied by using high-resolution cameras and other sensors (such as Lidar) that are mounted on ships; paired with artificial intelligence, in situ observations can take place in real time. Further testing is needed to validate the consistency of these sensors. In addition to ship-based cameras, autonomously operated vehicles (AOVs) have the potential to monitor surface/subsurface marine litter at sea. For example, Wave Gliders, which use wave energy for propulsion, are often equipped with video cameras that can be used for marine litter quantification (Galgani *et al*. 2013).

Remotely operated vehicles (ROVs), such as submarines or manned submarines, can view seabed litter plastic and draw sediment cores and seabed samples to detect the presence of microplastics and other litter (Woodall *et al*. 2014). ROVs are often preferable for litter surveys on continental slopes, uneven terrain or on the deep seafloor. Litter can accumulate in certain locations on the seafloor such as in coastal canyons and in other areas with steep slopes, rocky bottoms, or ocean trenches. These areas specifically benefit from and often necessitate the use of ROVs to observe and/or collect marine litter. Video cameras can record high-resolution images, while other light devices, such as lasers, can measure transect areas, object size and distances on the seafloor. Learning algorithms intended to gain a more successful vision detection of litter will be beneficial, as autonomous underwater vehicles explore and map litter. While ROVs have proven useful, limitations exist in the form of high operational costs and of specific skill sets needed for both operations and observations.

A variety of technologies, with varying levels of effort, scale, and accuracy, exist to estimate riverine sources directly. DRONET[10] is developing a standard method for drone-based surveys of plastics in river basins.

Visual imagery and video are used in relevant environments, but they require standardization. We have accordingly assigned a readiness level of six to the analysis of marine litter by visual imagery and video.

Readiness Level: Visual Imagery and Video

6: Validation of a system, process, service or tool in a relevant environment (demonstrated potential).

1.7 Synthetic Aperture Radar

The presence of marine litter and its displacement can potentially be monitored by a satellite-borne Synthetic Aperture Radar (SAR). SAR provides high-resolution radar reflectivity to an

[10] https://www.theplastictide.com/blog-1/2018/4/22/launching-the-marine-litter-dronet

observed scene, and thus to surface roughness (Garello *et al*. 2019). This measurement provides information on ocean parameters such as topography, surface waves, winds and currents. These parameters, in turn, provide direct identification of convergent fronts where floating debris accumulate, and offer information (ancillary data, see below) on marine debris movement. Larger floating objects can also be directly detected by SAR or through secondary surface wave patterns. However, false alarms remain a significant obstacle. Interestingly, SAR is also sensitive to the presence of substances that can dampen surface waves, such as oil spills, algal blooms, megalitter (or an accumulation of smaller marine debris) or any other substances influencing the surface tension of water. These are often referred to as surfactants.

There are two main SAR-based methodologies that could lead to the detection of plastics on the water surface: a) the direct detection of large plastic debris and b) the detection of surfactants associated with microplastics

a) Megalitter: SAR has been proven to detect medium to large metallic objects on the sea surface such as ships. However, there is still a debate on the impact of large concentrations of plastic debris on SAR pixels brightness. In an experiment by Topouzelis, Papakonstantinou and Garaba (2019), the Sentinel-1 satellite mission SAR instrument demonstrated an ability to detect large square targets of plastic bottles, but only a limited capacity when detecting other targets (different types of plastic, shapes etc.).

b) Microplastics: Plastic in the ocean is heavily colonized by microbes that produce substances and biofilms known as surfactants (Mouchot and Garello 1998). Davaasuren *et al*. (2018) showed that surfactants, such as sea-slicks and biofilms, were visible on Sentinel-1 SAR images as dark curved stripes. They hypothesized that these “stripes” occurred because of microbial colonization of microplastics and not algal blooms as chlorophyll-*a* concentration was low.

As the use of space-borne SAR for marine litter monitoring is still in the research and development phase, we have assigned a readiness level of one to SAR.

Readiness Level: Synthetic Aperture Radar

1: Basic research and/or development principles observed and reported.

1.8 Multispectral and Hyperspectral Imaging

Satellite remote sensing of beach litter and sea surface litter through multispectral and hyperspectral imaging is currently in the research and development phase. It is primarily made up of repurposed missions not originally designed for litter monitoring. Relevant satellite imagery for the remote sensing of beach and floating litter include visual imagery and spectral analysis.

The Copernicus Sentinel 2 satellite constellation will likely be the most valuable existing mission, thanks to its freely available data and relatively high-resolution (10m GSD) spectral radiometry with global coverage. Floating aggregations combining seaweed, sea foam, and macroplastics are detectable on subpixel scales. First steps towards a future monitoring system using statistical methods on spectral analyses were taken to identify macroplastics. Suspected floating plastics were successfully classified as plastics with 86 per cent accuracy (Biermann *et al*. 2020).

Commercially available satellite-borne hyperspectral sensors, such as HyMap, are also of relevance when detecting litter on beaches and rivers (Garaba and Dierssen 2018; Goddijn-Murphy *et al*. 2018). Very high-resolution satellite data are thus available for purchase but have low temporal resolution.

Research activities mapping the spectral signatures of marine plastics are underway and show some potential for the characterization of marine litter on beaches (Acuna-Ruz *et al*. 2018; Garaba and Dierssen 2018). Preliminary studies have shown that floating litter could be detected through the synergetic use of satellite images and UAVs (Topouzelis *et al*. 2019). Statistical indicators and density heat maps can be derived based on predefined requirements.

It is currently only possible to apply multispectral satellite remote sensing of plastic in the water column for larger elements that are on, or close to, the water surface. In all cases, and no matter the resolution, cloud cover and sea surface conditions affect the detection of debris. An initial assessment of the observation requirements needed to measure marine plastic debris from space can inform further sensor development (Martínez-Vicente *et al*. 2019).

Multispectral and hyperspectral satellite remote sensing of marine litter is still in the research and development phase, but it shows promising results for automation. We have therefore assigned it a readiness level of two.

Readiness Level: Multispectral and Hyperspectral imaging

2: Formulation of a concept for operations, application, commercialization or other uses for societal benefits.

1.9 GPS Tags and Transmitters

The direct tracking of floating marine items can be done by tagging debris with GPS tags and transmitters. The path of plastic can be retraced from source to fate by compiling the trajectories of marine litter. Debris can be tracked with Argo-tracking sensors or GPS devices, but these tools remain too expensive to be widely implemented. More affordable solutions could be found in 2021 with the arrival of the Kineis constellation by CLS[11][12], or with low-tech solutions such as PandaSat[13] offered by WWF. Large floating plastic debris are tagged and tracked using satellite

[11] https://mcc.jrc.ec.europa.eu/main/dev.py?N=simple&O=394&titre_page=RIMMEL%2520observation%2520Network

[12] https://www.cls.fr/en/kineis-unique-constellation/

[13] https://space-science.wwf.de/project/pandasat/

trackers that are deployed from vessels in the Pacific[2]. However, this method comes with the caveat of introducing electrical waste into the environment. For areas close to shore, cheaper and accurate IoT (Internet of Things) technology can be deployed using conventional 3G networks or Lora systems to provide better coverage when mobile data is lacking. The deployment of Iridium satellite connectivity is prohibitively expensive. As the method under development relies on readily available technology, a readiness level of three has been assigned to the use of GPS tags and transmitters to monitor the trajectory of marine litter.

> **Readiness Level: GPS tags and transmitters**
>
> **3:** Proof-of-concept (established viability).

1.10 Modelling

High-resolution hydrodynamic models are seen as critical in resolving key marine litter questions: they offer a platform on which very sparsely available observation data can be integrated and given much greater value (Martinez-Vicente *et al*. 2019). An analogous example is the assimilation of the relatively sparse Argo float data into the Mercator global forecast, which greatly improved the model's performance and reliability (e.g. Turpin, Remy and Le Traon 2016) Technical hurdles exist, such as: establishing a common currency, metrics and uncertainties among specific observation types and models, or establishing the necessary submesoscale global nests of models required for the appropriate simulation of litter dispersion and accumulation (D'Asaro *et al*. 2018). The combination of high-resolution numerical simulations and sparse observations will certainly play a major role in better understanding global dispersion and accumulation.

The primary aim of beach litter numerical modelling is to forecast litter accumulation on beaches in order to support cleanup efforts and to identify potential hot spots (Granado *et al*. 2019; Haarr *et al*. 2019; Yoon, Kawano and Igawa 2010). Predicting beach litter accumulation poses the challenge of needing a fine resolution ranging from a few hundred metres to one kilometre. This can limit forecasting along shorelines that lack high resolution data and oceanographic models (Critchell and Lambrechts 2016). Combining local and regional high-resolution circulation models with satellite-observed surface debris could provide a basis for the forecasts of beaching events. This approach is discussed to forecast the beaching of *Sargassum* and could be used for marine litter. While still in the research and development phase, research efforts are underway to develop and improve beach litter forecasts through new techniques such as machine learning and GIS-based tools (Critchell *et al*. 2015; Critchell and Lambrechts, 2016; Granado *et al*., 2019; Yoon *et al*., 2010).

Ocean surface currents are very important auxiliary inputs when modelling the trajectories of plastics in the ocean. The output from regional and global Ocean General Circulation Models (OGCM) can map and predict past and future trajectories of marine plastics (Chassignet, Le Sommer and Wallcraft 2019). The data used to generate modelled surface currents include wind speed and direction, mapped sea level anomaly (MSLA), and sea surface temperature, all of which are available almost daily (for a review, see Chassignet *et al*. 2018). This can assist in identifying sources and accumulation locations (Chassignet, Xu and Zavala-Romero 2021; van

Sebille, England and Froyland 2012). These models can be fine-tuned using data from buoys, High Frequency radar observations or GPS-tracked plastic pieces (van der Mheen, Pattiaratchi, and van Sebille, 2019; GESAMP 2019). International projects such as TOPIOS[14] are developing three-dimensional models of marine plastic (Stuparu *et al*. 2015).

Modelling is a promising approach to build on existing knowledge regarding litter dynamics in marine environments and to obtain new insights in areas where information is lacking (Thompson *et al*. 2009). For example, data on the abundance of plastic litter on the seabed is very limited. It is also assumed that substantial quantities of plastic litter have accumulated in the natural environment due to the continued input of marine litter over the last decades; however, the location of possible accumulation areas is not well delimited. The modelling approach provides a link between the source and the fate of microplastics. By describing the pathways of microplastic, an overview of estimated accumulation areas is possible and can be a helpful tool for guided monitoring and data collection campaigns (Chassignet *et al*. 2021).

Most models do not fully account for the life cycle of plastic at sea, nor do they consider the specifics linked to litter size, or differences in windage and biofouling. In the hydrodynamic models, there are large uncertainties associated with ocean currents, and with winds and waves used to move the marine litter. As marine litter models are presently being developed on existing particle models but need additional development, we have assigned a readiness level of four to modelling.

Readiness Level: Modelling

4: Validation of a system, process, product, service or tool in a laboratory or in another experimental environment.

1.11 Ancillary Data

Ancillary data provide essential information to support the monitoring and the study of marine debris dispersion. Winds, waves, and surface ocean currents transport marine debris on a global scale to the first order. Eddies and density fronts associated with river plume edges determine the finer scale distribution of marine debris. The topology of the environment steers processes of stranding, sedimentation, and resuspension, and, thus, also drives marine debris dispersion. A thorough review of the different processes governing the transport of floating marine plastic debris was conducted by the SCOR-FLOTSAM working group (van Sebille *et al*. 2020).

Studying the data from these physical parameters give indications on the possible distribution of marine debris. The probability of marine build-up in specific locations could be inferred in near real-time and could provide clues for targeted monitoring via other means. With the development

[14] http://topios.org/

of artificial intelligence, novel opportunities are arising to take greater advantage of the variety of available data.

Ancillary data include the observation of the parameters described above by in situ technologies, such as Argo floats, oceanographic moorings or equipment mounted on vessels; by remote-sensing tools such as coastal High Frequency Radars, active and passive satellite-borne instruments or equipment mounted on drones and airplanes, and by hydrodynamic modelling.

Since ancillary data used to support marine litter monitoring are still in the research and development phase but are based on operational observing systems, we have assigned them a readiness level of two.

Readiness Level: Ancillary Data

2: Formulation of a concept for operations, application, commercialization or other uses for societal benefits.

Table1.4. Summary of marine litter monitoring techniques

Technique	Type	Readiness Level	Size Class	Application Area	Pros	Cons
Human eye	In situ	7	Mega and macro litter	• Beach/shoreline litter • Floating/water column litter • Ingestion of marine litter/entanglement • Sources of marine litter	• Advanced technology not required • Can be implemented by citizen science volunteers • Well-developed methods and studies exist	• Depends on regular sampling and on a commitment to human resources • Dependent on human error • Resource and time intensive • Requires global agreement and the implementation of comparable methods
Microscopy	In situ	4	Meso and micro litter	• Beach/shoreline litter • Floating/water column litter • Ingestion of marine litter/entanglement • Sources of marine litter	• Provides information on smaller classes of litter • Provides important information on ingestion	• Sample collection and analysis present contamination risks • Sample preparation and analysis vary, and require being in agreement and implementing comparable methods • Time consuming • Human error in identifying material types • Global standardized protocols are not implemented
Weight	In situ	3	Mega, macro and micro litter	• Beach/shoreline litter • Floating/water	• Allows for relatively quick and simple analysis of beach	• Beach litter water content, sand and biofouling bias results

				column litter • Ingestion of marine litter/entanglement • Sources of marine litter	litter quantities • Can be tied to voluntary beach cleanup efforts	• Presence of light-weight items such as Styrofoam and wrappers may lead to underestimating beach litter severity
Spectroscopy	In situ	3	Meso and micro litter	• Beach/shoreline litter • Floating/water column litter • Ingestion of marine litter/entanglement • Sources of marine litter	• Provides information on types of plastics in a sample • Can provide information on the fate and breakdown of litter • Semi and fully automated analysis under test • Based on existing technology	• Time consuming and expensive • Consistent sample preparation methods are not agreed upon • A limited number of samples can be analysed • Highly trained technician needed
Mass Spectrometry	In situ	3	Micro litter	• Beach/shoreline litter • Floating/water column litter • Ingestion of marine litter/entanglement • Sources of marine litter	• Provides information on polymers and chemicals associated with litter (such as contaminants) • Based on existing technology	• Time consuming and expensive • A limited number of samples can be analysed • Highly trained technician needed
Visual Imagery and Video	Remote	6	Mega and Macro litter	• Beach/shoreline litter • Floating litter • Ingestion of marine litter/entanglement • Sources of marine litter	• Simple and affordable technology • Variety of available systems, including cameras attached to air planes, drones and submersibles • Access to hard-to-	• Limited to large debris items • Image processing can be time consuming • Regulatory issues can restrict airborne platforms' areas of operation • Imagery can be limited

					reach beaches	by weather conditions
Synthetic Aperture Radar	Remote	1	Mega litter	• Beach/shoreline litter • Floating litter • Sources of marine litter	• Ability to survey large areas in short periods of time by using satellites, planes or drones • New sensors and processing tools are in development • Can be used to identify convergent zones where marine litter accumulation is likely	• Limited to large debris items • Processing data is resource intensive
Multispectral and Hyperspectral Imaging	Remote	2	Macro litter	• Beach/shoreline litter • Floating litter • Sources of marine litter	• Ability to survey large areas in short periods of time by using satellites, planes or drones • Global and nearly continuous observations from satellites • Many existing satellite missions	• Regulatory issues can restrict airborne platforms' areas of operation • Limited to large debris items • Imagery can be limited by weather conditions • Image processing can be challenging and time consuming • Most high-resolution data are commercial
GPS tags and transmitters	Remote	3	Mega and macro litter	• Floating/water column litter	• Can provide information on marine litter pathways • Data can improve modelling and source identification efforts	• Iridium satellite connectivity is prohibitively expensive for deployment into the sea • Introduces electronic litter into the marine

					• Based on existing technology	environment
Modelling	Simulated	4	Mega, Macro, Meso and Micro litter	• Beach/shoreline litter • Floating/water column litter • Ingestion of marine litter/entanglement • Sources of marine litter	• Predictive ability can support identification of beach litter hot spots in areas lacking on-the-ground data • New processing technologies such as machine learning and GIS-based tools show promise • Developed from existing particle tracking models	• Many oceanographic models are not at a high enough resolution to predict beach litter • Running of models can be resource intensive, requiring high levels of computing resources • Additional research and testing required before models can be used for decision making
Ancillary Data	N/A	2	Mega, Macro, Meso and Micro litter	• Beach/shoreline litter • Floating litter • Water column • Seabed	• Taking advantage of the development of Artificial Intelligence and existing technologies • Based on near real-time operational observing and modelling capacities	• Does not provide direct monitoring of marine debris but preferred locations for build-up • Dependant on the availability of observation/modelling (better coverage of the surface than the water column/seabed)

2 Existing Marine Litter Databases and Major Data Sets

Understanding the workings of the current available platforms is crucial to make accurate recommendations on how to develop a global monitoring platform effectively and to inform action on marine litter. In the past two decades, there has been a steady increase in the amount of data, reports and studies related to marine litter. In the past five years alone, the level of information and work focused on marine litter and subsequent areas of interest has spiked. Areas of interest within marine litter monitoring include: marine litter distribution in the water column, marine litter ingestion and entanglement, marine litter on the seabed/seafloor, marine litter on beaches and shorelines, sources of marine litter, waste management, the plastic life cycle, and microplastics. Figure 2.1 shows findings based on a Web of Science Search highlighting the trends of marine litter research over the past ~20 years.

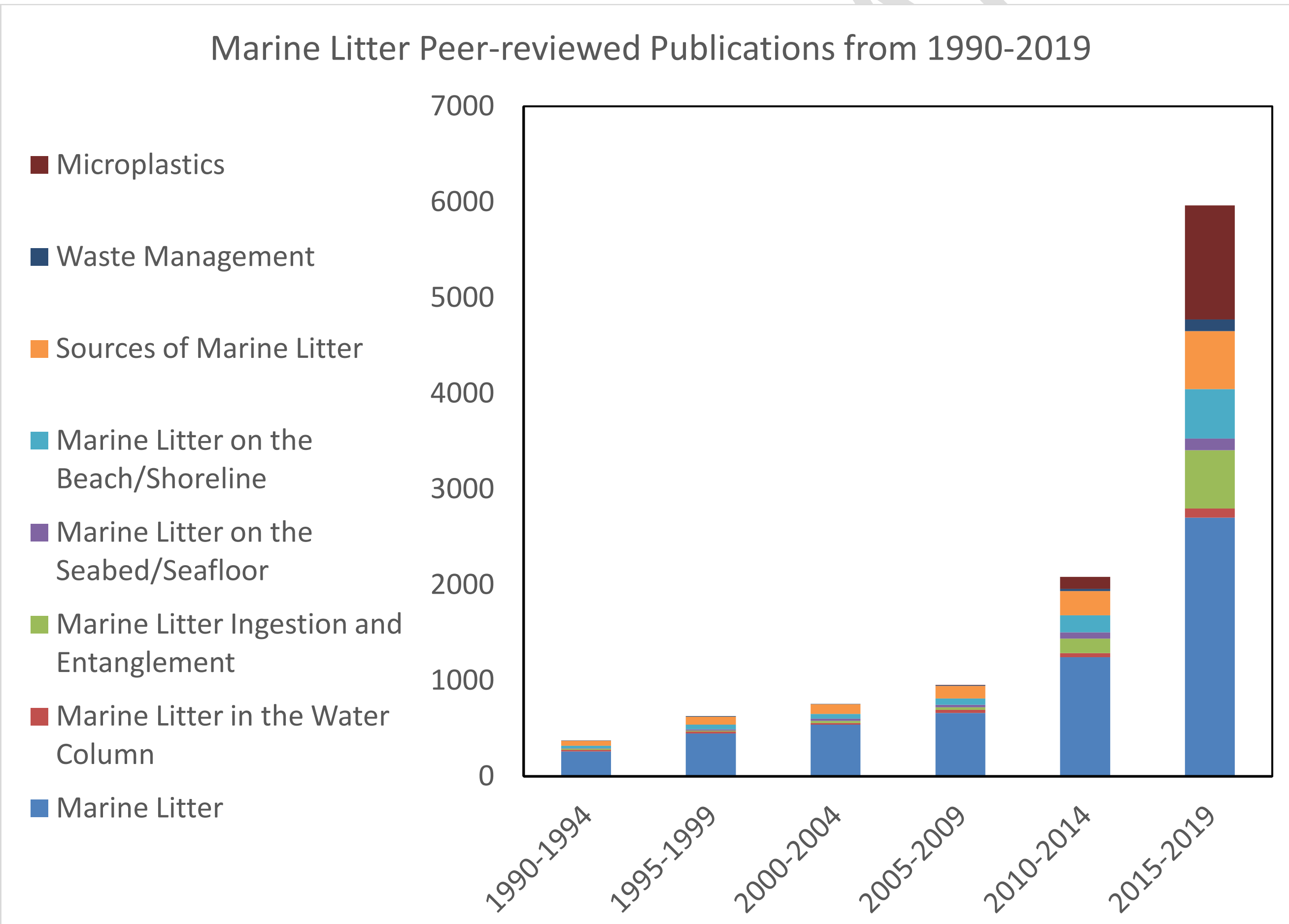


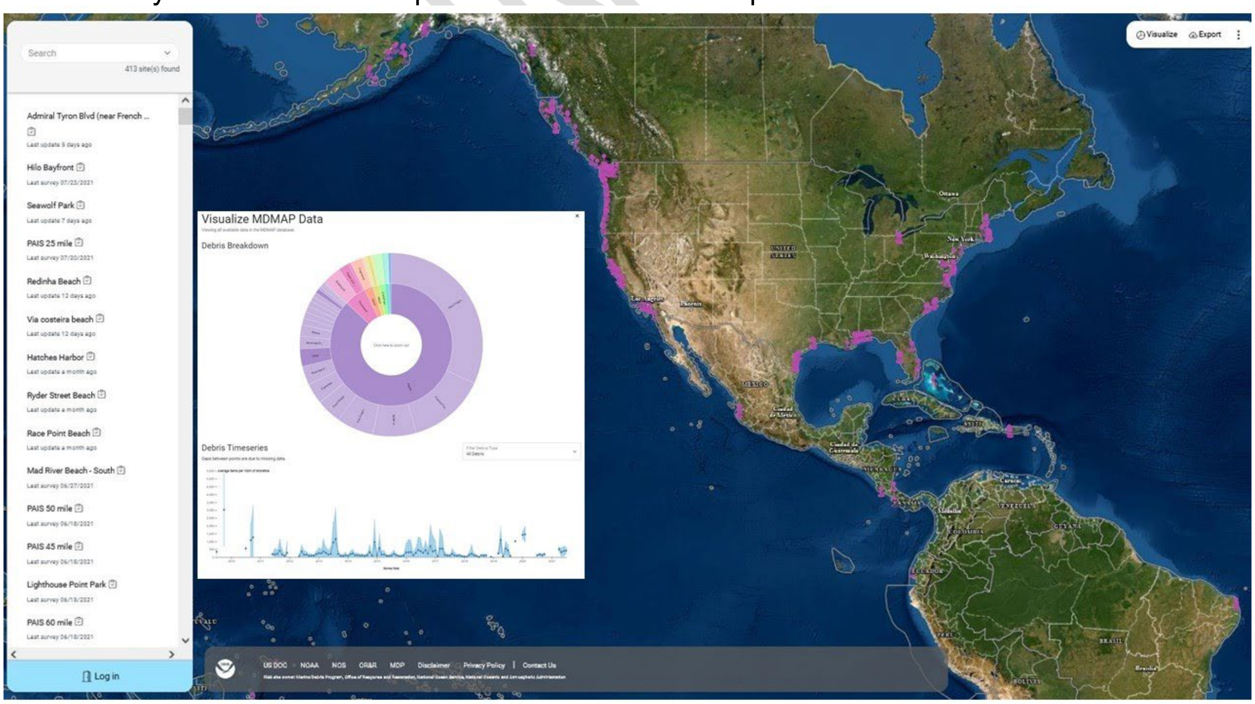
Figure 2.1. Published research articles on marine litter and on subcategories of marine litter: beach litter, ingestion and entanglement, seabed and seafloor, water column, and sources of marine litter. Data were collected using Web of Science search and analysis from 1990 to 2019.

As research and data on marine litter have become more readily accessible to global audiences, databases have made large repositories of data available to decision makers (such as managers and policymakers) and to the scientific community. After having sought input from diverse groups including academic research teams, the private sector, governments and non-profit/NGO organizations worldwide, we have compiled an extensive, though not complete, summary of available marine litter databases and data sets (see Annex A for additional information).

The majority of the databases contain beach and shoreline information, followed by information on seafloor/seabed, water column, sources of marine plastic, and plastic ingested by biota. A number of the beach or shoreline monitoring databases work in conjunction with citizen science groups to collect litter data. Across the world, projects and programs from all sectors are working to solve the marine litter crisis. Below, we present a few examples of marine litter databases and data sets to show the differences between government, NGO and academic efforts. For additional information on these and other databases and data sets, see Annex A.

2.1 The NOAA Marine Debris Monitoring and Assessment Project

The NOAA Marine Debris Monitoring and Assessment Project (MDMAP, Figure 2.2) began in 2011 and is run by the NOAA Marine Debris Program. Data collection follows a rigorous, well-tested protocol[15]. It is designed to document the quantity and composition of shoreline marine debris greater than 2.5 cm. The initiative operates as a network of citizen science volunteers and of agency and academic personnel. The data produced from the protocol can be input from anywhere in the world. At the time of writing (2021), data are concentrated in the U.S. coastal zone. The verified data set can be freely accessed through a browser application and exported into a .csv file or via an API. Raw counts of items according to material and type can be converted into units of items per linear metre, items per metre^2, or flux of items per unit time. The browser application provides data summaries in the form of time series of items (all or a selected type) per 100 metres of shoreline, and in the form of composition at user-defined scales. All data are reviewed by NOAA staff and published online in an open format that can be downloaded.



[15] MDMAP Protocol Documents and Field Datasheets | OR&R's Marine Debris Program (noaa.gov)

Figure 2.2. The Marine Debris Monitoring and Assessment Project Database homepage (MDAMP v.3.1.0, viewed on 28 July 2021). Pink dots on the map represent survey sites. Data can be filtered using the search bar to the left, and visualized using the visualization button. The export tab downloads the raw data set.

2.2 Marine LitterWatch

Marine LitterWatch (Figure 2.3) is operated by the European Environment Agency (EEA). Its focus is on litter located on most of Europe's coastline, in an effort to "strengthen Europe's knowledge base and provide support to European policy making." The database includes a total count and an itemized breakdown of all collected/observed items. Information on the specific sampled locations also includes the total number of cleanups, the average amount of collected items per event and the organizations that aided with the cleanups. Marine LitterWatch works as a mobile application for citizen science volunteer organizations and for more formal Regional Seas programs to participate in cleanups. The application is used to survey given areas meant for cleanups based on specific items broken down into categories: plastic, cloth/textile, glass/ceramics, metal, paper/cardboard, rubber and wood, with subsections within those categories. At present, Marine LitterWatch data are representative of the efforts made by the communities that collect the data. They are therefore illustrative of the amounts and types of items found on the surveyed beaches. Additional handling would be required to use the data for further statistical purposes. Data sets are not quality-controlled or monitored once data are input into the survey. The EEA- wide policy on data management, access and sharing is meant to provide open, free and readily available access to data.[16]

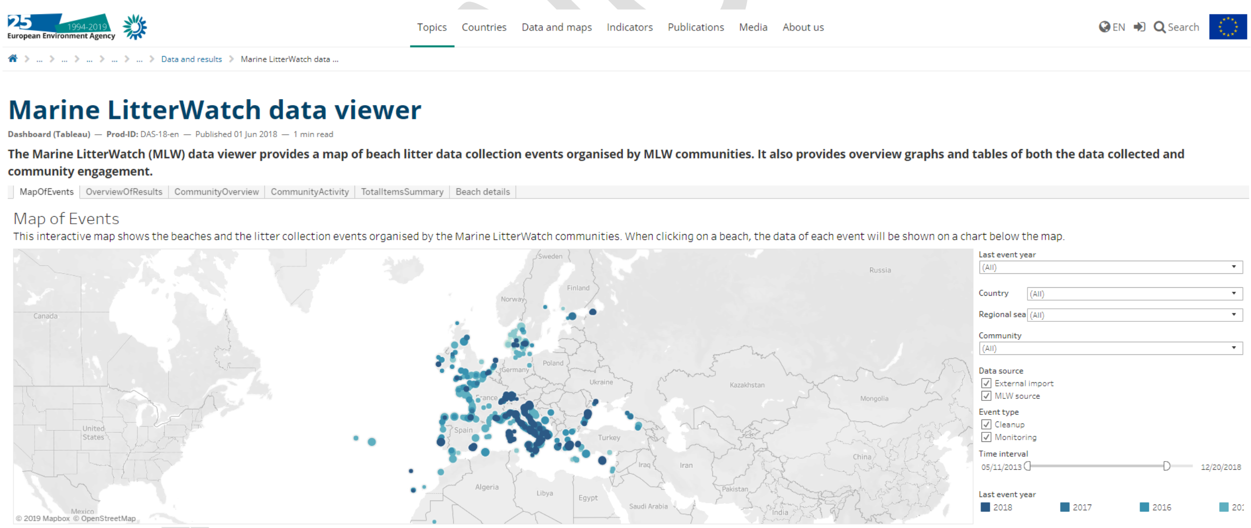


Figure 2.3. The Marine LitterWatch Data Viewer (viewed on 20 November 2019).

2.3 The Deep-Sea Debris Database (Figure 2.4), operated by the Japan Agency for Marine-Earth Science and Technology (JAMSTEC), is a composite of filmed and photographed debris found on the seafloor off the coast of Japan and in the Pacific. Each image includes its location, date observed, type of debris (plastic, glass, rubber, cloth, etc.), whether organisms have interacted or are near the debris, the characteristic of the sediment, and the location depth of the

[16] https://www.eea.europa.eu/legal/eea-data-policy/data-policy

debris. The database has a total quantity of observed debris, the latter of which are broken down by type. A specified area for the observation of debris is filmed by cameras that are deployed towards the seabed below the water's surface. Raw data and images are available on the database. While some of the data are labelled and protected as intellectual property, most information is open and available for others to use. The data and samples collected using JAMSTEC facilities and equipment belong to JAMSTEC. Organisations, institutes and researchers can use data and samples managed by JAMSTEC for scientific and educational purposes as the agency promotes the use of their data to help industries and society. Some industry actors may be required to pay for the data, but all other scientific and educational uses are free of charge.

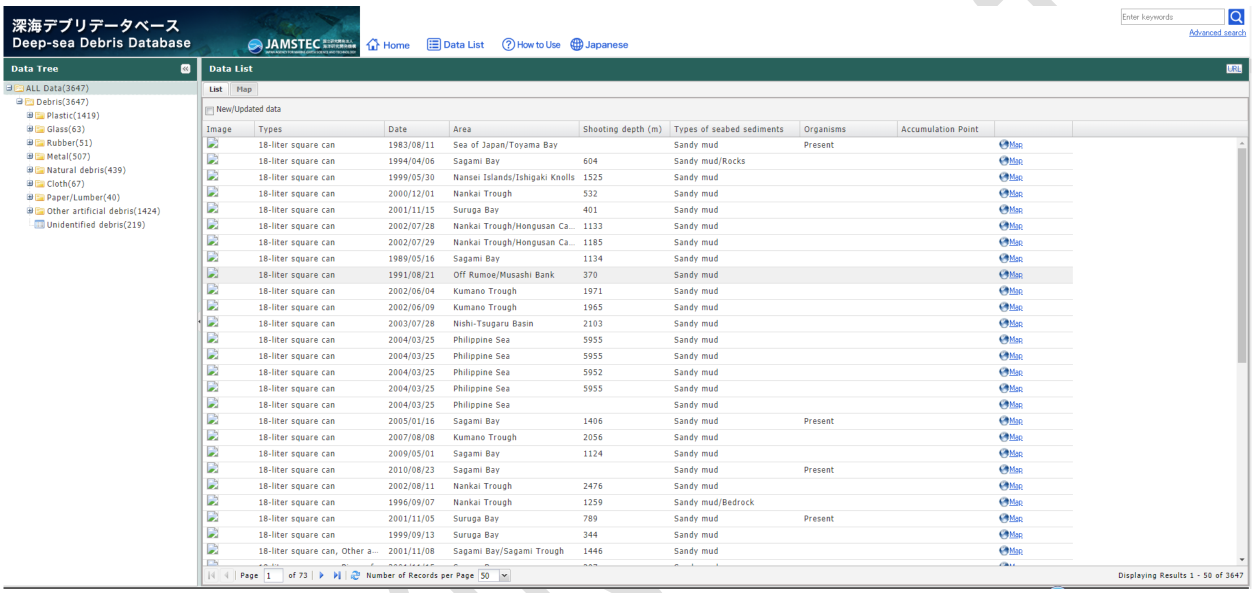


Figure 2.4. The Deep-sea Debris Database (viewed on 20 November 2019)

2.4 The Coastal Observation and Seabird Survey Team (COASST)

The Coastal Observation and Seabird Survey Team (COASST) is a part of the University of Washington. It focuses on beach litter, ingested litter and on sources of litter in parts of Washington and Oregon, USA (Figure 2.5). This database provides information on counts and on specific characteristics of items (item type, colour, material, size, loops, floppiness, brands, logos, languages, shininess, biofouling, weathering, intactness, etc.) as observed during standardized beach surveys. Specific protocols are applied for the sampling of debris that range between 2.5 mm and 2.5 cm, 2.5 cm and 50 cm, and that are greater than 50 cm. Trained citizen scientist volunteers collect the data by adhering to the standard protocols developed by COASST. The raw data from collections are unpublished but are available upon request. The team requires a Data User Agreement to establish terms of use, and data are quality-controlled by the team. The validity of the data is also ensured through post-processing procedures.

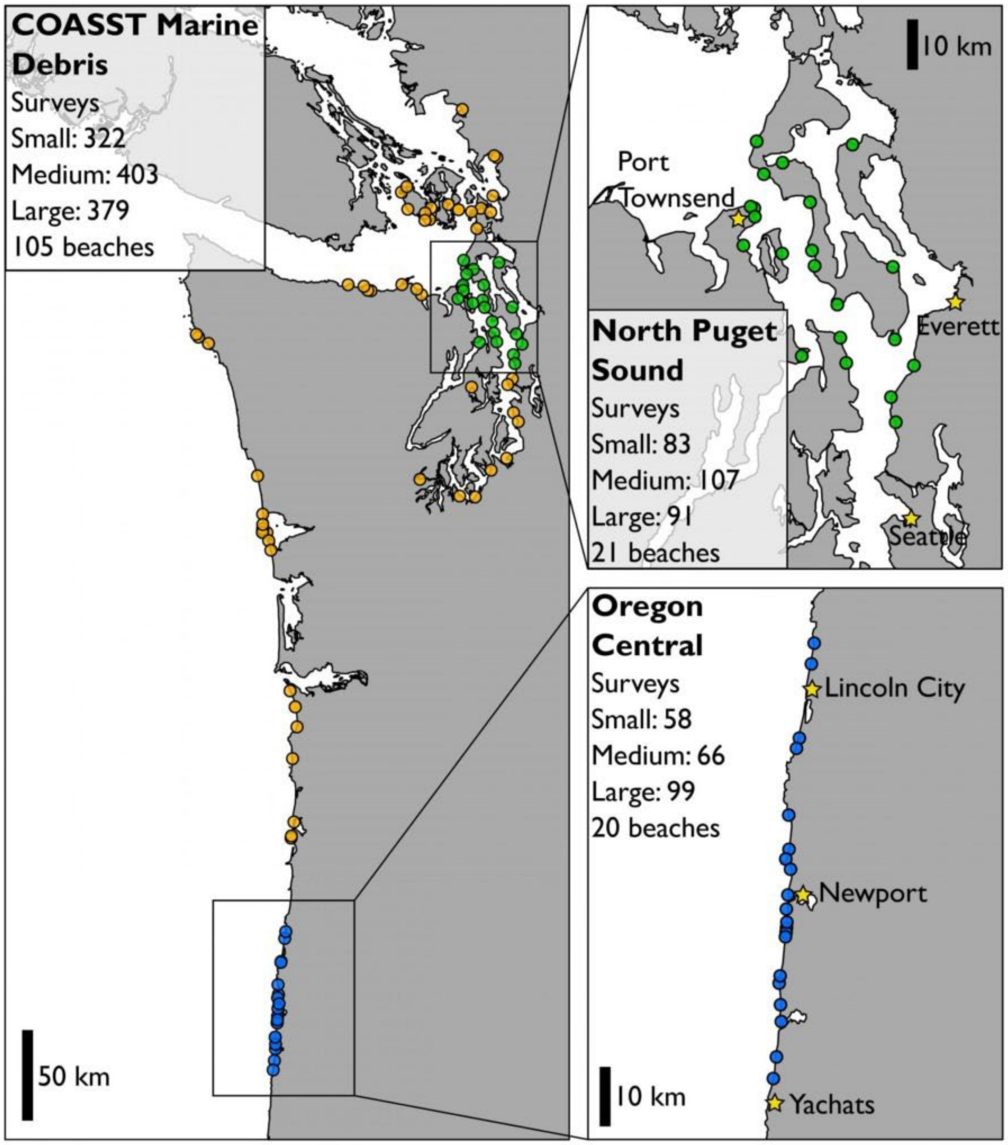


Figure 2.5. Map showing the locations of data collected for the COASST program as of 2018 (Image credit: COASST).

2.5 The European Marine Observation and Data Network Marine Litter Database

The European Marine Observation and Data Network Marine Litter Database is part of EMODnet Chemistry, one of the seven thematic portals of EMODnet[17] (Figure 2.6). EMODnet Chemistry is operated at a European scale through a network of National Oceanographic Data Centres and monitoring agencies, all coordinated by OGS (Istituto Nazionale di Oceanografia e di Geofisica Sperimentale), an internationally-oriented public research institution in Italy. The Marine Litter Database (Molina Jack *et al*. 2019)is the first pan European database on marine litter and focuses

[17] www.emodnet.eu

mainly on beach litter (Addamo *et al*. 2018; European Commission 2018), floating micro-litter in the water column and seafloor litter from fishing trawls. Data are assembled by national and regional marine monitoring programmes from across European member states and from bordering countries (such as Ukraine, Russia, Georgia and Montenegro). The database is a strong collaboration with the European Commission's Joint Research Centre (JRC) to safeguard the compilation of the data requested by the European Commission's Marine Strategy Framework Directive (MSFD) and by the Regional Sea Conventions. It builds on existing databases, mainly on OSPAR/MCS for beach litter in the North East Atlantic, and on ICES DATRAS for sea floor litter in the North East Atlantic and in the Baltic Sea. It also hosts litter data from wider monitoring and observing programmes, including: scientific research studies, citizen science actions, and specific initiatives such as the partnership with the Volvo Ocean Race to collect samples from racing yachts. Quantities and types of beach litter, sea floor litter and floating microlitter are collated in the database. A product viewer can be found on the online EMODnet Chemistry platform, along with an access service in which marine litter geospatial data can be found, viewed and visualized as pan-European map layers. To better describe the collection of data and to acknowledge the original data collector, data sets can be downloaded together with metadata. Generally, there are no restrictions to access or reuse the raw data available in the database[18]. Where specific access requirements exist, as in the case of particular countries, it is specified.

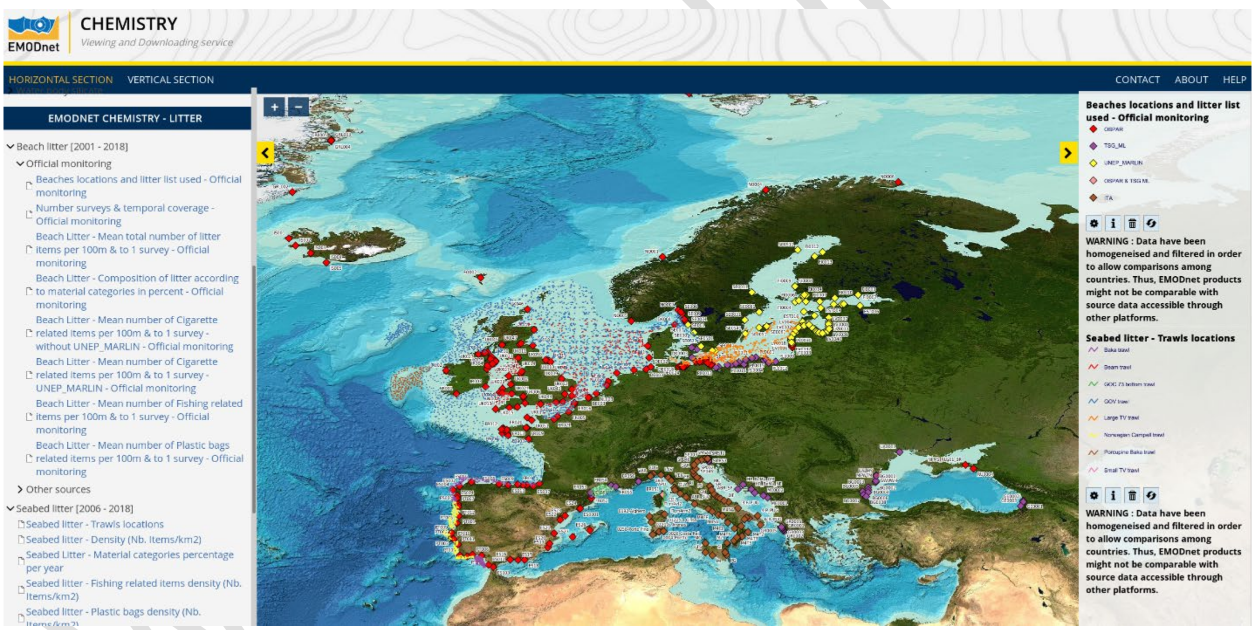


Figure 2.6. [Map showing the locations of the beaches](#) (the various reference lists used to describe litter items are specified in the legend; viewed on 25 November 2019).

2.6 The Australian Marine Debris Database

The Australian Marine Debris Database is coordinated by an Australian NGO called the Tangaroa Blue Foundation, as part of the Australian Marine Debris Initiative (Figure 2.7). The collected data on beach litter mainly originate from the Australian Coast, with some data from the Asia Pacific and Oceania region. Debris is described using 140 categories based on material type and name.

[18] https://emodnet-chemistry.maris.nl/search

To collect the data, volunteers perform beach cleanups of coastal areas on both land (beaches) and sea (near-shore surface levels). Volunteers count itemised pieces of litter based on specifications. Reports include approximate litter weight and the length of the cleanup area, as well as optional photographs. Data are vetted before approval. The database has an open access policy that allows community groups, schools and partner organizations to generate a specific set of data reports to assist in identifying marine debris trends and to create local source reduction plans. It is mandatory to acknowledge both the Australian Marine Debris Initiative and the data contributor for any public use of the data, for any purpose. This information is available by emailing info@tangaroablue.org with both the location and the date of the requested data. Additionally, a data management system is in place: the submitted data are placed in a holding folder for vetting before entering the database.

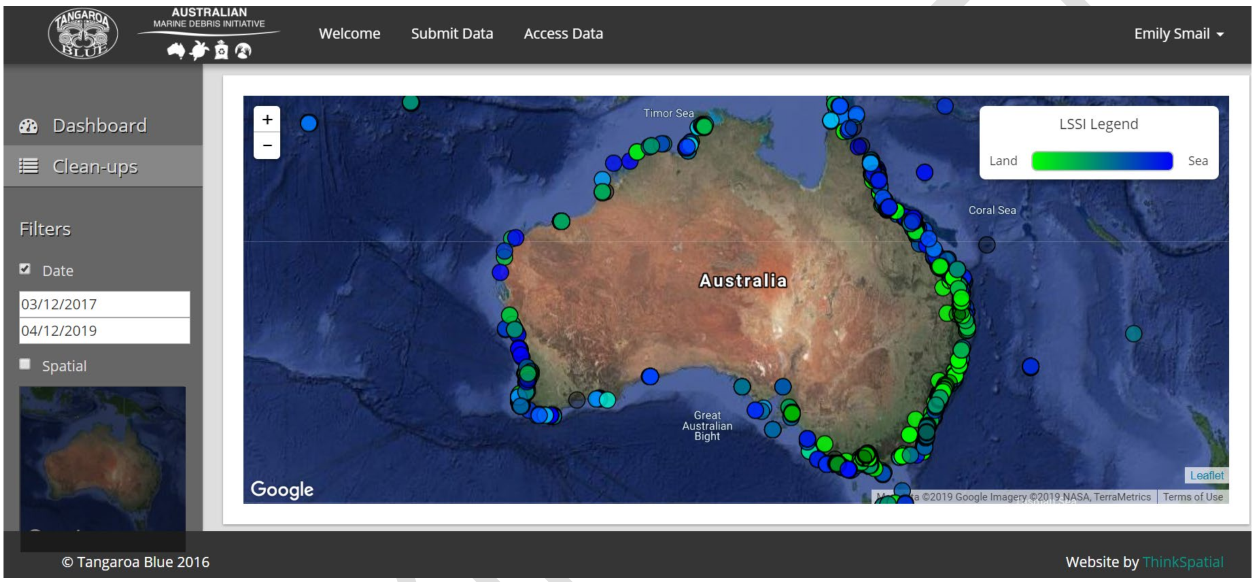


Figure 2.7. The Australian Marine Debris Initiative Database (viewed on 3 December 2019)

2.7 The TIDES (Trash information and Data for Education and Solutions) database

The TIDES (Trash information and Data for Education and Solutions) database is operated by the Ocean Conservancy, focuses on cataloguing and collecting litter found on beaches, shorelines, and in the water column (Figure 2.8). This database contains information on the total mass of collected trash, the total number of filled trash bags, the total distance of area covered. An itemised list of all collected litter is broken down into the following categories: most likely to be found items, fishing gear, packaging materials and other personal hygiene products, smaller trash items (less than 2.5 cm) and items of local concern. The public can collect data and report debris as land-based litter, underwater debris, or litter collected by watercraft. Data are in large part collected during the international cleanup events organised by the International Coastal Cleanup. Citizen science volunteers and coordinators can either use the Clean Swell mobile app or paper forms to enter the information. Regardless of whether the application or data sheets are used, groups and individuals collect the litter, tally the total number of specific items found, and record the overall mass of total trash. Data are input into the TIDES database and made publicly available. Site-specific data sets of past years are available and archived. They can easily be accessed and downloaded from the platform.

Figure 2.8. The [Trash information and Data for Education and Solutions Database] (viewed on 3 December 2019)

2.8 Litterbase

Litterbase is a global portal coordinated by the Alfred-Wegener-Institut Helmholtz-Zentrum für Polar and Meeresforschung (Figure 2.9). Its focus is on litter present on beaches/shorelines, in the water column, on the seafloor, and ingested plastics scoping across oceans, rivers, lakes, and other inland waters. The following specific information can be found on the portal: quantitative geo-referenced data on aquatic and terrestrial debris; peer-reviewed literature on microplastics and nanoplastics; quantitative geo-referenced data on the effects of marine debris; peer-reviewed literature (field studies) on the effects of microplastics and nanoplastics on aquatic and terrestrial biota; and reports of impacts of marine debris, microplastics and nanoplastics on aquatic and terrestrial biota from peer-reviewed literature (laboratory studies, species lists).

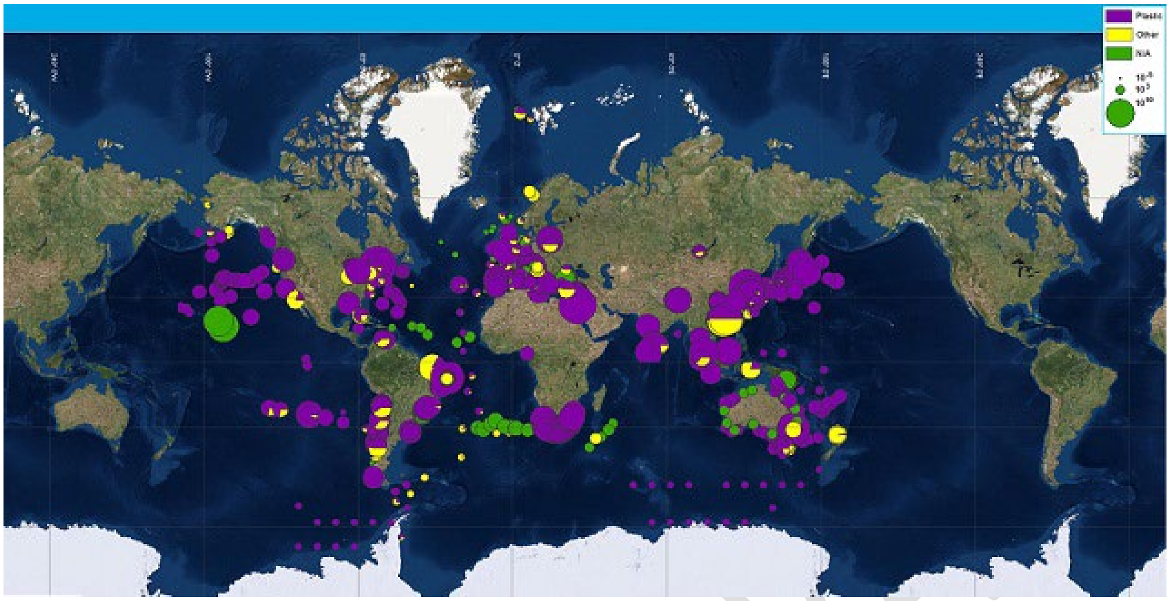


Figure 2.9. [Global map of litter distribution in Litterbase](Image source: https://www.maritime-executive.com/article/ocean-litter-portal-established)

2.9 The Global Ghost Gear Initiative's Data Portal

The Global Ghost Gear Initiative's data portal is coordinated by the Ocean Conservancy's Global Ghost Gear Initiative (Figure 2.10). This initiative works to find fishing gear that has been lost, abandoned or otherwise discarded. It operates with global partners, including the fishing industry, the private sector, NGOs, academia, and governing bodies. The portal hosts data from the US coasts, the European Coasts and the Asia-Oceania Pacific region. Information can be found on different types of "ghost gear", including found nets, lines, pots and traps; total counts and location, dates, and gear class are also available. Data are collected through volunteers and partners who upload them to the "GGGI Ghost Gear Reporter" mobile application. Bulk uploads can also be done on their website. Additionally, all data are available on the portal and specific measurements are available upon request.

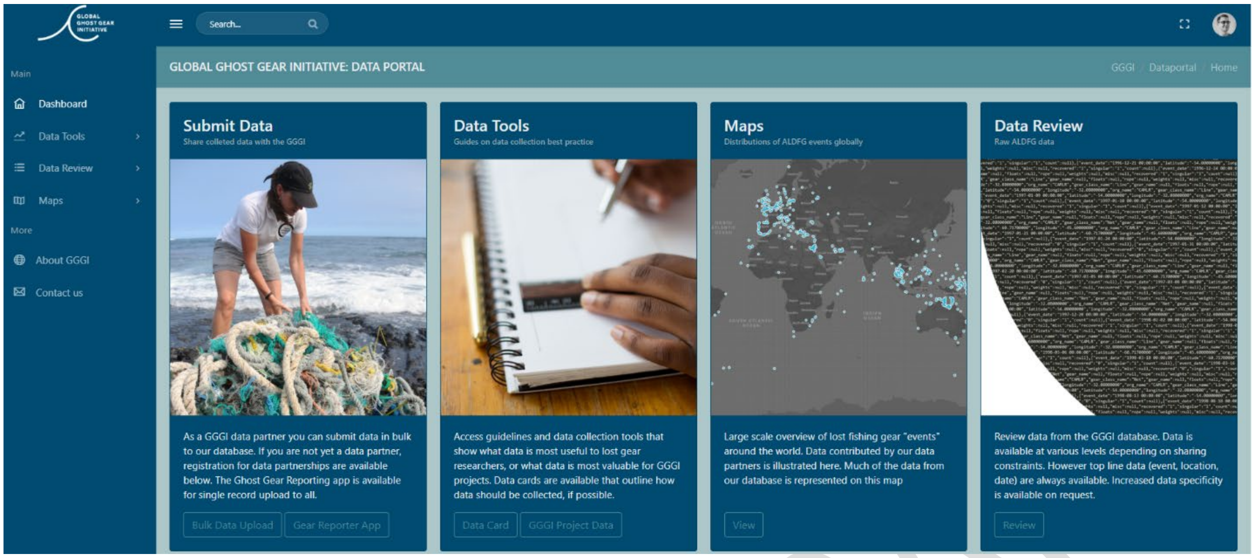


Figure 2.10. The Global Ghost Gear Initiative Data Portal (viewed on 3 December 2019)

3 Indicators and Applications of Technologies

Indicators aim to monitor and report progress on complex issues in a simplified form (European Environment Agency 2003; Niemeijer and Groot 2008). In the policy context, environmental indicators are primarily used to grasp the scope of an environmental problem, to support the development of policies and the setting of priorities, and to monitor and evaluate progress made towards policy goals (European Environment Agency 1999).

The following questions are answered by marine litter indicators made to grasp the scope of an environmental problem and to support the development of policies and the setting of priorities:

1. What is the abundance, distribution and composition of marine litter, and are these attributes changing over time?
2. What are the socioeconomic drivers of marine litter, and are they changing over time?
3. What is the flow of marine litter, and how is it changing over time?
4. What are the impacts of marine litter, and are they changing over time?

Different indicators aligning with these four questions are included in various policy frameworks. For example, to evaluate sustainable development progress through the SDG framework, a subindicator on marine litter, the SDG indicator 14.1.1b, is included under Goal 14, Life Below Water. This section provides a summary of existing indicators and considerations for the development of future indicators.

3.1 Indicators to Track the Abundance, Distribution and Composition of Marine Litter

Indicators for the abundance, distribution and composition of marine litter have been developed for beach/shoreline litter, floating/water column litter and seafloor litter (GESAMP 2019; UNEP 2018b). These indicators seek to measure the state of marine litter in the environment (GESAMP 2019).

3.1.1 Beach/shoreline litter

Beach litter indicators are produced using various methods that take into consideration types, quantities, distribution and flux. The numbers of various types of marine litter are recorded in certain studies while the mass of litter is scrutinized in others. Some studies examine both aspects (Galgani *et al*. 2015; Galgani *et al*. 2013). Beach litter indicators can be used to focus on mitigation measures and to evaluate the effectiveness of legislation and regulations by providing information on the amounts, trends and sources of marine litter (OSPAR Commission 2010). Beach litter indicators are the most developed and common. They have been used extensively for analysis in regions that include the North East Atlantic, the Baltic Sea and the United States (European Commission Joint Research Commission 2013; Hardesty *et al*. 2017; OSPAR Commission 2017). Although many initiatives related to the collection and the monitoring of beach litter exist, comparability and global analysis are impaired by the inconsistencies of the methods used.

By focusing on distribution, the GESAMP report highlights the importance of understanding the physiology of a shoreline. The dynamic nature of shorelines – due to oceanographic and meteorological factors such as tides, waves and currents, and winds and rain – are dominant when determining how marine litter reaches beaches. The shoreline's nature, namely its surface structure and slope, determines the type of litter that remains on the beach and where that litter is located over space and time. Ekman transport is a process during which on and offshore winds blow floating litter onto or off the shoreline; this, in turn, leads to pronounced currents both on and offshore. It is highlighted as a means of understanding the flux process between floating and shoreline litter.

Tourism and increased human activity are often linked to beach litter quantities. Seasonal increases of visitors to the beach lead to an increase in quantities and in types of litter load in an area. Conversely, lower levels of larger types of litter can indicate high levels of human activity due to organized beach sweeps (Opfer *et al*. 2012; Ryan *et al*. 2009). An effective way of knowing when to conduct monitoring activities is to use temporal, geographical, and oceanographic metrics for indicators so as to know when beach litter attains high quantities and when certain types of litter are present.

3.1.2 Floating and water column

Ocean circulation, material density, degradation, and biofouling are a few factors that influence the distribution of marine litter on the surface and throughout the water column. The composition of marine litter in the water column ranges from large items, such as abandoned, lost or discarded fishing gear (ALDFG), to microplastics (GESAMP 2019). Indicators for floating and water column debris are essential when deciding on a sampling strategy to monitor marine debris. The indicators ought to provide information on the global quantity of marine litter and on its spatial distribution across the global ocean and the water column; but they should also give information on the material type (polymer) and on associated chemical compounds.

As with beach or shoreline litter, many factors influence the horizontal distribution of marine litter across the ocean, including tidal conditions, local wind and rain events, currents, waves, and interactions with the biosphere. The vertical distribution and composition of litter within the water column is slightly easier to determine based on the structure, make-up and size of litter. For example, polystyrene sinks while polyethylene and polypropylene polymers tend to float (GESAMP 2016).

3.1.3 Seafloor

Litter is pervasive all across the seafloor, from shallow coastal areas to deep trenches. Since the seafloor is a sink for marine litter, these indicators are more straightforward than the ones described above (Galgani *et al*. 2000; Pham *et al*. 2014; Woodall *et al*. 2014; GESAMP 2019). The two main indicators used in the present literature are based on potential seafloor litter sources. The first is proximity to maritime activities, such as fisheries, aquaculture, shipping, construction, energy extraction and recreational activities. The second is shore-based leakage or run-off points, such as major river deltas, populated and industrialized coastlines, and coastal tourism. Although not all seafloor litter sinks to the seafloor near its source location, the physical characteristics of litter found on the sea floor, especially density and size, can be useful (Pham *et al*. 2013; Loulad *et al*. 2017). Seafloor topographic features may also be key indicators, but hypothesizing on their effectiveness is made harder by a lack of seafloor litter monitoring and a lack of baseline studies. Water depth, surface and deep-water currents may also provide useful clues (GESAMP 2019).

3.1.4 Socioeconomic drivers of marine litter

Urban development, population proximity to the ocean and economic status are indicators of marine litter from coastal sources. Transport infrastructure, along with storm and wastewater management systems, are key urban development parameters that drive litter into the marine environment (Glanville and Chang, 2015; UN Environment Programme 2016a; Willis,*et al*. 2017). Roads, for instance, lead to direct and indirect inputs of litter in the environment through tire wear that is washed off by rainwater, and by bringing users and visitors to coastal areas, which results in increased debris deposition. Storm water washes off litter and is usually drained directly into the ocean, thus delivering litter from the land to the marine environment (Hardesty *et al*. 2017). The number of storm water drains could be a potential indicator as it positively correlates with the abundance of marine litter, even when controlling for population density (Willis *et al*. 2017).

Wastewater, on the other hand, can be treated before being released in aquatic environments. But it still transports many microplastic particles that stem from the washing of synthetic clothes and from cosmetic products, among other things (Browne *et al*. 2011).

Although most marine debris originates from land, a significant portion of it enters the water from sources at sea (NOWPAP CEARAC 2007). Monitoring shipping and fishing routes could therefore be a useful indicator to locate sources of marine debris.

The geographical scale of the indicator depends on the relationship between population size, its distance from the coastline and the abundance of marine litter. Large quantities of marine debris can accumulate on remote and uninhabited islands: this is a reflection of global marine litter issues and not of a singular point source (Lavers *et al*. 2019). At regional levels, the abundance of marine litter scales positively with population size (Browne *et al*. 2011; Hardesty *et al*. 2017). Even isolated sites in regions with large populations have high litter deposition. In some locations, environmental stewards from the community actively remove litter and reduce litter deposits by influencing beachgoer behaviour (Hardesty *et al*. 2017). The interplay between societal norms and local policies influences litter accumulation and stewardship. Communities can pressure their governments to provide and maintain municipal waste removal services, the latter of which are scarce in disadvantaged communities (Cordova and Nurhati 2019; Hardesty *et al*. 2017). Governments can also take a proactive approach by banning major sources of marine litter. For example, Styrofoam being the largest source of marine litter in Indonesia, the city of Bandung chose to prohibit this type of food packaging; it is the only city to do so in the country (Cordova and Nurhati 2019).

Waste production and resulting marine litter are determined by economic status. Low and middle income countries generate less plastic waste per capita than high income countries (Jambeck *et al*. 2015). However, low and middle income countries have less infrastructure and financial resources for proper waste management (Brooks *et al*. 2018). Gross Domestic Product (GDP) can serve as an indicator, as mismanaged waste has a high potential of becoming marine litter. Since the 1980s, high-income countries have been major exporters of plastic waste to low and middle income countries, thus placing further strain on countries with limited capacities for proper waste management. This issue has been more apparent in the wake of the 2017 Chinese import ban on nonindustrial plastic waste (Brooks *et al*. 2018). In countries like Australia, biosecurity laws prevent litter imports, thereby making debris removal from remote islands logistically difficult and expensive (Lavers *et al*. 2019).

3.2 Indicators to Track the Flow of Marine Litter

Useful source indicators for the input of litter into the marine environment are: floating litter spatial distribution and current, tidal and riverine information. This can lead to decisive evidence regarding pathway and input zones, which are useful to determine the potency of the source and the efficacy of the management practices in place. Using specific items from industrial or fishing vessels as indicators of marine input sources or pathways is an effective practice.

The major land-based sources of marine plastic include: landfills, floodwaters, industrial outfalls, discharge from storm water drains, untreated municipal sewerage and the littering of beaches and coastal areas due to tourism and other activities. Existing databases, social media and public documents can provide information on these sources.

A system integrating information and modelling would provide a basis for risk assessments. As an example, the functional dependency network analysis (Pinto and Garvey 2013) is a contender for the assessment of the risk of seafood contamination from ocean plastics; the model system would support it. Likewise, the model system would facilitate cost-benefit analyses for the purposes of mitigation.

This integrated system would also allow for a scenario-based exploration of possible futures. After careful validation and calibration, this model could assess the future trajectories of ocean plastics based on scenarios of plastic production, waste management, recycling and reuse practices, as well as based on efforts to remove plastics from the ocean. Transformative policies can be identified through desirable futures to ensure such a vision.

3.2.1 Plastic debris in rivers, including in the mouths of rivers and in estuaries

Marine litter entering the ocean through rivers is largely due to improperly managed plastic waste, which includes failed recycling, inadequate sewage systems, and inadequate disposal processes (Jambeck *et al*. 2015). By combining an intensive two-week in situ sampling program with hydrological data, it was revealed that the Saigon River in Vietnam carried macroplastic loads that were at least four times higher than previously estimated (van Emmerik *et al*. 2018). This highlights the importance of case studies in rivers that contribute significantly to the flow of plastic into the ocean. The Ocean Cleanup initiative[19] is working with governments to prevent plastic from entering the world's oceans from a thousand of the most polluting rivers all over the world by 2025.

Sediment outflows at river mouths, which are indicative and correlated with land-based sources of pollution, might be a potential indicator for plastic debris. Sediment samples in estuaries could also give information on plastic contents, potentially providing time variability over the last five to seven decades.

In addition to estimates of plastics at river mouths and in estuaries, mapping the input of plastic into rivers is important. Meaningful auxiliary data, which would be harvested from existing sources, would include variables such as: watershed pollution, sources of waste and leakages into the environment, management practices, and run-off.

The link between plastics from river outflows and ocean circulation was recently highlighted in a very thorough survey in the Indonesian basin, following a project from the Institute of Research for Development and resulting in a documented atlas (Dobler *et al*. 2021).

Many sea-based activities contribute to marine debris, large amounts deriving from fishing and aquaculture, shipping (for transport and tourism), dredged material, offshore mining and extraction, sewage sludge, and illegal dumping at sea. As most sea-based sources of plastic come from ship presence or traffic, the comprehensive Automatic Identification System (AIS) provides a database of valuable information on ships and their movements. While various free sources of AIS data exist online, these are limited in scope. The full database is available for purchase. Based on this full database, pattern recognition and matching algorithms could be used to match hotspots of marine litter with ship presence, taking into account the trajectories of these hotspots based on ocean currents. Ship size, type and flag country could be determined to identify the most likely polluters.

By knowing where the most important fishing areas are at any given point in time (namely through the Global Fishing Watch[20]) one can learn to detect the major potential sources and locations of ghost gear.

A key convention for the International Maritime Organization (IMO) is the International Convention for the Safety of Life at Sea (SOLAS). Regulation 19 of Chapter V of SOLAS – carriage requirements for shipborne navigational systems and equipment – lists the navigational equipment that must be carried on-board in accordance to ship type. All ships are required to carry an AIS, which must provide the ship's information to other ships and to coastal authorities automatically. More specifically, regulation 19 of SOLAS Chapter V requires an AIS to be installed

[19] https://theoceancleanup.com/rivers/

[20] https://globalfishingwatch.org

on-board all ships of 300 gross tonnage and upwards that are engaged in international voyages, cargo ships of 500 gross tonnage and upwards that are not engaged in international voyages, and all passenger ships irrespective of size.

This means that most fishing vessels are not necessarily tracked by an AIS. However, it is mandatory for all fishing vessels engaged in commercial activities to broadcast their positions via encrypted satellite communication every two hours. This system, known as the Vessel Management System (VMS), monitors national fishing fleets and foreign vessels that fish within national waters. The information is only available to national government authorities and to groups that share access. By enlisting national authorities and the Food and Agriculture Organization (FAO) of the United Nations, VMS data can track, monitor, model and evaluate the sources and locations of fisheries' ghost gear at a global level.

Aquaculture is also a known source of lost fishing gear and apparatus. High-resolution imaging can reliably detect the locations of these activities (Trujillo, Piroddi, and Jacquet 2012).

The International Maritime Organization's Marine Environment Protection Committee (MEPC) agreed on an Action Plan to address marine litter from ships, including from fishing vessels (Dae-Jung. Building on the existing policy and regulatory frameworks, such as the International Convention for the Prevention of Pollution from Ships (MARPOL) (MARPOL) Convention (MARPOL 1973) and the Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter (abbreviated as the London Convention and Protocol [LCP] 1972), the action plan introduces new supporting measures to address the issue of marine litter from ships (Dae-Jung, 2020). The global platform feeds into the action plan and responds to the plan's requirements.

3.2.2 Marine litter from coastal disasters

A large fraction of plastic material is found in our modern built environment. Considering the global population's migration patterns, construction is largely located on coastal zones and flood zones; it is therefore exposed to hydro-meteorological hazards. The built environment's rapidly expanding exposure to floods and storms has increased the likelihood of plastic and other debris entering the ocean. The expected increase in the frequency and intensity of hydro-meteorological hazards due to climate change further exacerbates this risk (Axelsson and van Sebille 2017).

It has become urgent to compile information on the amount of marine debris resulting from coastal disasters. Databases compiled by insurances, real estate companies and municipalities could be harvested to estimate and map the presence of plastic in the built environment. Overlaying this information with disaster assessments would provide a basis on which to quantify the amount of plastic and other debris washed into the ocean during major hazardous events.

3.2.3 Primary microplastics

Microplastics in the environment are categorized as primary and secondary microplastics. Boucher and Damien (2017) define primary and secondary microplastics as follows:

- **Primary microplastics** are directly released into the environment in the form of small particles. Some are a voluntary addition to products, such as scrubbing agents in toiletries and cosmetics (as in shower gels). They can also originate from the abrasion of large plastic objects during manufacturing, use or maintenance, such as when tires erode while driving or when synthetic textiles undergo abrasion during washing cycles.

- **Secondary microplastics** originate from larger plastic items that degrade into smaller plastic fragments once exposed to the environment. This happens through photodegradation and through other weathering processes of mismanaged waste, such as discarded plastic bags, or from unintentional losses like fishing nets.

Indicators for marine microplastics pollution include emission estimates of primary microplastics. Primary microplastics include tire dust/particles, road markings, synthetic textiles, maritime coatings, personal care products, plastic pellets and artificial turf (Boucher and Damien 2017; Wang *et al*. 2019). Emission estimates can then be tied to estimates of microplastics entering the aquatic environment through various pathways (such as through domestic sewage, road run-off, wind or adjacent waters) (Burton 2017; Lassen *et al*. 2015; Verschoor *et al*. 2016).

A recent study by Wang *et al*. (2019) utilized this process to estimate the ways in which various items contributed to primary microplastics emissions and the amounts that entered aquatic environments in mainland China (Figure 3.1).

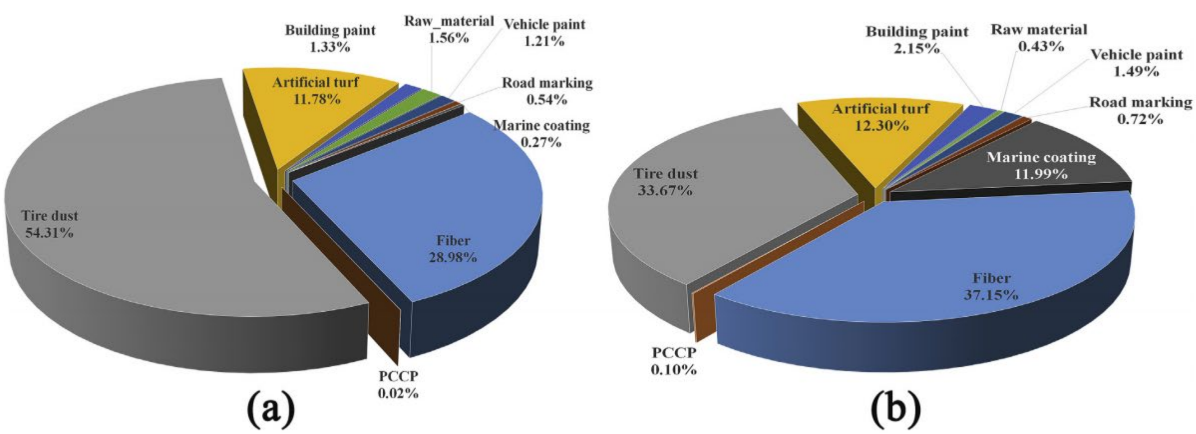


Figure 3.1. The contributions of various sources to total primary microplastics emissions (a) and the amounts entering the aquatic environment (b) in mainland China in 2015. Source: Wang *et al*. 2019.

These estimates can be corroborated through the study of microplastics in known sources such as in storm water and in the marine environment (Sutton *et al*. 2019). Additional analysis and research are however needed before routinely using primary microplastics emissions as indicators.

3.3 Indicators for the impacts of marine litter

Marine organisms interact with litter deposited into the ocean. Litter and debris have an impact on myriad marine biota through a number of different means, such as: filter feeders incidentally consuming microplastics, birds nesting on floating debris on the ocean surface or on beaches, larger fish eating litter that has travelled upwards through the different trophic levels, or coral reef habitats being disturbed by litter on the ocean floor. Monitoring how, where, why, and when organisms interact with litter is crucial for the safety and wellbeing of the oceans.

Biological and classical indicators play a pivotal role in marine litter monitoring. Since not all litter items are bound to be collected or counted, biological indicators act as a way of measuring the impact of marine debris on the environment. They also serve to assess the impacts of specific measures or policies in place. For example, the INDICIT II project found that an effective biological indicator should be "accurate, sensitive, reliable and easy to use for all the stakeholders in order to be applied to a large geographic area." Sea turtles, crustaceans and fish are useful indicators: they tend to ingest or become entangled in marine debris, they have a large spatial distribution and they use all ecological marine components, from the seabed to the sea surface[21].

Entanglement and ingestion are two biological indicators that provide information on interactions between organisms and marine debris. Monitoring entangled organisms can indicate changes in the abundance of the debris responsible for the entanglements (Ryan *et al*. 2009). Entanglement also serves as an indicator for the harm caused by the incorporation of marine debris into the nests of breeding birds. While it occurs less frequently than ingestion, using a consistent monitoring approach could potentially allow entanglement to be an indicator used to measure the success of mitigation efforts (European Commission Joint Research Commission 2013). In addition, the presence of plastic items in nests can be an indicator of the amount of litter present in natural environments surrounding nesting areas, as well as of risks of entanglement (Ryan *et al* 2009).

Marine debris ingestion can be a useful indicator for several reasons. The first is that regional differences in the abundance of marine debris can be determined through the plastic content of a bird's stomach. Comparing the plastic loads of birds in different regions can show where more pollution acts as both a source and a sink (European Commission 2013). By using the stomach contents of fulmars, the OSPAR Commission developed an indicator to demonstrate the changes in quantities of floating debris in the North Sea as well as its impact on biota[22].

To aid with consistency and accuracy, the CleanSea Project[23] (2013 – 2015) developed a series of considerations when selecting or implementing an organism as a bio-indicator (as opposed to collecting samples from naturally available species). As with experiments, the selection should occur on site-specific and case by case bases. The general selection guidelines provided are as follows: adopt region-specific indicator species, use non-threatened or protected species, use species that can be kept in cases for simple field deployment or retrieval (such as bi-valves), opt for invertebrate species (which require less training and handling than vertebrates), perform sampling in a cost-effective manner by developing synergies with pre-existing programs, find species which, when measured, are directly linked to impact and effects (more difficult to achieve), use species that are directly linked to measures and that could be used to evaluate targeted

[21] https://indicit-europa.eu/cms/wp-content/uploads/2018/09/Protocole_v7_hd.pdf

[22] https://oap.ospar.org/en/ospar-assessments/committee-assessments/eiha-thematic-assessments/marine-litter/plastic-particles-in-fulmar-stomachs-north-sea/

[23] https://cordis.europa.eu/project/id/308370/reporting

progress and the effectiveness of mitigation activities (Ryan *et al*. 2009). While these guidelines are not comprehensive and do not fully incorporate all debris, they can be a useful starting point when selecting a bio-indicator.

Fossi, *et al* (2018) developed a more general approach for the selection of sentinel species as indicators. This study surveyed reports of marine species impacted by debris in the Mediterranean Sea, specifically species that had ingested debris. Based on their findings, the researchers determined six key criteria when selecting an indicator based on ecological and biological data. The first is background information, which includes the species' biological and ecological characteristics, as well as knowledge regarding non-affected species to generate a point of comparison. The second is the species' habitat information, including its habitat and its home range (sessile, motile, depth, travel, migration). The third is trophic information and feeding behaviour, more specifically feeding mechanics and behaviour knowledge, to select a wide range of food scale levels. The fourth is the species' spatial distribution; this is important because of the spread of debris across the surface, the seabed and throughout the water column. The fifth is commercial importance and conservation status, which can lead to measuring potential plastic transfers from seafood to humans. It is also important to monitor species of concern and see how they are affected by marine litter. The sixth recommendation is to indicate the documented ingestion of marine litter based on available data and statistics (Fossi *et al*. 2018). As with the CleanSea Project, the criteria of selection represent a set of guidelines. The needed information isn't necessarily readily available and the species used cannot be all-telling indicators. As with any form of data collection, having a consistent foundation on how to sample and prepare data presents a number of long-term benefits, namely the ability to accurately compare data from across different regions of the world.

3.3.1 Economic impacts

Various industries are the source of marine litter while also being vulnerable to economic losses due to marine litter. Economic consequences can be immediate, as in the case of repairing fishing gear, or they can be long term due to lasting changes to the ecosystem's function. Marine litter poses hazards to human health; understanding welfare risks can therefore incentivize marine litter mitigation efforts.

3.3.1.1 Fisheries

While the fishing industry is a source of marine litter it also incurs direct and indirect costs from it. Direct costs include repairing or replacing lost or damaged gear, time spent clearing litter from nets, reduced catches due to contamination and the need for rescue services (Moaut, Lopez Lozano, and Bateson 2010). A case study from the Shetland Islands revealed that the direct costs of marine litter to the Scottish fishing industry ranged from \$15.5 million to \$17.2 million, or 5 per cent of overall revenue annually (Mouat *et al*. 2010). The estimated direct cost of marine litter to the EU fishing industry is \$81.7 million (UNEP 2017). Indirect costs of marine litter come from derelict fishing gear and lost fishery equipment such as trawl nets, gill nets, traps and pots (National Resource Council 2008). A phenomenon known as "ghost fishing" occurs when derelict fishing gear continues to capture marine life once the equipment is lost (Newman *et al*. 2015). This can diminish potential harvests and have long-term impacts on the sustainability of fisheries (Matsuoka, Nakashima, and Nagasawa 2005; UNEP 2017). For example, derelict crab pots in Puget Sound, Washington, cause an estimated 4.5 per cent of harvest loss in *Cancer magister* landings, or \$744,000 annually (Antonelis *et al*. 2011).

By harming marine life, marine litter impacts the fishing industry's economic development since it contributes to a negative public perception of seafood safety. The stomach, gills, and tissues of fish and bivalves contain microplastics and are reflective of plastic use by local human populations (Barboza *et al*. 2018; Rochman *et al*. 2015). Ingested microplastics can affect growth rate and marine life mortality by blocking feeding appendages or by altering hormone levels (Wright, Thompson, and Galloway, 2013). It is unclear how microplastics and their associated chemicals transfer up through the food chain (Smith *et al*. 2018). Seafood contamination by plastics, or the perception of it, can reduce consumer demand, which leads to economic loss throughout the fishing industry.

3.3.1.2 Tourism

Beach users place aesthetic value on recreational spaces and are deterred from coastlines which they perceive as having too much litter. This can negatively impact coastal communities that rely on visitors for revenue, such as the UK, which generates between $7.6 billion and $12 billion from coastal tourism annually (Moaut, Lopez Lozano, and Bateson 2010). Following heavy rainfall on Goeje Island, South Korea, a large pulse of marine litter resulted in 500,000 fewer visitors to the island (Jang *et al*. 2014). Without tourists to spend money on food and lodging, Goeje Island lost an estimated $25.2 million to $31.7 million in 2011. A garbage and medical waste spill on the New Jersey shore caused an estimated 22 per cent drop in beach visitations and a total loss of $1.4 billion (Tyrell 1992). Based on public questionnaires, in Cape Peninsula, South Africa, 40 per cent of foreign tourists and 60 per cent of domestic tourists said they would avoid visiting if there were more than 10 items of litter per square metre (Balance, Ryan, and Turpie 2000). Along the coast of Paraná, Brazil, 85 per cent of users would avoid visiting beaches with more than 15 items per square metre, which would cost up to $8.5 million in lost revenue (Krelling, Williams, and Turra 2017).

Beach cleaning can generate revenue by attracting visitors. Using the travel cost model designed by Leggettt *et al*. (2014), a 75 per cent reduction in marine litter would generate $53 million in Orange County, California. However, beach cleaning comes at a cost. In cities along the coasts of Oregon and California, beach cleanups, street sweeping, storm water capturing devices, storm drain cleaning and maintenance, public education, and losses from tourism cost between $9.5 million and $10 million, depending on population size (Stickel, Jahn, and Kier 2012). Coastal municipalities in the UK spend $19.7 million annually on marine litter removal and $11.4 million annually in Belgium and the Netherlands combined (Moaut, Lopez Lozano, and Bateson 2010). The amount each municipality spends on these efforts depends on the touristic value of its beaches. Voluntary stewardship programs also play an important role in removing marine litter and raising public awareness for coastal issues. Five coastal stewardship organizations in the UK used $14,525 for program support such as cleaning supplies, liability insurance, and transportation to waste management facilities. However, program costs do not tend to account for the time donated by volunteers. In the UK, 8,809 volunteers contributed the equivalent of $143,673 of their time based on the British minimum wage (Moaut, Lopez Lozano, and Bateson 2010).

3.3.1.3 Ecosystem services

Marine ecosystem services are valued at $18.1 trillion (Costanza 1999). Marine litter threatens the three components of ecosystem services: provisioning (namely food and materials), regulatory services (such as climate regulation and diseases control), and cultural services (as in recreation and heritage) (Beaumont *et al*. 2019). This leads to vast economic costs for various sectors, as reviewed above. Invasive species can have a detrimental impact on biodiversity and disrupt ecological processes, which in turn affects ecosystem services. Marine litter can serve as a raft for the transportation of invasive species over long distances, bringing these species to areas in which they do not naturally occur (Rech *et al*. 2016). Economic costs are then generated for the eradication and the monitoring of invasive species. As an example, the eradication and monitoring of the introduced carpet sea squirt (*Didemnum vexillum*) in Wales cost $733,208 over ten years (Newman *et al*. 2015). Without this intervention, such an introduction would have cost an estimated $9.4 million to the local mussel fishery (Newman *et al*. 2015). In the north Pacific, the folliculinid ciliate (*Halofolliculina* spp.), responsible for skeletal eroding band disease in corals, was found on plastic debris (Goldstein, Carson, and Eriksen 2014). Their original distribution was in the South Pacific and Indian Ocean, but their presence in the North Pacific and the accumulation of plastic debris in the Hawaiian Islands suggests that marine litter facilitated the transport of the ciliate (Goldstein, Carson, and Eriksen 2014). Coral diseases can cause changes to the diversity and abundance of marine life, which can have economic costs associated with tourism and fishery activities.

3.3.1.4 Human health

The health care costs of marine litter depend on the severity of acute and chronic medical conditions. Maritime collisions with large litter or entanglement can lead to injury or death, and the litter created from these accidents can persist as hazards to people at sea (Newman *et al*. 2015). Medical and hygiene waste threaten water quality, and exposure to contaminated seawater can result in infections (Tyrell 1992). Injury claims in New Zealand cost thousands of dollars, with injuries primarily due to punctures. Children are most vulnerable to marine litter related injuries, as they are unaware of potential hazards (Campbell *et al*. 2019).

Toxins associated with marine litter pose a threat to bodily functions. Contaminants from agricultural and industrial run-off, such as polychlorinated biphenyls (PCBs), dichlorodiphenylchloroethane (DDT) and bisphenol A (BPA), are linked to organ damage, hormonal disruption and reproductive abnormalities (Center for Disease Control). The chemical composition of plastic polymers facilitates the accumulation of contaminants, causing litter to be orders of magnitude more toxic than surrounding seawater (Galloway 2015). Pollutants absorbed in lower trophic levels can propagate throughout a food web (Ross and Birnbaum 2003). Current research suggests that toxin bioaccumulation is dependent on contaminant type, dosage and prior exposure (Lohmann 2017).

Marine litter can serve as a vector of diseases (Lamb *et al*. 2018; Barnes 2002). Plastic litter harbours its own "plastisphere", a microbial community that is different from the surrounding seawater (Zettler *et al*. 2013). *Vibrio* strains of bacteria responsible for infectious diseases are present in the plastisphere, which suggests that marine life and human life can be susceptible to infections and that the spread of diseases can be far reaching (Zettler *et al*. 2013).

3.4 Indicators to Track Progress towards Sustainable Development

The 14.1.1b SDG indicator suggests looking at the accumulation of plastic in the environment. The methodologies for the indicators were initially developed with GESAMP and aim to support the creation of standardized tools to monitor and report marine litter at national and regional levels. Indicators are divided into subindicators for beach litter, floating plastic and plastic in the sea column, plastic on the sea floor, and additional option indicators included in the approved methodology (Table 3.1, UNEP 2021). These subindicators are broken down into three levels:

Level 1: Global indicators

- Plastic patches greater than 10 metres (for areas beyond national jurisdiction or for total oceans)
- Beach litter originating from national land-based sources

Level 2: National indicators

- Beach litter count per km^2 of coastline (surveys and citizen science data)
- Floating plastic debris density (visual observation, manta trawls)
- Water column plastic density (demersal trawls)
- Seafloor litter density (benthic trawls (such as fish survey trawls), divers, video/camera tows, submersibles, remotely operated vehicles)

Level 3: Supplementary indicators

- Beach litter microplastics (beach samples)
- Floating microplastics (manta trawls such as the Continuous Plankton Recorder)
- Water column microplastics (demersal plankton trawls)
- Seafloor litter microplastics (sediment samples)
- Plastic ingestion by biota (such as birds, turtles, fish)
- Plastic litter in nests
- Entanglement (of marine mammals, birds)
- Plastic pollution potential (based on the use and landfilling of plastics)
- River litter
- Other parameters related to plastic consumption and recycling
- Health indicators (human health and ecosystem health)

Table 3.1. Monitoring parameters for marine plastic litter to track progress against the SDG Target 14.1 (UNEP 2021).

Monitoring parameters (and methods)	Level 1	Level 2	Level 3
Plastic patches greater than 10 metres*	X		
Beach litter originating from national land-based sources	X		
Beach litter (beach surveys)		X	
Floating plastics (visual observation, manta trawls)		X	
Water column plastics (demersal trawls)		X	

Seafloor litter (benthic trawls (such as fish survey trawls), divers, video/camera tows, submersibles, remotely operated vehicles)	**X**	
Beach litter microplastics (beach samples)		**X**
Floating microplastics (manta trawls such as the Continuous Plankton Recorder)		**X**
Water column microplastics (demersal plankton trawls)		**X**
Seafloor litter microplastics (sediment samples)		**X**
Plastic ingestion by biota (such as birds, turtles, fish)		**X**
Plastic litter in nests		**X**
Entanglement (of marine mammals, birds)		**X**
Plastic pollution potential (based on the use and landfilling of plastics)		**X**
River litter		**X**
Other parameters related to plastic consumption and recycling		**X**
Health indicators (human health and ecosystem health)		**X**

** This indicator is most useful for areas that extend beyond national jurisdictions or total ocean area; it is not as useful for national monitoring.*

These indicators are marked as levels 1, 2 or 3. Level 1 consists of global data or is globally modelled, level 2 includes national monitoring, and level 3 describes supplementary/recommended indicators

3.5 Considerations for the Future Development of Indicators

As global, regional and national indicators continue to be developed, one must remember that an indicator's primary function is to simplify complex information (European Environment Agency 2003). Environmental indicators are often developed using casual chain frameworks such as Pressures-State-Response (PSR), Driving-State-Response (DSR) and Driving forces-Pressures-States-Impacts-Responses (DPSIR) (figure 3.2) (Niemeijer and Groot 2008).

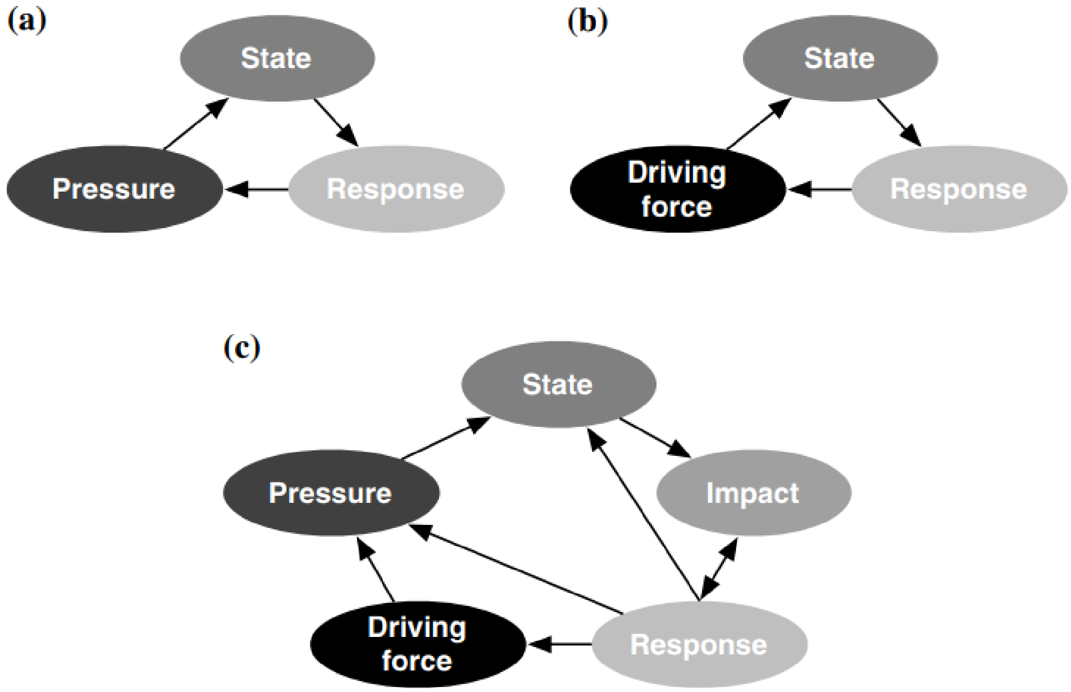


Figure 3.2. The (a) PSR, (b) DSR and (c) DPSIR frameworks. Modified figure based on Niemeijer and de Groot (2008).

Moving forward, sets of indicators as arranged into casual networks in an enhanced DPSIR framework (eDPSIR) have been considered for complex environmental sustainability issues (Chandrakumar and McLaren, 2018; Niemeijer and Groot, 2008) and could be useful for the complex issue of marine litter. However, major challenges in developing functional indicator frameworks include a lack of baseline data and a lack of consistency across indicators developed by the various regional organizations.

.

4 Monitoring the Plastics Value Chain

Monitoring marine litter is essential to understand the extent and impact of marine litter and plastic pollution, but it isn't enough to inform effective policy decisions. A complete life cycle approach – from the way plastic is produced, how it is used in products and how it eventually becomes waste – must be adopted in order to weigh management options when tackling the global problem of marine litter and when considering issues related to waste in terrestrial and freshwater environments.

This approach pushes us to assess all sorts of environmental impacts generated by the use of resources (such as land, water, minerals, biomass) and of emissions (namely greenhouse gas emissions, toxic emissions, nutrient pollution) throughout the production and consumption life cycles. With life cycle approaches, systems acquire the perspective to assess how plastic is used for which product. Alternatives can also be compared: how to use plastic (opting for reusable versus disposable products) or considering products made with alternative materials.

UNEP (2018a) and Ryberg *et al*. (2019) followed such a life cycle approach when they mapped the global losses of plastic across its main value chains, differentiating between polymer types, applications, macroplastics and microplastics and other variables. According to this research, approximately 6.2 Mt of macro-plastics and 3.0 Mt of microplastics were lost to the environment in 2015 (Figure 4.1). These losses are distributed across marine, freshwater, and terrestrial components of the environment and can be analysed per life cycle phase (Figure 4.2)[24]

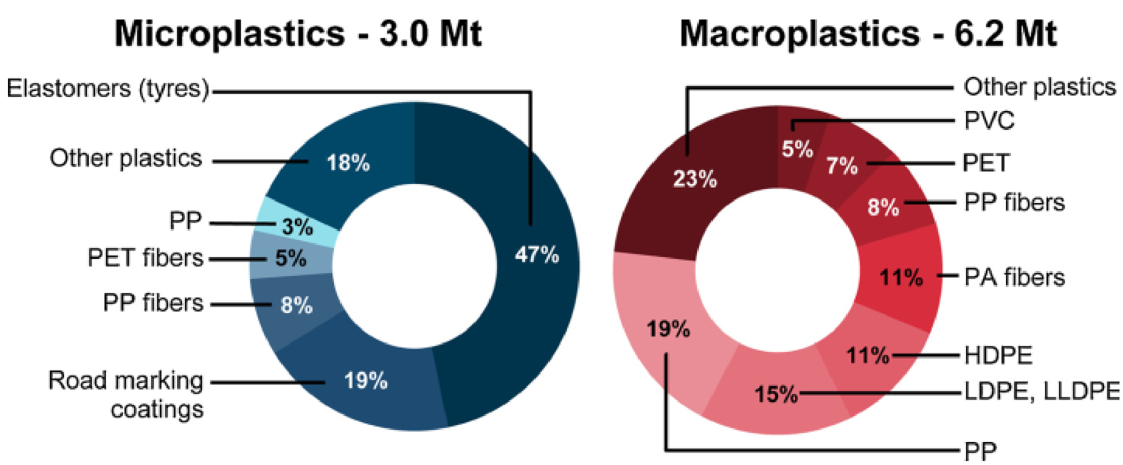


Figure 4.1: Losses of Macroplastic to the environment in 2015. Source: Ryberg (2019).

[24] The mass of plastics produced is not equal to the mass of plastics disposed of due to plastic service lifetime extending beyond the year of production. Accordingly, a fraction of the plastic wastes disposed of in 2015 were produced in the years before 2015.

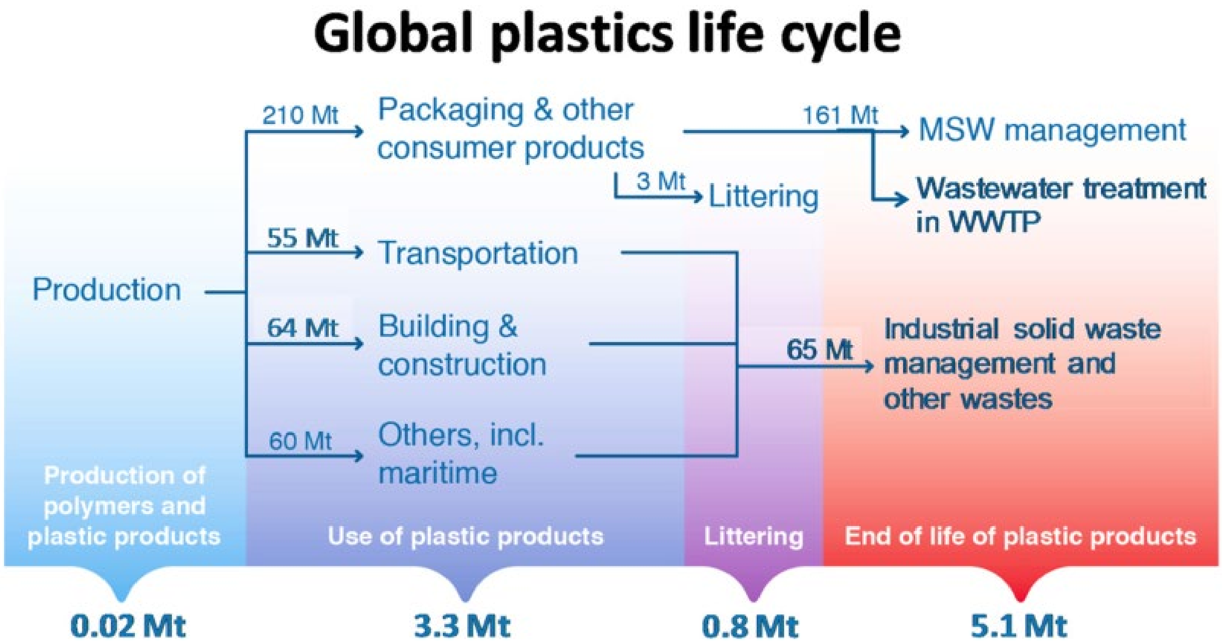


Figure 4.2. Global plastics life cycle value chain, estimated losses to the environment for the year 2015. Source: Ryberg *et al*. (2019).

Across the plastics life cycle, the largest losses of plastics occur during use and end-of-life (EoL) stages, which account for approximately 36 per cent and 55 per cent of total plastics losses to the environment, respectively. In comparison, losses during plastics production are relatively small and account for 0.25 per cent of total plastic losses. In general, about 90 per cent of microplastics losses are attributed to the use stage, about 77 per cent of macro-plastics losses are from the EoL stage, and 13 per cent of macro-plastics losses stem from littering. Plastic losses to the environment can also be analysed by geographical regions, by decomposition status as macro and microplastics, and by loss sources (Figure 4.3), among other potential variables.

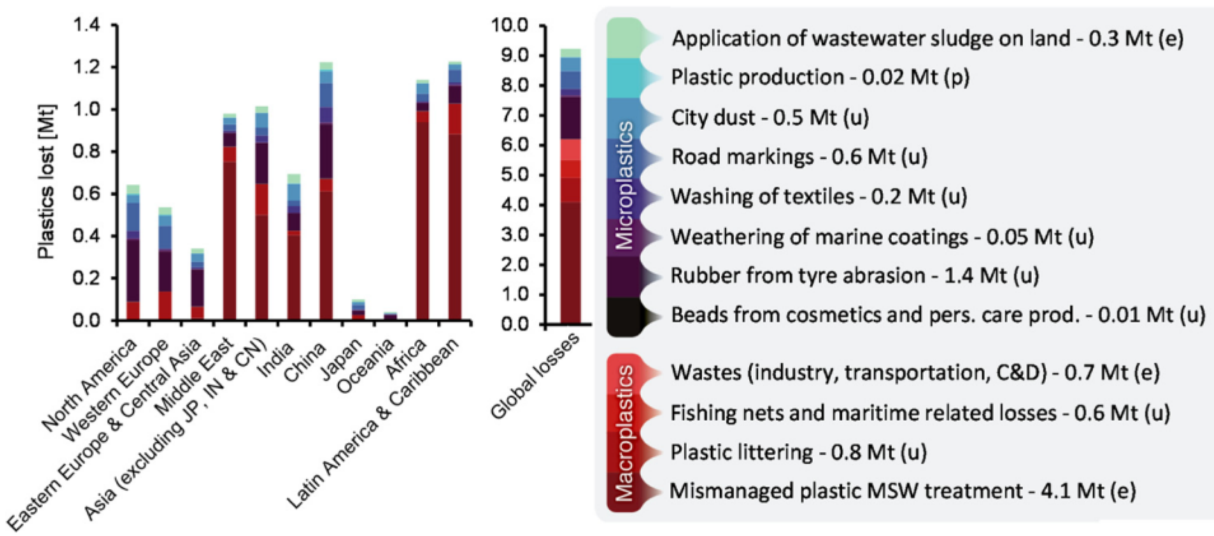


Figure 4.3. Losses of macroplastics and microplastics to the environment, including marine, freshwater, and terrestrial compartments, characterized according to region and loss sources. Losses from maritime activities like fishing or shipping, and losses from the building industry and the transportation sector could not be assigned to specific regions and are only indicated in the global estimates. (p) shows losses during the production stage, (u) shows losses during the use stage, (e) shows losses during the end-of-life stage. Source: Ryberg *et al.* (2019).

As shown above, life cycle studies provide a systems perspective. They show how plastics are manufactured and how they flow through the economic sector up to their final destination. The geographical resolution of such approaches strongly depends on the source of the data and on the ways in which data is collected. As with the monitoring of plastic pollution and marine litter, two main monitoring styles stand out: top-down, and bottom up. Both approaches can be applied in order to understand plastic pollution from a life cycle perspective.

Top-down approaches rely primarily on reported waste management data and on reported trading databases that feature manufactured amounts, imports and exports. Their system boundaries are often limited to a country level. Many of the SDG indicators under SDG goal12 – Responsible Production and Consumption – fall under this category. With these top-down approaches, the challenge is to reduce the geographical resolution beyond the country level. In such cases, life cycle studies can provide valuable information on the origin (as in the country) of the estimated amounts of plastic present in the marine environment. However, allocating different amounts of manufactured plastic to specific cities remains difficult within the scope of these studies. Similarly, clearly understanding which disruption in the waste management system causes pollution is also complex.

In the context of bottom-up approaches, primary data are mainly (but not exclusively) collected at the city level, as one of the aims is to thoroughly understand the value and service chains of plastic materials. Many SDG indicators under goal 11 – Sustainable Cities and Communities – fall under this category. These approaches have the advantage of providing information on the source of marine plastic litter, in a particular city for example. Bottom-up approaches can also provide valuable contextual information for the examination of potential policy and infrastructure operations. Due to an in-depth understanding of disruptions in the municipal solid waste management (MSWM) system, these approaches can be instrumental when considering ways of reducing plastic waste emissions in terrestrial environments, lakes and rivers or when attempting to curtail harmful waste burning practices.

Both approaches are complementary. The decision to elect a top-down or a bottom-up approach to monitor and report progress is often determined by data availability. In ideal cases, when data from both approaches are available, the various sources of information can be used for triangulation and to develop a deeper and more nuanced understanding of the situation.

SDG 12 and SDG 11 illustrate how selected stages of the life cycle can be monitored and reported. However, the full life cycle approach is inherently complex, with thousands of interrelated processes that span across sectors and country borders. Therefore, significant parts of the system must be modelled rather than directly measured or monitored. Reliable databases of key "check points" are needed for such modelling to take place. These points include: production volumes, amounts of waste generated and collected, final destinations of discarded plastics including recycling collection, amounts that are genuinely recycled, incinerated fraction with/without energy recovery, landfills, dump/environment/litter, and amounts of recyclates re-entering the system at the transformation stage.

A full life cycle approach ties in directly with a number of SDG targets and indicators (table 6):

- 8.4.1 and 12.2.1, on domestic material consumption and material footprint, draw on the amounts of raw materials used by an economy and include information on plastic production;
- 11.6.1 and 12.5.1 on municipal solid waste management and recycling, respectively;
- 6.3.1 and 6.3.2 on pollution in wastewater and freshwater;
- 14.1.1.b on plastic pollution as measured through marine debris.

See Annex B for additional information on data for related SDGs.

Table 4.1. SDG targets and indicators relating to a life cycle approach.

Goal 6: Ensure availability and sustainable management of waste and sanitation for all		
Target		*Indicator*
6.3	By 2030, improve water quality by reducing pollution, eliminating dumping and minimizing release of hazardous chemicals and materials, halving the proportion of untreated wastewater and substantially increasing recycling and safe reuse globally	6.3.1: Proportion of wastewater safely treated
		6.3.2: Proportion of bodies of water with good ambient water quality

Goal 8: Promote sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all		
Target		*Indicator*
8.4	Improve progressively, through 2030, global resource efficiency in consumption and production and endeavour to decouple economic growth from environmental degradation, in accordance with the 10-year framework of programmes on sustainable consumption and production, with developed countries taking the lead	8.4.1 Material footprint, material footprint per capita, and material footprint per GDP
		8.4.2 Domestic material consumption, domestic material consumption per capita, and domestic material consumption per GDP
Goal 11: Make cities and human settlements inclusive, safe, resilient and sustainable		
Target		*Indicator*
11.6	By 2030, reduce the adverse per capita environmental impact of cities, including by paying special attention to air quality and municipal and other waste management	11.6.1 Percentage of urban solid waste regularly collected and with adequate final discharge with regard to the total waste generated by the city
Goal 12: Ensure sustainable consumption and production patterns		
Target		*Indicator*
12.2	By 2030, achieve the sustainable management and efficient use of natural resources	12.2.1 Material footprint, material footprint per capita, and material footprint per GDP
		12.2.2 Domestic material consumption, domestic material consumption per capita, and domestic material consumption per GDP

12.4	By 2020, achieve environmentally sound management of chemicals and all wastes throughout their life cycle, in accordance with agreed international frameworks, and significantly reduce their release to air, water and soil in order to minimize their adverse impacts on human health and the environment	12.4.1 Number of parties to international multilateral environmental agreements on hazardous and other chemicals and waste that meet their commitments and obligations in transmitting information as required by each relevant agreement
		12.4.2 Hazardous waste generated per capita and proportion of hazardous waste treated, by type of treatment (including e-waste)
12.5	By 2030, substantially reduce waste generation through prevention, reduction, recycling and reuse	12.5.1 National recycling rate, tons of material recycled
14.1.	By 2025, prevent and significantly reduce marine pollution of all kinds, in particular from land-based activities, including marine debris and nutrient pollution	14.1.1.b. Floating plastic debris density (including subindicators described in Section Three).

In 2020, UNEP, in collaboration with the International Union for the Conservation of Nature (IUCN) and the Life Cycle Initiative, published a National Guidance for Plastic Pollution Hotspotting Action. This guidance provides countries with a systemic methodology based on the life cycle approach to help identify hotspots related to the most relevant plastic polymers, products, sectors and regions. Under this guidance, measuring the leakages that occur at each life cycle stage and their associated impacts will help identify hotspots from the value chain. Potential key hotspots along the value chain also include: high amounts of plastic product production, high littering rates, low waste collection rates in rural areas and insufficient recycling capacity across the country. The guidance is founded on a comprehensive hotspot analysis. It provides further help in identifying key intervention areas and instruments tailored to the local context to enable actions at relevant life cycle stages (UNEP 2020).

5 Current and Emerging Global Data Platforms

The proliferation of databases and portals poses a challenge for ocean data as a whole, including specific data on marine litter and plastic pollution. In recognition of this issue, several global efforts are in development to create aggregated platforms that search and/or harvest data from multiple databases and repositories. This section provides summaries of existing and developing platforms relevant to the GPML Digital Platform, including a more detailed overview of the GPML Digital Platform at the time of the Phase II release in September 2022.

5.1 The Global Earth Observation System of System (GEOSS) Platform

The Group on Earth Observations (GEO) is a partnership of more than 100 national governments and over 100 participating organizations with the vision of "a future wherein decisions and actions for the benefit of humankind are informed by coordinated, comprehensive and sustained Earth observations" (Group on Earth Observations 2005). The GEO community is creating a Global Earth Observation System of Systems (GEOSS) to better integrate observing systems and to share data by connecting existing infrastructures using common standards[25].

The GEOSS Platform[26] proactively links existing and planned observing systems around the world; it also supports the development of new systems where gaps appear. The GEOSS Platform promotes the use of common technical standards in order to combine data from thousands of different instruments into coherent data sets. Essentially, the GEOSS Platform (Figure 16) is a brokering infrastructure. The GEO Discovery and Access Broker (GEO DAB) is the primary mechanism designed to discover and access all data and information. The GEO DAB implements the necessary mediation and harmonization services through APIs that allow data providers to share resources without having to make major changes to their technology or standards.

The GEOSS Platform presently brokers more than 150 autonomous data catalogues and information systems (Figure 5.1). Data providers are constantly being added and brokered according to user needs. It would be possible to add and broker marine litter data from a variety of sources, including from the GPML Digital Platform.

Upgraded features are being tested on the GEOSS Platform through the implementation of scenarios that showcase the platform's potential to support the access and the use of data and knowledge, and to be results-oriented. It shows how the GEOSS Platform could potentially provide value to different categories of users – including earth scientists and policy makers – when finding, producing and analysing information, the ultimate goal being to support the final consumers' knowledge acquisition process.

[25] http://www.earthobservations.org/geo_community.php

[26] http://www.earthobservations.org/gci.php

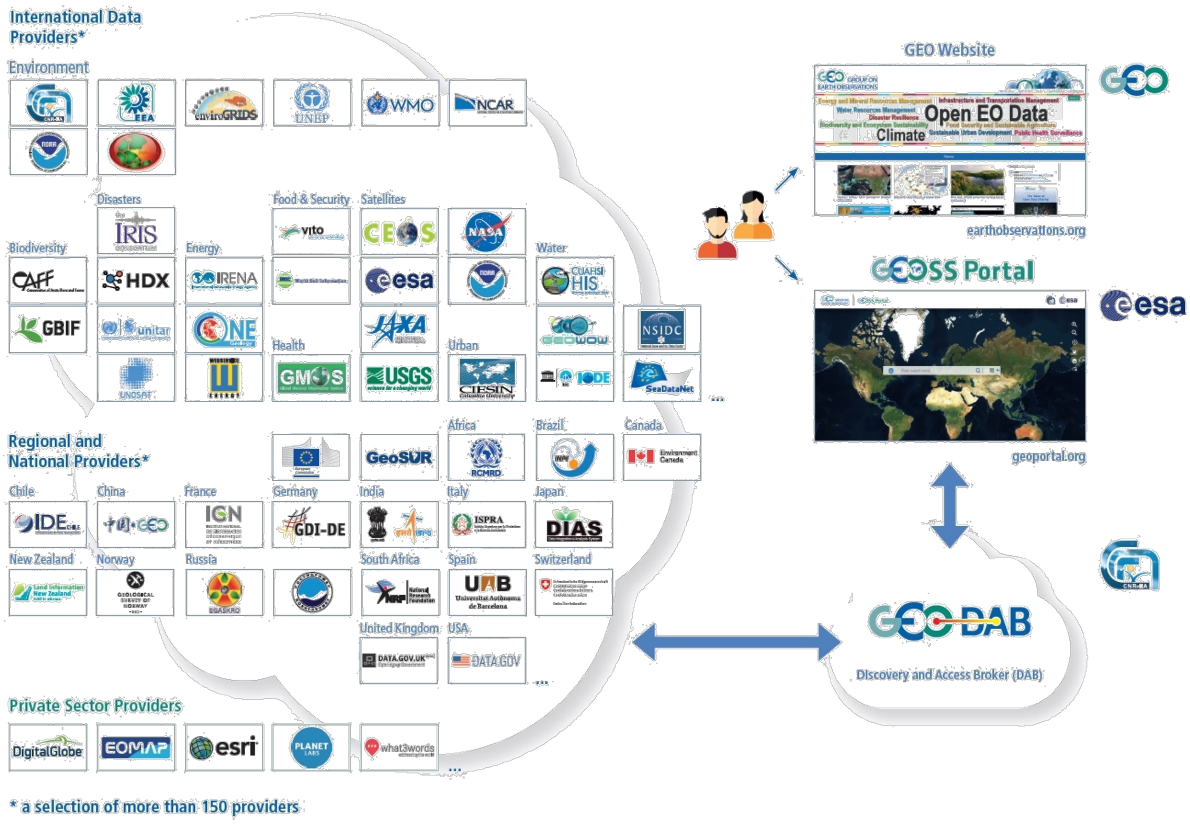


Figure 5.1. Components of the GEOSS Platform.

The GEOSS Portal currently offers a single access point to search and to identify available data sources. The GEOSS infrastructure will evolve between 2020 and 2022 to include the development of GEO Community Portals, or hubs (DeLoatch 2019). The development of a GEO Marine Litter Community Portal is a possibility.

5.2 The European Marine Data and Observation Network (EMODnet)

EMODnet is a long-term flagship initiative of the EU (funded by the European Commission Directorate-General for Maritime Affairs and Fisheries, Figure 5.2). Its mandate is to deliver open access to aggregated and standardized marine data and to data products across seven thematic areas, namely: bathymetry, biology, chemistry, geology, human activities, physics and seabed habitats. It offers a broad range of in situ data as well as products that combine data with satellite-derived data such as bathymetry. Products include the digital terrain model for high-resolution bathymetry, seabed habitat maps (based on the EUNIS classification), vessel density maps (monthly composites) and the marine litter maps from the Marine Litter Database. EMODnet delivers this in collaboration with other key marine data initiatives including the Copernicus Space programme (and Copernicus Marine Service) and the Data Collection Framework, which focuses on fisheries.

While initially EU-focused, EMODnet's user community is becoming more and more international. Thanks to its data ingestion service and a number of international collaborations, EMODnet now offers a wider coverage of data sets that extend beyond Europe. EMODnet Chemistry is one of seven thematic portals; it provides access to chemical data on topics as wide ranging as chlorophyll, dissolved gases and pollutants, and marine litter. Data products for eutrophication, contaminants and marine litter are also available across six European seas and bordering ocean regions. In the case of marine litter, data are assembled, standardized and aggregated. The data policy for the collected litter data is defined by the data originators. For restricted data, the relevant National Oceanographic Data Centre facilitates a negotiation process between the user and the data originator. When data are used, an acknowledgement of the data source is requested. EMODnet Chemistry provides access to litter data sets through a dedicated discovery and access service[27] that allows searches using the available parameters (space, time, matrix, group of variables, discovery parameter, data distributor and country). The aggregated data sets are also described in the product catalogue[28] (which provides information on the unique persistent identifier (DOI). The viewing service and the product catalogue provide data products on the concentration and the composition of litter items, on plastic bags, smoking and fishing related items along the European coasts, and on the density and composition of litter on the seafloor.

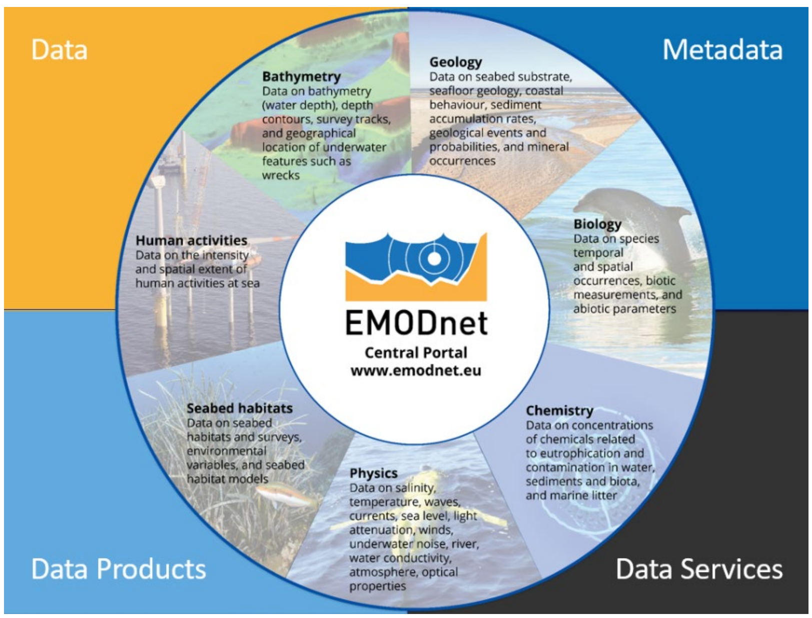


Figure 5.2. EMODnet open access marine data, metadata and data products across seven thematic areas. Data and web services offer unique ways of discovering, visualizing, downloading and working with marine data.

5.3 The Living Atlas of the World

The Living Atlas of the World[29] is, at present, the world's largest GIS digital library. It boasts a rich set of thousands of ready-to-use online data layers and maps, and offers other related features such as geocoding, routing, or geo-enrichment (Figure 5.3). All assets can be accessed with desktops, servers, mobiles, and/or web mapping applications. While the content is hosted by Esri,

---

[27] https://emodnet-chemistry.maris.nl/search

[28] https://www.emodnet-chemistry.eu/products/catalogue

[29] https://livingatlas.arcgis.com/en/

the mostly open-access contributions originate from scores of government partners, NGOs, academia, and the private sector. These contributions represent the top 1% of ArcGIS Online's[30] 44 million public items. They are accessed by 1.6 million users daily, with 4.5 billion map tile requests monthly. The Living Atlas is a useful and reliable source for hundreds of topics (such as the oceans' chapter of the atlas)[31] including ocean conservation, coastal and marine spatial planning, ocean resource management and marine litter surveys. The Living Atlas currently hosts a marine and lake litter data set for Italy, the first preliminary study on the presence of microplastic particles in Italian lakes, and monitoring data on floating waste along the sea routes of Goletta Verde. Global ocean plastic data sets and story maps are also featured in the catalogue. The Living Atlas is configured for users to readily consume and/or share live data feeds through a limited set of open-source and third-party APIs (such as Leaflet, JS, OpenLayers, MapBox GLS JS, etc.[32]) and through the ArcGIS REST API and the ArcGIS API for Python.

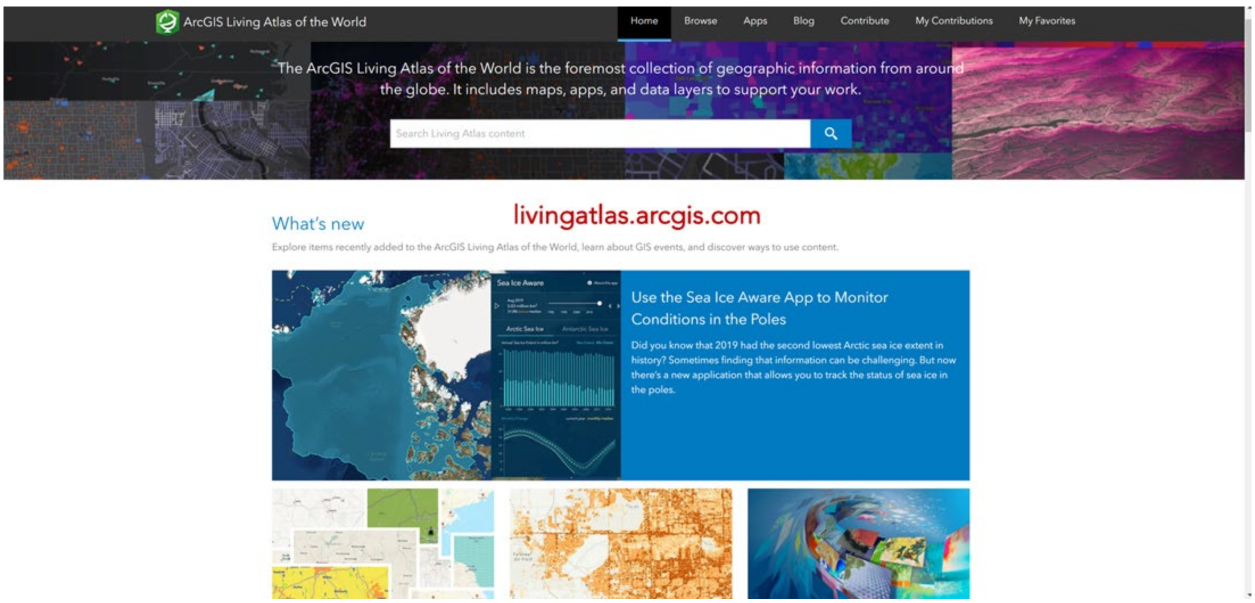


Figure 5.3. The Living Atlas of the World includes over 8,000 ready-to-use data sets, maps and apps to power many environmental data systems. Partners with and contributors to the Atlas include the NOAA, the Marine Conservation Institute, the European Space Agency, NatureServe, GRID-Arendal, and the UNEP World Conservation Monitoring Centre.

5.4 Resource Watch

The Resource Watch[33] platform, hosted by the World Resources Institute (WRI), is a free, open data visualization platform that includes more than 200 data sets on topics ranging from climate

---

30 http://www.arcgis.com/home

31 https://livingatlas.arcgis.com/en/browse/#d=2&q=oceans&categories=Environment:0110000000

32 https://developers.arcgis.com/documentation/mapping-apis-and-services/)

33 https://resourcewatch.org/

change to agriculture. Data are curated by WRI experts and extracted from peer reviewed and verified sources. Resource Watch data visualization features include the ability to overlay data sets, to create dashboards and to download data from the original source.

5.5 The Global Earth Challenge

In recognition of Earth Day's fiftieth anniversary on 22 April 2020, a consortium of partners – led by the Woodrow Wilson International Center for Scholars, the Earth Day Network, and the U.S. Department of State – launched the 2020 Earth Challenge, which was designed as the world's largest coordinated citizen science campaign. The focus of this challenge was initially set around six research areas including plastics pollution. Its aim was to harmonize existing citizen science data through an open, API-enabled platform, and to enable new data collection options through a mobile application. While the project initially launched in April 2020 with a global outreach campaign, this initiative's ultimate goal is to create long-lasting infrastructure to support interoperable citizen science data.

In 2020 and 2021, a new integrated data set for plastic pollution, measured through beach cleanup campaigns, was created. Drawing on data from three programs – NOAA's Marine Debris Monitoring and Assessment Project, EEA's Marine Litter Watch, and Ocean Conservancy's TIDES database – the project first harmonized classification schemes, then produced a single, interoperable, multi-year data set available through an open API. In February 2021, this integrated data set was used in SDG reporting as a proxy indicator for beach litter for six years, from 2015 to 2020. In addition to the integration of data from beach cleanup campaigns, citizen scientists can use a mobile application to contribute data in two ways. First, a simple protocol allows any person anywhere in the world to record and classify plastic pollution in terrestrial, marine, and freshwater environments. Second, the program has partnered with the University of São Paulo and the UN Environment Programme-Brazil on an app to support beach cleanups using an alternative, user-friendly methodology.

5.6 The Ocean Data Information System (ODIS)

The International Oceanographic Data and Information Exchange (IODE)[34] programme of the Intergovernmental Oceanographic Commission (IOC) of the United Nations Educational, Scientific and Cultural Organization (UNESCO) serves to enhance marine research and marine exploitation and development. Its aim is to facilitate the exchange of oceanographic data among participating member states, and by meeting users' needs regarding data and information products.

Several marine data and information products and repositories are currently supported by IODE. These include the Ocean Biogeographic Information System (OBIS)[35], which is a data system for biodiversity and biogeographic information on marine life, and the Ocean Data Portal[36], which is

[34] https://www.iode.org/

[35] http://www.iobis.org/

[36] http://www.oceandataportal.org/

a data system that collects, integrates and manages physio-chemical data. IODE also has a number of National Oceanographic Data Centres (NODCs) and Associate Data Units (AUDs) that work to support data and information management in member states[37].

At present, IOC data cannot be accessed through a single portal or platform. A 2016 external audit therefore recommended that IODE implement a universal marine data and information system. In response to this audit recommendation, IODE produced a concept paper for the development of an Ocean Data and Information System (ODIS) that would improve the accessibility and interoperability of existing information related and unrelated to the IOC. A conceptual architecture for the system (Figure 5.4), an implementation plan, and a cost-benefit analysis (Spears *et al*. 2017) are outlined in the concept paper.

[37] https://www.iode.org/index.php?option=com_content&view=article&id=61&Itemid=100057

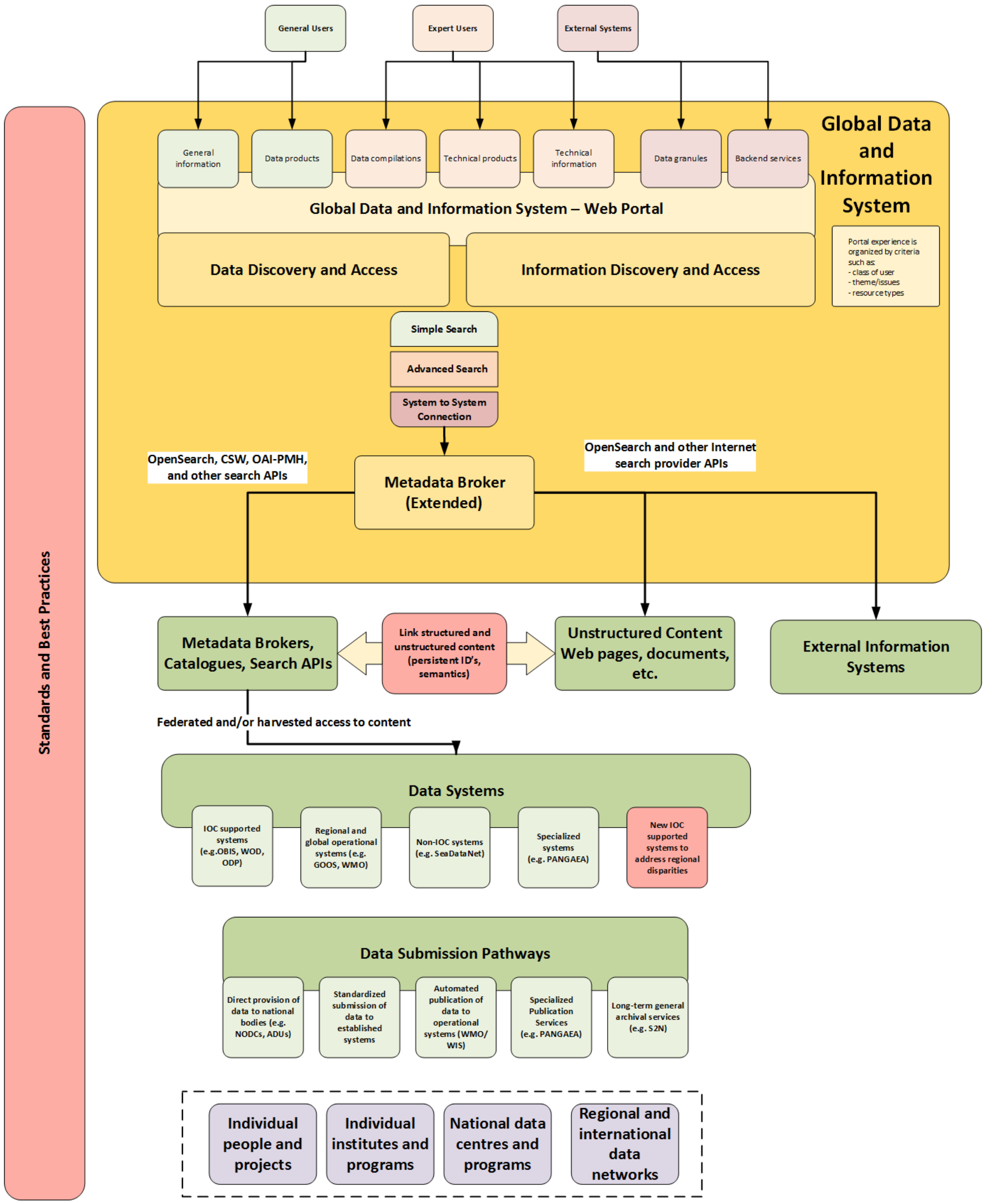


Figure 5.4. The conceptual architecture of ODIS (Spears *et al*. 2017)

At the thirtieth session of the IOC-UNESCO assembly, IODE was invited to submit a fully detailed and quantitative ODIS project proposal for the IOC Executive Council's fifty-third session in 2020 (Intergovernmental Oceanographic Commission of the United Nations Educational, Scientific and Cultural Organization [IOC-UNESCO] 2019). With funding, ODIS could potentially support access to significant sources of information, notably to global marine litter data from the GPML Digital

Platform. The GPML Digital Platform, along with other similar portals, could also benefit from ODIS's conceptual and technical architecture.

5.7 The Ocean Data Platform

The Ocean Data Foundation (ODF)[38] is a not-for-profit foundation funded by the Resources Group, a philanthropic foundation established by Norwegian businessperson Kjell Inge Røkke. The Ocean Data Platform (ODP), an ODF initiative, is an open and collaborative data platform that harnesses the power of data liberation and data contextualization for the general public, the industry sector, academia, science, policymakers and governments. The platform strives to connect data, people and technology to drive sustainable ocean governance and blue economy.

The platform is designed as an open collaborative tool for ocean data; it brings together existing data providers and knowledge hubs[39]. The ODF is currently developing selected key use cases around which it will build the platform. Depending on the Ocean Data Platform's development timeline and on its features, access to global marine litter data could be supported by the platform.

5.8 The GPML Digital Platform Phase II Release

The GPML Digital Platform is openly co-developed via a phased approach based on a human-centred design that prioritizes an engaging user experience and that draws on design thinking and agile methods. An initial minimum viable product (MVP), known as Phase I, was released in February 2021; a beta version of the platform's Phase I was made available to the general public. This release focused on formulating an initial version of the knowledge exchange component. Though limited, the beta features, associated with the data hub and the "connect stakeholders" component, allowed users to preview forthcoming developments.

An updated release took place in September 2021 (Phase II) and included an MVP of the data hub[40]. The landing page provides the option of filtering topics such as ”water,” ”waste,” ”ocean,” ”policy,” ”biodiversity,” and ”protected areas”. Specific data sets are then displayed on a GIS interface. The prototype for a data catalogue, which currently lists each individual data layer alongside access information, was created using Esri's ArcGIS Hub technology. The Phase II MVP was defined to include both technical features – the GIS interface and the data catalogue with an API – as well as a wide range of data sources (Appendix B). For instance, the 22 data sets featured in the GPML Digital Platform Phase II release correspond to each of the topics mentioned above, and represent a range of SDGs including goals 6, 11, 12, and 14. Both regional and global-scale data sets are included, along with complementary information such as global population data.

UNEP has, to date, handled the project's technical development and the selection of the initial data sets. Both future technical efforts and the selection of additional data sets will be driven by a mix of expert assessments – through the present White Paper, among other sources – and by

---

[38] www.oceandata.earth

[39] https://www.revocean.org/platform/oceandata/

[40] https://digital-gpmarinelitter.hub.arcgis.com/

an open, user-centred design approach. Recommendations for immediate next steps are explored in the following section.

6 Next Steps

As observed throughout this paper, data sources on marine litter and on plastic pollution are diverse and hard to access. Existing data are collected through a wide range of observational methods and monitoring methodologies characterized by different technology readiness levels (TRLs) and stewarded by a range of individuals and organizations working at local, regional, national, and global scales. While efforts have been made to develop indicators, including those for SDG 14, additional efforts are needed on multiple fronts.

First, foundational scientific and technical efforts are required to help monitoring methodologies mature. Second, existing sources of data need to be identified and integrated as best as possible. Marine litter data are distributed across multiple databases and publications, and are available in different formats; consolidating these data sets will be a challenge. A third required effort is to process the available information into indicators that inform and report on progress. Much remains to be done for SDG 14.1.1b indicators to be carried out globally and for more advanced global indicators to be developed and implemented. Fourthly, a life-cycle approach will need to be adopted to manage plastic pollution effectively; with this approach, stocks and flow are quantified during all phases: production, use, and disposal.

The need to move from pre-defined data products to a content-as-a-service model is answered through the construction of a customer-centric and user defined Global Data Platform. Cloud computing and data analyses across different types of spatial and non-spatial data are imperative. Combining spatial earth observation data with socio-economic data generates knowledge and information (such as indicators) that respond to policy needs. The platform must be collaborative and federated. Data producers must be able to host, manage and share their own data locally. Open standard interfaces should also be instituted to allow users to exchange information and to access services from existing national/regional platforms and systems. Additional work is also required to help realize the GPML Digital Platform's vision of offering a coordinated, authoritative point of access for information on a range of topics related to plastic pollution and marine litter. The next key steps can be identified by considering the information presented in this White Paper, along with feedback from a range of stakeholders involved in the design and the development of the GPML Digital Platform's Phase I and Phase II releases.

In an effort to improve new versions of the platform following the initial Phase II release, user-centred design techniques – such as interviews, surveys and workshops – were employed to collect feedback from users. In 2021, nine user consultations with 60+ partners highlighted tensions that could be addressed to enhance our collaborative understanding of marine litter and plastic pollution. Key tensions and opportunities, which the GPML Digital Platform can help advance, include:

- **Documentation, Standardization, and Interoperability.** Moving away from a lack of harmonization and going towards interoperability; moving away from different observational methods, protocols and standards, and from a lack of metadata standards across the value chain; promoting unified approaches.

- **Coordination.** Moving away from distributed data sets with inconsistent data documentation and unclear use conditions; tending towards more accessible and integrated data, information, and knowledge through a coordinated point of access with clear open data policies.
- **Partnerships**. Moving away from a lack of both ad hoc and regular data and information sharing while increasing broader collaboration among stakeholders to create a more connected multi-stakeholder community.
- **Informed Action.** Moving away from uncoordinated action and from activities conducted on disparate spatial and temporal scales; tending towards a common framework to implement actions and to monitor progress.

6.1 Documentation, Standardization and Interoperability

As it was described in Section One, many different parameters are involved in the formation of marine litter data. These parameters emerge because of the use of a variety of monitoring methods that are laden with multiple protocols and standards, disparate temporal and geospatial scales, distinct quality levels and contrasting technology readiness levels. Our overall understanding of marine litter's sources, transportation trajectories, global distribution, fate, and impacts is limited by a lack of standardized parameters and consistent data criteria and observation methods, as well as by an absence of methods of extracting information and knowledge from the available data,

In the short term, efforts should be made to document existing sources of data and information more effectively. These efforts include the standardization of marine litter terms and common vocabularies (semantics). For example, the development of a marine litter ontology and a glossary of key terms is currently underway. Existing environmental data resources are being utilized to reach more semantic interoperability. These ontologies include the Environment Ontology (ENVO)[41] and the Sustainable Development Interface Ontology (SDGIO). While led by UNEP, this work is conducted in collaboration with a range of ontology experts; it includes a multi-stakeholder process for the identification of initial terms of interest and for the peer review of draft resources. Work on semantic interoperability, conducted in parallel with the GPML Digital Platform, will help enhance the discovery and value of the resources hosted on the data hub. It will also present a framework for the sharing of knowledge with other partners and repositories. For example, the SeaDataNet pan-European infrastructure for ocean and marine data management also identifies common terminologies, metadata attributes, data schemes and models to uniformly populate the EU EMODnet Chemistry marine litter database and to implement the Marine Strategy Framework Directive (MSFD) (Addamo *et al*. 2018; European Union 2008; Molina Jack *et al*. 2019). Once work on a targeted Marine Litter Ontology and Glossary matures, a necessary next step will be cross-walking key terms with other projects, such as the collection of initiatives under SeaDataNet.

Standardizing semantics, particularly to assist with the documentation of data sources and/or information about data sets (such as metadata), is one step towards interoperability. Additional challenges related to the actual format and exchange of data remain. Since the beginning, the management plan for marine litter data made available through the GPML Digital Platform has

[41] https://sites.google.com/site/environmentontology/

been to adopt consolidated data formats, when available, and to adapt them as needed. Following this approach, three specific methods for microlitter on the beach, seafloor and water surface have been adopted, using the best available reference documents to develop a tailor-made approach at the European scale (Martín Míguez *et al*., 2019). The ingestion of the litter data sets have been challenging due to the complexity of the information and the heterogeneity of the source data. For the GPML Global Data Platform, the Statistical Data and Metadata eXchange (SDMX) standard[42] is also adopted for the SDG indicators data sets using the SDG Data Structure Definition (DSD) for data collection and data sharing. The SDMX-JSON API feeds into the platform with the SDG Indicators data.

6.2 Coordination

As explored in Sections Two and Five, a number of entities and platforms are already coordinating different types of data and information on various topics related to marine litter and plastic pollution. Many of the primary data sources identified in Section Two directly focus on different types of marine litter data. Some – including MLW, MDMAP, TIDES, and COASST – include information collected and shared by citizen science, which presents both an opportunity and a challenge. The use of citizen science data can be very useful, especially where "official" monitoring programs are scarce or not in place. However, it is necessary to implement tools that ensure a minimum quality of data.[43]

In some cases, the GPML Digital Platform may ingest data on marine litter from a single data provider specializing in a particular type of information. For beach litter, the ingestion of EEA Marine Litter Watch (MLW) data sets is still ongoing. EEA MLW collects data both from official monitoring and from citizen science. Data from citizen science represents a really interesting and relevant source of marine litter data due to its wide distribution (bottom-up approach). However, data sets collected with the MLW app show a strong heterogeneity in metadata and data quality. MLW data from some monitoring activities also vary in quality. For example, specifying the identity of the data originator is not mandatory in single citizen surveys; therefore, the feedback quality loop that regularly occurs with known originators cannot take place through traditional methods, such as through expert reviews. Additionally, the identification of surveyed beaches is very relevant for consolidated monitoring in order to obtain time-series data on the same place. In the case of citizen science data, the focus is on survey location aside from the beach where the survey was performed. As a result, the identification of surveyed beaches along a timeline can be difficult. An online beach catalogue or an OGC layer providing information (coordinates and metadata) of the surveyed beach can help integrate official monitoring data and citizen science

[42] https://sdmx.org/

[43] A number of citizen science projects already employ substantial mechanisms for data quality assurance and quality control (QA/QC). In addition to already existing strategies, such as expert review, a promising area for future work is cross-validating citizen science data and small aircraft data, including information collected through drones. A second option is the use of machine learning (ML) to identify different types of marine debris photographed by citizen science volunteers as an alternative, or as a complement to expert-based data validation techniques.

apps, and identify areas to prioritize for repeated sampling to promote the collection of time-sensitive data.

In other cases, the GPML Digital Platform may partner with other data curation or aggregation initiatives. An example of this is the Global Earth Challenge,[44] which integrated citizen science data on a range of topics available through both an API management platform and an Esri ArcGIS Hub, the Citizen Science Cloud.[45] Global Earth Challenge data was used for the first time in 2021 when reporting the SDG Indicator 14.1.1b as a proxy indicator for beach litter, with data uploaded over the course of multiple years, from 2015 to 2020. As a citizen science initiative specializing in both data collection and data aggregation, the Global Earth Challenge data set used in the reporting of SDG 14.1.1b contained information from three citizen science initiatives described in Section Two: MLW, MDMAP, and TIDES. For this reason, there may be some data duplication with broader MLW data, including citizen science information collected on beach surveys and data from other sources, such as professional research. For this reason, along with many others, the GPML Digital Platform is careful not to directly combine data sets, but rather to support a technical approach to data layering that is coupled with GIS analysis tools in an effort to help identify duplicates and describe each data set in as much detail as possible.

The process of looking across diverse yet related data sets, and bringing information together through a coordinated point of entry, allows potential data users to identify the fitness-for-use of various information data sets and to suggest the one most suited to their particular needs. This process can also help identify the most promising opportunities when standardizing data collection methods or when further developing promising approaches. Building off of citizen science efforts such as TIDES and the Global Earth Challenge, work with the Ocean Conservancy is underway to develop step by step harmonized guidelines for beach cleanup surveys, in accordance with the recommended methodology for SDG Indicator 14.1.1b. These efforts – which will result in an accessible how-to guide for any citizen science project to use – will take into consideration the citizen science protocols that are already in place, and identify how these can be augmented to produce data that is more directly aligned with SDG 14.1.1b reporting requirements.

However, despite all the efforts to harmonize and integrate the available information, producing data products that manage to summarize and highlight specific features is not an easy task. Due to the complexity and heterogeneity of the surveyed data, their integration is not always possible. As an example, the use of different gears (nets with different characteristics) for seafloor litter sampling leads to non-comparable data due to the differences in the sampling efficiency of the nets. In such cases, individual data sets will be documented in the GPML Digital Platform's data catalogue and made available as complementary data layers, rather than directly combined.

Less mature observation techniques can be targeted, such as remote sensing (Section One, Table 1.4). Moving forward, the design of specific parts of the Data Hub component of the GPML Digital Platform could focus on cross-validating simultaneous observations using different techniques. For instance, in order to make progress on remote sensing applications, part of the data set should match simultaneous satellite observations. This practice is common for ground

[44] https://globalearthchallenge.earthday.org/

[45] https://cscloud-ec2020.opendata.arcgis.com/

truth and development purposes for ocean colour satellites (such as NASA's SeaBASS). This can be supported through standardized and quality-controlled data sets of marine plastics concentrations in combination with additional radiometric measurements.

In addition to partners collecting data on marine litter, the platforms identified in Section Five generally have a much broader mandate than the GPML Digital Platform, but still coordinate relevant data and support important stakeholder communities. These platforms could partner with the GPML Digital Platform by exchanging data directly, either by publishing GPML Digital Platform data or through a two-way knowledge exchange. Information and expertise on various aspects of data curation and community coordination could also be shared. For example, the EMODnet Chemistry experiment, which consists of integrating heterogeneous data sources (collecting, standardizing, quality-control and sharing), began in 2009 with data related to eutrophication and contaminants (MSFD descriptors five, eight and nine). The Chemistry consortium has experience managing physical and chemical oceanographic data and information thanks to the activities carried out during the SeaDataNet project. In recent years, this experience has expanded in response to the request to manage marine litter data (MFSD descriptor ten).

Finally, in addition to documentation, standardization and interoperability, working with a range of data sharing partners requires paying close attention to the legal and ethical aspects of data reuse. The advantages of adopting an open data policy are widely accepted and include supporting broad economic benefits and growth, enhancing social welfare, growing research and innovation opportunities, facilitating the sharing of knowledge, and engaging in effective governance and policy making (Committee on Data of the International Science Council and Uhlir, 2015). But adopting open data and open access policies is not sufficient on its own; it is important to provide a platform to maximize the reproducibility spectrum where data, code, analysis procedures, best practices and literature are shared and replicable. In addition, a data policy following FAIR (Findable, Accessible, Interoperable and Reusable) principles, will support the development of solutions which are co-designed with research institutions, societal groups, government agencies, the third sector and the industry.

Tanhua *et al*. (2019) outlined how open and FAIR principles apply to ocean data. They discuss why ocean science is an essential foundation for the development of new services made possible through big data technologies. Ideally, all data made available through the GPML Digital Platform will be open and documented with an open data license. In cases where this is not possible – for biodiversity data on sensitive species that are vulnerable to plastic entanglement, for example – all efforts will be made to ensure the data are FAIR.

6.3 Partnerships

A federated ecosystem of data providers and other experts are working on issues related to marine litter and plastic pollution. Many of the investments made in semantic interoperability, such as the Marine Litter Ontology and Glossary, are designed to help support and strengthen this ecosystem. In addition, UNEP already collaborates with a wide range of partners through the GPML Digital Platform partners, and will pursue partnerships with additional stakeholders, including those identified in this White Paper.

Public-private partnerships play a critical role in the successful implementation of the Global Platform. While some partners may directly provide the GPML Digital Platform with technologies or assist with their development, others may target a specific component or area relevant to the platform's scope. One example of such a public private partnership is the Freshwater Ecosystems Explorer[46], which works on making progress on SDG indicator 6.6.1. This free platform brings together the European Commission Joint Research Centre's expertise in satellite data and data analysis, Google's cloud computing and artificial intelligence, and UNEP's scientific knowledge.

Other partners may hail from non-government organizations (NGOs), including non-profits and academia. As mentioned earlier, UNEP is working with Ocean Conservancy to develop step by step harmonized guidelines for beach cleanup surveys in accordance with the recommended methodology for SDG Indicator 14.1.1b. Pilot testing of the guidelines is also taking place in some countries. Following the SDG Indicator 14.1.1b, UNEP and Florida State University are also collaborating to produce a global model for beach litter originating from national land-based sources.

While the above partnerships include components related to research, development, or education, data sharing partnerships are equally important. For the Phase II release of the GPML Digital Platform, a key element in the success of data ingestion was the interaction with data originators. The consortium established communication with data originators (direct or through contacts from the Regional Seas Conventions), thus setting up a quality feedback loop. This step was crucial to clarify doubts on reported data and to detect potential duplicates and errors in data sets (or parts of them).

Moving forward, a framework for five interrelated action tracks will provide a formal structure when bringing experts together in a collaborative approach, similar to working groups and communities of practice. These action tracks will be established with the specific goal of supporting and informing the developments of the GPML Digital Platform, though they should also produce knowledge and resources more broadly valuable to a range of stakeholders working on marine litter, plastic pollution and related topics.

6.4 Informed Action

One of the primary aims of the GPML Digital Platform is to help a range of parties, including policymakers working at all levels of government, to make evidence-based decisions. The numerous findings stemming from the GPML Digital Platform user consultations generated a number of valuable insights that will help shape future developments, all in an effort to maximize benefits for this particular stakeholder community.

First, the platform should be results-oriented to offer clear and objective guidance to decision makers. Raw data must be transformed into actionable knowledge to drive decisions, policymaking, and mitigation actions. Assimilative numerical models, intelligent algorithms, remote sensing and advanced visualization tools may help contextualize the information and help in the development of operational monitoring systems (Atwood *et al*. 2019). In addition, indicators

[46] https://www.sdg661.app/

must be cross-referenced with socio-economic data; these scenarios allow decision-makers to respond to the challenges of adapting to, and coping with, these impacts. Indicators must be contextualized for them to be used operationally in the decision-making process.

Second, the platform needs to deliver more than quantitative data. Policy makers primarily adapt or adopt tried and tested policies and "do not target plastic waste once it has entered the environment; instead they aim to reduce the quantity of plastic production and use, before it is likely to enter the environment. In contrast, waste abatement outreach programs and infrastructure commonly target plastic waste before and after it has entered the environment. These strategies try to prevent and remove plastic waste from entering the environment and prevent coastal deposition" (Willis *et al*. 2018). Associating decision makers to monitoring areas would be very useful for the success of policies, regulations, awareness/abatement campaigns and strategies to prevent and reduce plastic pollution in general, and marine plastic in particular. Section Four of this White Paper offers a starting point by surveying indicators that already exist or that are being developed.

Finally, the GPML Digital Platform must act as a single platform for multiple policy contexts. Decision makers should, for instance, have the right insights at the right scale, but the requirements linked to these insights sometimes vary between countries. The platform must therefore be configurable and scalable to let countries upload and analyse national data, to support national source inventories, to support national action plans, and to be used in a broader global context. As identified by UNEP (Raubenheimer, 2019; Campbell and Jensen 2019a; Campbell and Jensen 2019b), this is a necessary condition if the platform is to generate the correct insights at the right scale, deliver these at the right time and in the right format, all in an effort to influence decision-making.

When built on a strong scientific and technical foundation, and constructed using an iterative, user-centred design process, the GPML Digital Platform should provide a valuable resource for a range of stakeholders working to understand, and ultimately eradicate, marine litter and plastic pollution. It also serves as an example of a major digital transformation initiative that leverages the power of technology to help advance environmental and social good. Looking forward, effective environmental governance will require applying the best of science and technology, not just to marine litter, but to a wide range of topics across the SDGs, as required to secure a sustainable future for all.

References

Acuna-Ruz, T., Uribe, D., Taylor, R., Amezquita, L., Guzman, M.C., Merrill, J., *et al.* (2018). Anthropogenic marine debris over beaches: Spectral characterization for remote sensing applications. *Remote Sensing of Environment, 217*, 309-322. https://doi.org/10.1016/j.rse.2018.08.008.

Addamo, A., Brosich, A., Montero, M., Giorgetti, A., Hanke, G., Molina, M. *et al.* (2018). *Marine litter database. Lessons learned in compiling the first pan-European beach litter database*.

Andrady, A.L. (2011). Microplastics in the marine environment. *Marine Pollution Bulletin, 62*(8), 1596-1605. https://doi.org/10.1016/j.marpolbul.2011.05.030.

Antonelis, K., Huppert, D., Velasquez, D., and June, J. (2011). Dungeness Crab Mortality Due to Lost Traps and a Cost–Benefit Analysis of Trap Removal in Washington State Waters of the Salish Sea. *North American Journal of Fisheries Management, 31*(5), 880-893. https://doi.org/10.1080/02755947.2011.590113.

Arctic Council. (2015). *Arctic Marine Strategic Plan 2015-2025.* Retrieved from https://oaarchive.arctic-council.org/handle/11374/413.

Atwood, E.C., Falcieri, F.M., Piehl, S., Bochow, M., Matthies, M., Franke, J., *et al.* (2019). Coastal accumulation of microplastic particles emitted from the Po River, Northern Italy: Comparing remote sensing and hydrodynamic modelling with in situ sample collections. *Marine Pollution Bulletin, 138*, 561-574. https://doi.org/10.1016/j.marpolbul.2018.11.045.

Axelsson, C., and van Sebille, E. (2017). Prevention through policy: Urban macroplastic leakages to the marine environment during extreme rainfall events. *Marine Pollution Bulletin, 124*(1), 211-227. https://doi.org/10.1016/j.marpolbul.2017.07.024.

Balance, A, Ryan, P.G., and Turpie, J. (2000). How much is a clean beach worth? The impact of litter on beach users in the Cape Peninsula, South Africa. *South African Journal of Science, 96*(5), 210-213. https://doi.org/10.10520/AJA00382353_8975.

Barboza, L., Vethaak, A., Lavorante, B., Lundebye, A.K., and Guilhermino, L. (2018). Marine microplastic debris: An emerging issue for food security, food safety and human health. *Marine Pollution Bulletin, 133*. https://doi.org/10.1016/j.marpolbul.2018.05.047.

Barnes, D.K.A. (2002). Invasions by marine life on plastic debris. *Nature, 416*(6883), 808-809. https://doi.org/10.1038/416808a.

Beaumont, N.J., Aanesen, M., Austen, M.C., Börger, T., Clark, J.R., Cole, M., *et al.* (2019). Global ecological, social and economic impacts of marine plastic. *Marine Pollution Bulletin, 142*, 189-195. https://doi.org/10.1016/j.marpolbul.2019.03.022.

Biermann, L., Clewley, D., Martinez-Vicente, V., and Topouzelis, K. (2020). Finding Plastic Patches in Coastal Waters using Optical Satellite Data. *Scientific Reports, 10*(1), 5364. https://doi.org/10.1038/s41598-020-62298-z.

Boucher, J., and Damien, F. (2017). *Primary Microplastics in the Oceans: a Global Evaluation of Sources.* Gland, Switzerland.

Brooks Amy, L., Wang, S., and Jambeck Jenna, R. The Chinese import ban and its impact on global plastic waste trade. *Science Advances, 4*(6), eaat0131. https://doi.org/10.1126/sciadv.aat0131.

Browne, M.A., Crump, P., Niven, S.J., Teuten, E., Tonkin, A., Galloway, T., and Thompson, R. (2011). Accumulation of Microplastic on Shorelines Woldwide: Sources and Sinks. *Environmental Science and Technology, 45*(21), 9175-9179. https://doi.org/10.1021/es201811s.

Buckland, S.T., Anderson, D.R., Burnham, K.P., Laake, J.L., Borchers, D.L., and Thomas, L. (2001). Introduction to distance sampling: Estimating abundance of biological populations. *448*.

Burton, G.A. (2017). Stressor Exposures Determine Risk: So, Why Do Fellow Scientists Continue To Focus on Superficial Microplastics Risk? *Environmental Science and Technology, 51*(23), 13515-13516. https://doi.org/doi:10.1021/acs.est.7b05463.

Campbell, J. and Jensen, D.E., 2019a. The promise and peril of a digital ecosystem for the planet, United Nations Environment Programme (UNEP). https://medium.com/@davidedjensen_99356/building-a-digital-ecosystem-for-the-planet-557c41225dc2.

Campbell, M.L., Peters, L., McMains, C., de Campos, M.C.R., Sargisson, R.J., Blackwell, B., and Hewitt, C.L. (2019). Are our beaches safe? Quantifying the human health impact of anthropogenic beach litter on people in New Zealand. *Sci Total Environ, 651*(Pt 2), 2400-2409. https://doi.org/10.1016/j.scitotenv.2018.10.137.

Campbell, J. and Jensen, D.E., 2019b. Could a Digital Ecosystem for the Environment Have the Potential to Save the Planet? National Council for Science and the Environment. https://www.ncseglobal.org/ncse-essays/could-digital-ecosystem-environment-have-potential-save-planet.

Chandrakumar, C., and McLaren, S.J. (2018). Towards a comprehensive absolute sustainability assessment method for effective Earth system governance: Defining key environmental indicators using an enhanced-DPSIR framework. *Ecological Indicators, 90*, 577-583. https://doi.org/10.1016/j.ecolind.2018.03.063.

Chassignet, E.P., Le Sommer, J., and Wallcraft, J.L. (2019). General circulation models. In K. J. Cochran, H. J. Bokuniewicz, and P. L. Yager (Eds.), *Encyclopedia of Ocean Sciences (3rd edition)* (486-490).

Chassignet, E.C, Pasal, A. Tintoré, J., and Verron, J. (Eds.). (2018). *New Frontiers in Operational Oceanography* (pp. 815): GODAE OceanView. https://doi.org/10.17125/gov2018.

Chassignet, E.P., Xu, X., and Zavala-Romero, O. (2021). Tracking Marine Litter With a Global Ocean Model: Where Does It Go? Where Does It Come From? *Frontiers in Marine Science, 8*, 414. https://doi.org/10.3389/fmars.2021.667591.

Cheshire, A., Adler, E., Barbière, J., Cohen, Y., Evans, S., Jarayabhand, S., *et al.* (2009). *UNEP/IOC Guidelines on Survey and Monitoring of Marine Litter*. (Regional Seas and Studies No. 186 IOC Technical Series No. 83).

Choy, C.A., Robison, B.H., Gagne, T.O., Erwin, B., Firl, E., Halden, R.U., *et al.* (2019). The vertical distribution and biological transport of marine microplastics across the epipelagic and mesopelagic water column. *Scientific Reports, 9*, 9. https://doi.org/doi:10.1038/s41598-019-44117-2.

Committee on Data of the International Science Council and Uhlir, P. (2015). *The Value of Open Data Sharing: A CODATA Report for the Group on Earth Observations*.

Cordova, M.R., and Nurhati, I.S. (2019). Major sources and monthly variations in the release of land-derived marine debris from the Greater Jakarta area, Indonesia. *Scientific Reports, 9*(1), 18730. https://doi.org/10.1038/s41598-019-55065-2.

Costanza, R. (1999). The ecological, economic, and social importance of the oceans. *Ecological Economics, 31*(2), 199-213. https://doi.org/10.1016/S0921-8009(99)00079-8

Courtene-Jones, W., Quinn, B., Ewins, C., Gary, S.F., and Narayanaswamy, B. E. (2019). Consistent microplastic ingestion by deep-sea invertebrates over the last four decades (1976-2015), a study from the North East Atlantic. *Environmental Pollution, 244*, 503-512. https://doi.org/10.1016/j.envpol.2018.10.090.

Critchell, K., Grech, A., Schlaefer, J., Andutta, F.P., Lambrechts, J., Wolanski, E., and Hamann, M. (2015). Modelling the fate of marine debris along a complex shoreline: Lessons from the Great Barrier Reef. *Estuarine Coastal and Shelf Science, 167*, 414-426. https://doi.org/10.1016/j.ecss.2015.10.018.

Critchell, K., and Lambrechts, J. (2016). Modelling accumulation of marine plastics in the coastal zone; what are the dominant physical processes? *Estuarine Coastal and Shelf Science, 171*, 111-122. https://doi.org/10.1016/j.ecss.2016.01.036.

Dae-Jung, H. (2020). The IMO Action Plan to Address Marine Plastic Litter from Ships and Its Follow-Up Timeline, *Journal of International Maritime Safety, Environmental Affairs, and Shipping*, 4:2, 32-39. https://doi.org/10.1080/25725084.2020.1779428.

D'Asaro, E.A., Shcherbina, A.Y., Klymak, J.M., Molemaker, J., Novelli, G., Guigand, C.M., *et al.* (2018). Ocean convergence and the dispersion of flotsam. *Proc Natl Acad Sci U S A, 115*(6), 1162-1167. https://doi.org/doi:10.1073/pnas.1718453115.

Davaasuren, N., Marino, A., Boardman, C., Ackermann, N., Alparone, M., and Nunziata, F. (2018). *Exploring The Use Of SAR Remote Sensing To Detect Microplastics Pollution In The Oceans*. Paper presented at the 5th Advances in SAR Oceanography Workshop (SeaSAR 2018), Frascati, Italy.

Deidun, A., Gauci, A., Lagorio, S., and Galgani, F. (2018). Optimising beached litter monitoring protocols through aerial imagery. *Marine Pollution Bulletin, 131*, 212-217. https://doi.org/10.1016/j.marpolbul.2018.04.033.

DeLoatch, I. (2019). *GEOSS Infrastructure Development Task* Paper presented at the GEO Symposium 2019, Geneva, Switzerland.

Dobler, D., Martinez, E., Rahmania, R., Gautama, B.D., Riza Farhan, A., Maes, C., and Dounias, E. (Eds.). (2021). *Floating marine debris along Indonesian coasts : an atlas of strandings based on Lagrangian modelling*. Jakarta, IND.

Dumichen, E., Eisentraut, P., Bannick, C.G., Barthel, A.K., Senz, R., and Braun, U. (2017). Fast identification of microplastics in complex environmental samples by a thermal degradation method. *Chemosphere, 174*, 572-584. https://doi.org/10.1016/j.chemosphere.2017.02.010.

European Commission. (2018). *Reducing Marine Litter: action on single use plastics and fishing gear (Commission staff working document, impact assessment)*. (SWD(2018) 254 final).

European Commission Joint Research Council. (2013). *Guidance on Monitoring of Marine Litter in Europeans Seas*. https://ec.europa.eu/jrc/sites/jrcsh/files/lb-na-26113-en-n.pdf.

European Environment Agency. (1999). *Environmental Indicators: Typology and overview* (Technical report No 25).

European Environment Agency. (2003). *Environmental Indicators: Typology and Use in Reporting.* (EEA internal working paper).

European Union. (2008). *Directive 2008/56/EC of the European Parliment and of the Council Establishing a Framework for Community Action in the Field of Marine Environmental Policy (Marine Strategy Framework Directive).*

Fossi, M.C., Peda, C., Compa, M., Tsangaris, C., Alomar, C., Claro, F., *et al.* (2018). Bioindicators for monitoring marine litter ingestion and its impacts on Mediterranean biodiversity. *Environmental Pollution, 237*, 1023-1040. https://doi.org/doi:10.1016/j.envpol.2017.11.019.

Galgani, F., Hanke, G., and Maes, T. (2015). Global Distribution, Composition and Abundance of Marine Litter. . In M. Bergmann, L. Gutow, and M. Klages (Eds.), *Marine Anthropogenic Litter*: Springer, Cham.

Galgani, F., Hanke, G., Werner, S., and De Vrees, L. (2013). Marine litter within the European Marine Strategy Framework Directive. *Ices Journal of Marine Science, 70*(6), 1055-1064. https://doi.org/10.1093/icesjms/fst122.

Galgani, F., Leaute, J.P., Moguedet, P., Souplet, A., Verin, Y., Carpentier, A., *et al.* (2000). Litter on the Sea Floor Along European Coasts. *Marine Pollution Bulletin, 40*(6), 516-527. https://doi.org/10.1016/S0025-326X(99)00234-9.

Galloway, T.S. (2015). Micro- and nano-plastics and human health In L. Gutow and M. Klages (Eds.), *Marine anthropogenic litter* (347-370). Springer. Berlin, Germany.

Garaba, S.P., and Dierssen, H.M. (2018). An airborne remote sensing case study of synthetic hydrocarbon detection using short wave infrared absorption features identified from marine-harvested macro- and microplastics. *Remote Sensing of Environment, 205*, 224-235.
https://doi.org/10.1016/j.rse.2017.11.023.

Garello, R., Plag, H.P., Shapiro, A., Martinez, S., Pearlman, J., and Pendelton, L. (2019). *Technologies for Observing and Monitoring Plastics in the Oceans*. Paper presented at the OCEANS 2019 - Marseille, France.

Group on Earth Observations. (2005). *The Global Earth Observation System of Systems (GEOSS) 10 Year Implementation Plan.* Retrieved from Geneva, Switzerland: https://www.earthobservations.org/documents/10-Year%20Implementation%20Plan.pdf.

Geyer, R., Jambeck, J.R., and Law, K.L. (2017). Production, use, and fate of all plastics ever made. *Science Advances, 3*(7). doi:10.1126/sciadv.1700782

Glanville, K., and Chang, H.C. (2015). Mapping illegal domestic waste disposal potential to support waste management efforts in Queensland, Australia. *International Journal of Geographical Information Science, 29*(6), 1042-1058. https://doi.org/10.1080/13658816.2015.1008002.

Goddijn-Murphy, L., Peters, S., Van Sebille, E., James, N.A., and Gibb, S. (2018). Concept for a hyperspectral remote sensing algorithm for floating macro plastics. *Marine Pollution Bulletin, 126*, 255-262.
https://doi.org/10.1016/j.marpolbul.2017.11.011.

Goldstein, M.C., Carson, H.S., and Eriksen, M. (2014). Relationship of diversity and habitat area in North Pacific plastic-associated rafting communities. *Marine Biology, 161*(6), 1441-1453.
https://doi.org/doi:10.1007/s00227-014-2432-8.

González-Fernández, D., and Hanke, G. (2017). Toward a Harmonized Approach for Monitoring of Riverine Floating Macro Litter Inputs to the Marine Environment. *4*(86). https://doi.org/10.3389/fmars.2017.00086.

Granado, I., Basurko, O.C., Rubio, A., Ferrer, L., Hernandez-Gonzalez, J., Epelde, I., and Fernandes, J.A. (2019). Beach litter forecasting on the south-eastern coast of the Bay of Biscay: A bayesian networks approach. *Continental Shelf Research, 180*, 14-23. https://doi.org/10.1016/j.csr.2019.04.016.

Haarr, M. L., Westerveld, L., Fabres, J., Iversen, K.R., and Busch, K.E.T. (2019). A novel GIS-based tool for predicting coastal litter accumulation and optimising coastal cleanup actions. *Marine Pollution Bulletin, 139*, 117-126. https://doi.org/10.1016/j.marpolbul.2018.12.025.

Hardesty, B.D., Lawson, T.J., van der Velde, T., Lansdell, M., and Wilcox, C. (2017). Estimating quantities and sources of marine debris at a continental scale. *Frontiers in Ecology and the Environment, 15*(1), 18-25. https://doi.org/https://doi.org/10.1002/fee.1447.

Hardesty, B.D., Wilcox, C., Schuyler, Q.A., Lawson, T.J., and Opie, K. (2017). Developing a baseline estimate of amounts, types, sources and distribution of coastal litter – an analysis of US marine debris data. A final report for Ocean Conservancy and NOAA.

Intergovernmental Oceanographic Commission of the United Nations Educational, Scientific and Cultural Organization. (2019). *Adopted Decisions and Resolutions, Intergovernmental Oceanographic Commission of UNESCO Thirtieth Session of the Assembly.* (IOC-XXX/ Decisions). http://www.ioc-unesco.org/index.php?option=com_oeandtask=viewDocumentRecordanddocID=24911.

Jambeck, J.R., Geyer, R., Wilcox, C., Siegler, T.R., Perryman, M., Andrady, A., *et al.* (2015). Plastic waste inputs from land into the ocean. *Science, 347*(6223), 768-771. https://doi.org/10.1126/science.1260352.

Jang, Y.C., Hong, S., Lee, J., Lee, M.J., and Shim, W.J. (2014). Estimation of lost tourism revenue in Geoje Island from the 2011 marine debris pollution event in South Korea. *Mar Pollut Bull, 81*(1), 49-54. https://doi.org/10.1016/j.marpolbul.2014.02.021.

Joint Group of Experts on the Environmental Aspects of Marine Environmental Protection. (2019). *GESAMP 2019 Guidelines for the monitoring and assessment of plastic litter in the ocean Reports and Studies 99 (editors Kershaw, P.J., Turra, A. and Galgani, F.)* (Rep. Stud. GESAMP No. 99). http://www.gesamp.org/publications/guidelines-for-the-monitoring-and-assessment-of-plastic-litter-in-the-ocean

Krelling, A.P., Williams, A.T., and Turra, A. (2017). Differences in perception and reaction of tourist groups to beach marine debris that can influence a loss of tourism revenue in coastal areas. *Marine Policy, 85*, 87-99. doi:https://doi.org/10.1016/j.marpol.2017.08.021

Kuhn, S., van Oyen, A., Booth, A.M., Meijboom, A., and van Franeker, J.A. (2018). Marine microplastic: Preparation of relevant test materials for laboratory assessment of ecosystem impacts. *Chemosphere, 213*, 103-113. doi:10.1016/j.chemosphere.2018.09.032.

Lamb, J., Willis, B., Fiorenza, E., Couch, C., Howard, R., Rader, D., *et al.* (2018). Plastic waste associated with disease on coral reefs. *Science, 359*, 460-462. https://doi.org/10.1126/science.aar3320.

Lassen, C., Hasen, S.F., Magnusson, K., Hartman, N.B., Rehne Jensen, P., Torkel, G., and Brinch, A. (2015). *Microplastics: Occurrence, effects and sources of releases to the environment in Denmark.* . Retrieved from Copenhagen, Denmark: https://orbit.dtu.dk/files/118180844/Lassen_et_al._2015.pdf.

Lavers, J.L., Dicks, L., Dicks, M.R., and Finger, A. (2019). Significant plastic accumulation on the Cocos (Keeling) Islands, Australia. *Scientific Reports, 9*(1), 7102. https://doi.org/10.1038/s41598-019-43375-4.

Lebreton, L., Slat, B., Ferrari, F., Sainte-Rose, B., Aitken, J., Marthouse, R., *et al.* (2018). Evidence that the Great Pacific Garbage Patch is rapidly accumulating plastic. *Scientific Reports, 8*. https://doi.org/10.1038/s41598-018-22939-w.

Lebreton, L.C.M., Van der Zwet, J., Damsteeg, J.W., Slat, B., Andrady, A., and Reisser, J. (2017). River plastic emissions to the world's oceans. *Nature Communications, 8*, 10. https://doi.org/10.1038/ncomms15611.

Leggett, C., Scherer, N., Curray, M., and Bailey, R. (2014). *Assessing the Economic Benefits of Reductions in Marine Debris: A Pilot Study of Beach Recreation in Orange County, California*.

Lenz, R., Enders, K., Stedmon, C.A., Mackenzie, D.M.A., and Nielsen, T.G. (2015). A critical assessment of visual identification of marine microplastic using Raman spectroscopy for analysis improvement. *Marine Pollution Bulletin, 100*(1), 82-91. https://doi.org/10.1016/j.marpolbul.2015.09.026.

Lohmann, R. (2017). Microplastics are not important for the cycling and bioaccumulation of organic pollutants in the oceans-but should microplastics be considered POPs themselves?: Should Microplastics Be Considered POPs. *Integrated Environmental Assessment and Management, 13*, 460-465. https://doi.org/10.1002/ieam.1914.

Loulad, S., Houssa, R., Rhinane, H., Boumaaz, A., and Benazzouz, A. (2017). Spatial distribution of marine debris on the seafloor of Moroccan waters. *Mar Pollut Bull, 124*(1), 303-313. https://doi.org/10.1016/j.marpolbul.2017.07.022.

Martin, C., Parkes, S., Zhang, Q.N., Zhang, X.L., McCabe, M.F., and Duarte, C.M. (2018). Use of unmanned aerial vehicles for efficient beach litter monitoring. *Marine Pollution Bulletin, 131*, 662-673. https://doi.org/10.1016/j.marpolbul.2018.04.045.

Martínez-Vicente, V., Clark, J.R., Corradi, P., Aliani, S., Arias, M., Bochow, M., *et al.* (2019). Measuring Marine Plastic Debris from Space: Initial Assessment of Observation Requirements. *Remote Sensing, 11*(20).

doi:10.3390/rs11202443.

Matsuoka, T., Nakashima, T., and Nagasawa, N. (2005). A review of ghost fishing: scientific approaches to evaluation and solutions. *Fisheries Science, 71*(4), 691-702. https://doi.org/10.1111/j.1444-2906.2005.01019.x.

Maximenko, N., Corradi, P., Lavender Law, R., van Sebille, E., Garaba, S.P., Lampitt, R.S. *et al.* (2019). Towards the Integrated Marine Debris Observing System Frontiers in Marine Science. *Frontiers in Marine Science*. https://doi.org/10.3389/fmars.2019.00447

Moaut, J., Lopez Lozano, R., and Bateson, H. (2010). *Economic Impacts of Marine Litter*. Retrieved from https://www.kimointernational.org/wp/wp-content/uploads/2017/09/KIMO_Economic-Impacts-of-Marine-Litter.pdf.

Molina Jack, M.E., Chaves Montero, M.d.M., Galgani, F., Giorgetti, A., Vinci, M., Le Moigne, M., and Brosich, A. (2019). EMODnet marine litter data management at pan-European scale. *Ocean and Coastal Management, 181*, 104930. https://doi.org/10.1016/j.ocecoaman.2019.104930.

Mouchot, M.C., and Garello, R. (1998). SAR Application for Oceanography. In *Manual of Remote Sensing, Radar Volume* (631-675): American Society for Photogrammetry and Remote Sensing.

Moy, K., Neilson, B., Chung, A., Meadows, A., Castrence, M., Ambagis, S., and Davidson, K. (2018). Mapping coastal marine debris using aerial imagery and spatial analysis. *Marine Pollution Bulletin, 132*, 52-59. https://doi.org/0.1016/j.marpolbul.2017.11.045.

Newman, S., Watkins, E., Farmer, A., Brink, P. t., and Schweitzer, J.-P. (2015). The Economics of Marine Litter. In M. Bergmann, L. Gutow, and M. Klages (Eds.), *Marine Anthropogenic Litter* (367-394). Springer International Publishing.

Niemeijer, D. and Groot, R. (2008). Framing environmental indicators: Moving from causal chains to causal networks. *Environment Development and Sustainability, 10*, 89-106. https://doi.org/10.1007/s10668-006-9040-9.

National Oceanic and Atmosphieric Administration. (2017). *NOAA Administrative Order (NAO) 216-105B: Policy on Research and Development Transitions*. NOAA Office of the Chief Scientist. https://www.corporateservices.noaa.gov/ames/administrative_orders/chapter_216/Handbook_NAO216-105B_03-21-17.pdf.

NOAA Marine Debris Program. (2015). *Laboratory Methods for the Analysis of Microplastics in the Marine Environment: Recommendations for quantifying synthetic partciles in waters and sediments.* . (Technical Memorandum NOS-ORandR-48). https://marinedebris.noaa.gov/sites/default/files/publications-files/noaa_microplastics_methods_manual.pdf.

Northwest Pacific Action Plan Special Monitoring and Coastal Environmental Assessment Regional Activity Centre. (2007). *Guidelines for Monitoring Marine Litter on the Beaches and Shorelines of the Northwest Pacific Region.*

http://www.cearac-project.org/RAP_MALI/monitoring%20guidelines.pdf.

Opfer, S., Arthur, C. and Lippiatt, S. (2012). *NOAA Marine Debris Shoreline Survey Field Guide*. https://marinedebris.noaa.gov/sites/default/files/ShorelineFieldGuide2012.pdf.

OSPAR Commission. (2010). *Guidelines for monitoring marine litter on the beaches in the OSPAR Maritime Area*. https://www.ospar.org/ospar-data/10-02e_beachlitter%20guideline_english%20only.pdf

OSPAR Commission. (2017). *OSPAR Intermediate Assessment 2017* Retrieved from https://oap.ospar.org/en/ospar-assessments/intermediate-assessment-2017/pressures-human-activities/marine-litter/.

Pham, C.K., Gomes-Pereira, J.N., Isidro, E.J., Santos, R.S., and Morato, T. (2013). Abundance of litter on Condor seamount (Azores, Portugal, Northeast Atlantic). *Deep-Sea Research Part II: Topical Studies in Oceanography, 98*, 204-208. https://doi.org/10.1016/j.dsr2.2013.01.011.

Pham, C.K., Ramirez-Llodra, E., Alt, C.H.S., Amaro, T., Bergmann, M., Canals, M., *et al.* (2014). Marine Litter Distribution and Density in European Seas, from the Shelves to Deep Basins. *Plos One, 9*(4), e95839. https://doi.org/10.1371/journal.pone.0095839.

Pinto, C.A., and Garvey, P.R. (2013). Functional Dependency Network Analysis In *Advanced Risk Analysis in Engineering Enterprise Systems* CRC Press.

Raubenheimer, K. (2019). *Marine Litter: Gudelines for desigining action plans*. United Nations Environment Programme, Nairobi, Kenya: UNEP. https://wedocs.unep.org/bitstream/handle/20.500.11822/36470/aheg_inf_7_-_marine_litter-_guidelines_for_designing_regional_action_plans_summary_1.pdf?sequence=1&isAllowed=y.

Rech, S., Borrell Pichs, Y., and Garcia-Vazquez, E. (2016). Marine litter as a vector for non-native species: What we need to know. *Marine Pollution Bulletin, 113*. https://doi.org/10.1016/j.marpolbul.2016.08.032.

Richardson, K., Haynes, D., Talouli, A., and Donoghue, M. (2017). Marine pollution originating from purse seine and longline fishing vessel operations in the Western and Central Pacific Ocean, 2003–2015. *Ambio, 46*(2), 190-200. https://doi.org/doi:10.1007/s13280-016-0811-8.

Rivenson, Y., Wu, Y., and Ozcan, A. (2019). Deep learning in holography and coherent imaging. *Light: Science and Applications, 8*(1), 85. https://doi.org/10.1038/s41377-019-0196-0.

Rochman, C.M., Tahir, A., Williams, S.L., Baxa, D.V., Lam, R., Miller, J.T., *et al.* (2015). Anthropogenic debris in seafood: Plastic debris and fibers from textiles in fish and bivalves sold for human consumption. *Scientific Reports, 5*(1), 14340. https://doi.org/doi:10.1038/srep14340.

Ross, P., and Birnbaum, L. (2003). Integrated Human and Ecological Risk Assessment: A Case Study of Persistent Organic Pollutants (POPs) in Humans and Wildlife. *Human and Ecological Risk Assessment, 9*, 303-324. https://doi.org/doi:10.1080/727073292.

Ryan, P.G., Lamprecht, A., Swanepoel, D., and Moloney, C. L. (2014). The effect of fine-scale sampling frequency on estimates of beach litter accumulation. *Marine Pollution Bulletin, 88*(1-2), 249-254. https://doi.org/10.1016/j.marpolbul.2014.08.036.

Ryan, P.G., Moore, C.J., van Franeker, J.A., and Moloney, C.L. (2009). Monitoring the abundance of plastic debris in the marine environment. *Philosophical Transactions of the Royal Society B-Biological Sciences, 364*(1526), 1999-2012. https://doi.org/10.1098/rstb.2008.0207.

Ryberg, M.W., Hauschild, M.Z., Wang, F., Averous-Monnery, S., and Laurent, A. (2019). Global environmental losses of plastics across their value chains. *Resources, Conservation and Recycling, 151*, 104459. https://doi.org/10.1016/j.resconrec.2019.104459.

Schreyers, L., van Emmerik, T., Nguyen, T.L., Phung, N.A., Kieu-Le, T.C., Castrop, E., *et al.* van der Ploeg, M. (2021). A Field Guide for Monitoring Riverine Macroplastic Entrapment in Water Hyacinths. *9*(267). https://doi.org/10.3389/fenvs.2021.716516.

Schuyler, Q., Willis, K., Lawson, T. J., Mann, V., Wilcox, C., and Hardesty, B.D. (2018). *Handbook of Survey Methodology Plastics Leakage (developed for CSIRO Global Plastic Pollution Project).*

Smith, M., Love, D.C., Rochman, C.M., and Neff, R.A. (2018). Microplastics in Seafood and the Implications for Human Health. *Current Environmental Health Reports, 5*(3), 375-386. https://doi.org/10.1007/s40572-018-0206-z.

Spears, T., Simpson, P., Chandler, C., Michida, Y., and Pissierssens, P. (2017). *Ocean Data and Information System - Concept Paper*. Paper presented at the Twenty-fourth Session of the IOC Committee on International Oceanographic Data and Information Exchange (IODE-XXIV), Kuala Lumpur, Malaysia. https://www.iode.org/index.php?option=com_oeandtask=viewDocumentRecordanddocID=18703.

Spengler, A., and Costa, M.F. (2008). Methods applied in studies of benthic marine debris. *Marine Pollution Bulletin, 56*(2), 226-230.

Stickel, B.H., Jahn, A., and Kier, W. (2012). *The Cost to West Coast Communities to Deal with Trash, Reducing Marine Debris.*

Stuparu, D., Van Der Meulen, M., Kleissen, F., Vethaak, D., and El Serafy, G. (2015). *Developing a transport model for plastic distribution in the North Sea*. Madrid: Iahr-Int Assoc Hydro-Environment Engineering Research.

Sutton, R., Franz, A., Gilbreath, A., Lin, D., Miller, L., Sedlak, M., *et al.* (2019). *Understanding microplastic levels, pathways and transport in the San Francisco Bay region* (SFEI-ASC Publication #950). San Francisco Estuary Institute

Tanhua, T., Pouliquen, S., Hausman, J., O'Brien, K., Bricher, P., de Bruin, T., *et al.* (2019). Ocean FAIR Data Services. *6*(440). https://doi.org/10.3389/fmars.2019.00440.

Thompson, R.C., Moore, C.J., vom Saal, F. S., and Swan, S.H. (2009). Plastics, the environment and human health: current consensus and future trends. *Philosophical Transactions of the Royal Society B-Biological Sciences, 364*(1526), 2153-2166. https://doi.org/10.1098/rstb.2009.0053.

Topouzelis, K., Papakonstantinou, A., and Garaba, S.P. (2019). Detection of floating plastics from satellite and unmanned aerial systems (Plastic Litter Project 2018). *International Journal of Applied Earth Observation and Geoinformation, 79*, 175-183. https://doi.org/10.1016/j.jag.2019.03.011.

Trujillo, P., Piroddi, C., and Jacquet, J. (2012). Fish Farms at Sea: The Ground Truth from Google Earth. *Plos One, 7*(2), 5. https://doi.org/10.1371/journal.pone.0030546.

Turpin, V., Remy, E., and Le Traon, P.Y. (2016). How essential are Argo observations to constrain a global ocean data assimilation system? *Ocean Sci., 12*(1), 257-274. https://doi.org/10.5194/os-12-257-2016.

Tyrrell, T. (1992). *Tourism and the Environment: Marine Debris, Beach Pollution and the Importance of Image*.

UN Environment Programme. (2016a). *Marine plastic debris and microplastics – Global lessons and research to inspire action and guide policy change*. http://wedocs.unep.org/handle/20.500.11822/7720.

UN Environment Programme. (2016b). *Regional Seas Core Indicators Set*. Paper presented at the 18th Global Meeting of the Regional Seas Conventions and Action Plans, Incheon, the Republic of Korea. http://wedocs.unep.org/bitstream/handle/20.500.11822/11078/wbrs18_inf9_rs_indicators.pdf?sequence=1andisAllowed=y.

UN Environment Programme. (2017). *Marine Litter Socio Economic Study.* Nairobi, Kenya: UNEP

UN Environment Programme. (2018a). *Mapping of Global Plastics Value Chain and Plastics Losses to the Environment (with a Particular Focus on Marine Environment*. Nairobi, Kenya: UNEP

UN Environment Programme. (2018b). *Regional Seas Follow Up and Review of the Sustainable Development Goals (SDGS)*. (UN Environment Regional Seas Reports and Studies No. 208). https://wedocs.unep.org/bitstream/handle/20.500.11822/27295/ocean_SDG.pdf?sequence=1andisAllowed=y.

UN Environment Programme. (2020). *National guidance for plastic pollution hotspotting and shaping action - Introduction report*. Nairobi, Kenya: UNEP. Retrieved from https://wedocs.unep.org/bitstream/handle/20.500.11822/33166/NGP.pdf?sequence=1andisAllowed=y.

UN Environment Programme. (2021). *Understanding the State of the Ocean: A Global Manual on Measuring SDG 14.1.1, SDG 14.2.1 and SDG 14.5.1*. Nairobi, Kenya: UNEP

United Nations Environment Programme. (2019). *4/6. Marine plastic litter and microplastics*. (UNEP/EA.4/Res.6). Nairobi, Kenya: UNEP. Retrieved from https://wedocs.unep.org/bitstream/handle/20.500.11822/28471/English.pdf?sequence=3andisAllowed=y.

van der Mheen, M., Pattiaratchi, C., and van Sebille, E. (2019). Role of Indian Ocean Dynamics on Accumulation of Buoyant Debris. *Journal of Geophysical Research-Oceans, 124*(4), 2571-2590. doi:10.1029/2018jc014806

van Emmerik, T., Kieu-Le, T.-C., Loozen, M., van Oeveren, K., Strady, E., Bui, X.T., *et al.* (2018). A Methodology to Characterize Riverine Macroplastic Emission Into the Ocean. *5*. https://doi.org/10.3389/fmars.2018.00372.

van Emmerik, T., Strady, E., Kieu-Le, T. C., Nguyen, L., and Gratiot, N. (2019). Seasonality of riverine macroplastic transport. *Scientific Reports, 9*(1), 13549. doi:10.1038/s41598-019-50096-1.

van Franeker, J. A., Blaize, C., Danielsen, J., Fairclough, K., Gollan, J., Guse, N., *et al.* (2011). Monitoring plastic ingestion by the northern fulmar Fulmarus glacialis in the North Sea. *Environmental Pollution, 159*(10), 2609-2615. https://doi.org/10.1016/j.envpol.2011.06.008.

van Sebille, E., Aliani, S., Law, K. L., Maximenko, N., Alsina, J. M., Bagaev, A., *et al.* (2020). The physical oceanography of the transport of floating marine debris. *Environmental Research Letters, 15*(2), 023003. https://doi.org/10.1088/1748-9326/ab6d7d.

van Sebille, E., England, M.H., and Froyland, G. (2012). Origin, dynamics and evolution of ocean garbage patches from observed surface drifters. *Environmental Research Letters, 7*(4), 6. https://doi.org/10.1088/1748-9326/7/4/044040.

Vandermeersch, G., Van Cauwenberghe, L., Janssen, C.R., Marques, A., Granby, K., Fait, G., Devriese, L. (2015). A critical view on microplastic quantification in aquatic organisms. *Environmental Research, 143*, 46-55.

https://doi.org/10.1016/j.envres.2015.07.016.

Verschoor, A., de Poorter, L., Droge, R., Kuenen, J., and de Valk, E. (2016). *Emission of microplastics and potential mitigation measures : Abrasive cleaning agents, paints and tyre wear* (RIVM Report 2016-0026). Bilthoven, the Netherlands.

Wang, T., Li, B. J., Zou, X.Q., Wang, Y., Li, Y. L., Xu, Y. J., *et al.* (2019). Emission of primary microplastics in mainland China: Invisible but not negligible. *Water Research, 162*, 214-224.
https://doi.org/10.1016/j.watres.2019.06.042.

Wesch, C., Elert, A.M., Wörner, M., Braun, U., Klein, R., and Paulus, M. (2017). Assuring quality in microplastic monitoring: About the value of clean-air devices as essentials for verified data. *Scientific Reports, 7*(1), 5424-5424.
https://doi.org/10.1038/s41598-017-05838-4.

Willis, K., Denise Hardesty, B., Kriwoken, L., and Wilcox, C. (2017). Differentiating littering, urban runoff and marine transport as sources of marine debris in coastal and estuarine environments. *Scientific Reports, 7*(1), 44479.
https://doi.org/10.1038/srep44479.

Willis, K., Maureaud, C., Wilcox, C., and Hardesty, B. D. (2018). How successful are waste abatement campaigns and government policies at reducing plastic waste into the marine environment? *Marine Policy, 96*, 243-249.
https://doi.org/10.1016/j.marpol.2017.11.037.

Woodall, L. C., Sanchez-Vidal, A., Canals, M., Paterson, G.L.J., Coppock, R., Sleight, V., *et al.* (2014). The deep sea is a major sink for microplastic debris. *Royal Society Open Science, 1*(4), 8.
https://doi.org/10.1098/rsos.140317

Wright, S. L., Thompson, R.C., and Galloway, T.S. (2013). The physical impacts of microplastics on marine organisms: a review. *Environ Pollut, 178*, 483-492.
https://doi.org/10.1016/j.envpol.2013.02.031

Yoon, J.H., Kawano, S., and Igawa, S. (2010). Modeling of marine litter drift and beaching in the Japan Sea. *Marine Pollution Bulletin, 60*(3), 448-463.
https://doi.org/10.1016/j.marpolbul.2009.09.033.

Yu, J.P., Wang, P.Y., Ni, F.L., Cizdziel, J., Wu, D.X., Zhao, Q.L., and Zhou, Y. (2019). Characterization of microplastics in environment by thermal gravimetric analysis coupled with Fourier transform infrared spectroscopy. *Marine Pollution Bulletin, 145*, 153-160.
https://doi.org/10.1016/j.marpolbul.2019.05.037.

Zarfl, C. (2019). Promising techniques and open challenges for microplastic identification and quantification in environmental matrices. *Analytical and Bioanalytical Chemistry, 411*(17), 3743-3756.
https://doi.org/10.1007/s00216-019-01763-9.

Zettler, E.R., Mincer, T.J., and Amaral-Zettler, L.A. (2013). Life in the “Plastisphere”: Microbial Communities on Plastic Marine Debris. *Environmental Science and Technology, 47*(13), 7137-7146.
https://doi.org/10.1021/es401288x

Zhao, S., Zhu, L., and Li, D. (2016). Microscopic anthropogenic litter in terrestrial birds from Shanghai, China: Not only plastics but also natural fibers. *Sci Total Environ, 550*, 1110-1115.
https://doi.org/10.1016/j.scitotenv.2016.01.112.

Zhu, A., Chen, B., Wang, C., Guo, D., Lei, E., and Jin, F. (2019). Plastic Solid Waste identification system based on Near Infrared Spectroscopy in combination with support vector machine. *Advanced Industrial and Engineering Polymer Research, 2*.
https://doi.org/10.1016/j.aiepr.2019.04.001.

Zulkifley, M.A., Mustafa, M.M., Hussain, A., Mustapha, A., and Ramli, S. (2014). Robust Identification of Polyethylene Terephthalate (PET) Plastics through Bayesian Decision. *Plos One, 9*(12).
https://doi.org/10.1371/journal.pone.0114518.

Annex A: Inventory of Marine Litter Databases and Data Sets

Database or Data Set	Topical Focus	Geographical Focus	Description	Data Collection Methods	Data Availability and Management
NOAA Marine Debris Monitoring and Assessment Project **https://marinedebris.noaa.gov/research/marine-debris-monitoring-and-assessment-project**	Beaches / Shoreline (beach litter)	The database can accept data from shoreline surveys that are completed using the NOAA protocol anywhere in the world, but most data is from the US Coastal Zones (primarily the West Coast)	Total quantity of beach debris larger than 2.5 cm in the longest dimension. There are both accumulation / flux data and standing / concentration data. Both are based on surveys of specific areas of the shoreline.	Citizen Science (partner organizations, volunteers), Shoreline Surveys	Anyone can request access to the MDMAP database, requests are approved by the NOAA and then all verified data is reportable / downloadable. Verified data is reviewed by NOAA staff before being published.
Australian Marine Debris Database **https://www.tangaroablue.org/database/**	Beaches / Shoreline (beach litter) Sea Surface	Australian Coast, Hawaii	Total number of cleanups completed, number of items removed (itemized), annual comparisons	Volunteers perform beach cleanups of coastal areas both on land (beaches) and sea (near-shore surface levels). Litter is counted and itemized based on specifications. Approximate weight of litter and length of area of cleanup is reported. Photos may also be attached. Data collected is vetted before approval.	Through an open access policy, a specific set of data reports can be generated for community groups, schools and partner organizations to assist in identifying marine debris trends and to create local source reduction plans. Both the Australian Marine Debris Initiative and the data contributor must be acknowledged when any type of data is used publicly

					for any purpose. This information is available by emailing info@tangaroablue.org with both the location and date of the data being requested.
Marine LitterWatch **https://www.eea.europa.eu/themes/water/europes-seas-and-coasts/assessments/marine-litterwatch**	Beaches / Shoreline (beach litter)	The Marine LitterWatch covers most of the European coastline, but not inland waters/rivers	The database includes a total count and an itemized breakdown of all items collected/observed. Additionally, the specific sampled locations are broken down by total cleanups, by average amount collected per cleanup, and by the organization who aided with the cleanups	Marine LitterWatch functions as a mobile application for volunteer organizations and regional seas programs in Europe to participate in cleanups. The application is used to survey the given cleanup area based on specific items broken into categories of plastic, cloth/textile, and glass/ceramics, with subsections within those categories.	At present, MLW data are representative of the efforts made by the communities that collect the data. They are therefore illustrative of the amounts and types of items found on the surveyed beaches. Additional handling would be required to use the data for further statistical purposes. Data sets are also not quality-controlled or monitored once data are input into the survey. The EEA-wide policy on data management, access, and sharing, is meant to provide open, free and readily available access to data. https://www.eea.europa.eu/legal/eea-data-policy/data-policy.
TIDES (Trash information and data for	Beaches /Shoreline (beach litter)	Global coasts and oceans	Total mass of trash collected, total number of trash bags filled, total distance of area covered. An itemized list of total trash collected is broken down into most	Annual international cleanup events and a mobile app called Clean Swell are used to collect and itemize	There is no specific database/data set management protocol, but site specific data sets from

education and solutions) **https://www.coastalcleanupdata.org/**	Water Column		likely to be found items, fishing gear, packaging materials, and other items such as personal hygiene products, smaller trash items (less than 2.5 cm) and items of local concern. Data can be collected and reported as land-based litter, underwater debris, or litter collected by watercraft.	trash found near and in bodies of water. Groups or individuals collect trash and tally the total number of specific items found, as well as the overall mass of the total trash. The data is recorded into the TIDES database and is publicly available.	past years of collected data are available and archived.
One Earth One Ocean (OEOO) Microplastic Pollution Map **https://oneearth-oneocean.com/en/the-association/microplastic-pollution-map/**	Beaches /Shoreline (beach litter) Water Column	Atlantic Coast along the European and North African shore and open waters	Data are collected from the shipping industry. Samples are collected from myriad locations mapped on their database. Microplastics are identified by colour, structure, depth collected, type of plastic and material type. The map also allows users to sort by specific plastic type to see where the plastic is found in the sampled locations.	One Earth One Ocean has worked with a shipping line called OPDR. Samples are taken from defined positions along the shipping routes. Using 20 litre containers, water is collected from the locations, and depths are specified. Samples are filtered through a 63 µm mesh sieve before analysis. The filtered samples are then concentrated in a glass fibre filter, photographed, and then inspected for microplastic materials and analysed using a Spektrum II FTIR spectrometer. Data, along with other materials, are recorded.	Data sets and sampling results are available on the interactive map on the OEOO website.

Deep-Sea Debris Database **https://www.sciencedirect.com/science/article/pii/S0308597X17305195**	Seafloor / Seabed	Primarily Japan and also the Western Pacific ocean.	The database is a composite of filmed and photographed debris found on the seafloor off the coast of Japan and in the Pacific. Each image includes its location, date observed, type of debris (plastic, glass, rubber, cloth, etc), whether organisms were found interacting or near the debris, the characteristic of the sediment, and the location depth of the debris. The database has a total quantity of observed debris that are broken down by type.	A specified area for the observation of debris is filmed by cameras that are sent below the surface of the water towards the seabed.	Raw data and images are available on the database. Some of the data are protected as intellectual property and labelled as such, but otherwise the data is open. The data and samples collected through the use of JAMSTEC facilities and equipment belong to JAMSTEC. The organization manages the data and samples that can be used by organizations, institutes and researchers for scientific and educational purposes. They promote the use of their data to help industries and society. Industry actors may need to pay for the data but all other scientific and educational uses are free of charge.
Dive Against Debris® **https://www.projectaware.org/**	Seafloor/Seabed	Global – since this is a global citizen science program, any certified scuba diver anywhere in the world can access	- site name and GPS coordinates - number of participants - survey duration - area of the seafloor surveyed - survey depth range (min. and max. depth) - debris-free sites recorded	Citizen science-generated data collected by volunteer scuba divers across the globe. Scuba divers survey their diving site of choice, collect and remove the debris they find on the	The raw data set is not shared publicly. Data sharing agreements are made between Project AWARE and third parties on a case by case basis. The entire data set, or a subset

diveagainstdebris		the materials and conduct a Dive Against Debris survey. Surveys are predominantly conducted in coastal waters, but freshwater environments can also be surveyed. Debris-free sites are also reported through Dive Against Debris.	- total weight of debris removed (unless survey site was free of debris) - itemized categorization of debris and quantities of each debris item removed (unless site was free of debris) - substrate / ecosystem type - weather and wave conditions - entangled animals found – dead / injured / released unharmed; type of entangled debris	seafloor. All debris collected is then ranked into eight main categories based on material composition (such as plastics). Each debris item is then counted based on the 100 itemized debris items listed. If an item is not listed in the 100 debris items, the user can add "other debris items". (see data card for all data fields: https://www.projectaware.org/sites/default/files/2017-06/569DT_DAD_Data_Card_v2_2_EN_formfields.pdf) Debris-free sites are also reported. Data is submitted to Project AWARE via the Dive Against Debris mobile app or the online submission form. Google play: https://play.google.com/store/apps/details?id=com.project.rantmedia.projectaware App store: https://itunes.apple.com/us/app/project-aware-dive-against-debris/id1260943783?ls=1andmt=8 Online submission form: https://www.projectaware.	of the global data set, may be shared depending on the requirements. Project AWARE shares the Dive Against Debris data (under agreement) with various stakeholders including NGOs, scientists, research entities and government bodies. Project AWARE manages the Dive Against Debris data set/database. All data submitted undergo an internal quality review process to ensure the integrity and quality of the global data set. Once a submission passes the quality review process, it can be visualized on the Dive Against Debris map (https://www.projectaware.org/diveagainstdebrismap) and added to the global data set.

				org/DiveAgainstDebrisData The survey methodology and data submission process is standardized globally and is defined in the "Survey Guide" (freely available online: https://www.projectaware.org/DiveAgainstDebrisToolkit)	As Dive Against Debris focuses exclusively on what is found beneath the waves, all land data is removed and any data inconsistencies are clarified with the survey leader and corrected. This is what makes Dive Against Debris so unique – it's the only program of its kind to focus exclusively on providing an accurate and quantitative perspective of litter found underwater on the seafloor.
ICES/DATRAS **https://ices.dk/marine-data/data-portals/Pages/DATRAS.aspx**	Seafloor / Seabed	North East Atlantic and Baltic Sea	Data on sea floor litter from European Fish stocks assessments in the North East Atlantic and the Baltic Sea (international Bottom Trawl Surveys and Baltic International trawl Surveys)	Harmonized Trawling (same net in most countries)	Data are regularly transferred to the EMODNET database (started in 2017 or 2018) and compiled for mapping.
EMODnet Marine Litter Databases **http://www.emodnet-chemistry.eu/marinelitter**	Beaches / Shoreline (beach litter) Water Column Seafloor / Seabed	European Member States extended with Ukraine, Russia, Georgia, Montenegro	Data on amounts of beach litter items, sea floor litter items and floating microlitter items and types (mainly microplastic)	The database compiles all data from MSFD or Regional sea conventions and links (compiles data) with existing databases (OSPAR/MCS for beach litter in the North East Atlantic, DATRAS for sea floor litter in the North East Atlantic and the Baltic, national beach litter monitoring from Non Ospar	Generally open access data but some member states may restrict access. Yes, specifications have been elaborated for microplastics since it is the only large-scale database in Europe for microplastics (while some member states

				areas, and data on floating microplastics entered in the database by member states.	did not start to provide data).
OpenLitterMap **https://openlittermap.com**	Beaches / Shoreline	Global	See https://rdcu.be/Vv0B	Citizen science + manual verification to train AI	Open database license. See https://rdcu.be/Vv0B
Macroplastic entanglements on the Continuous Plankton Recorder **https://www.dassh.ac.uk/doitool/content/macroplastic_entanglements_on_the_continuous_plankton_recorder**	Water Column	North Atlantic and North Sea	Macroplastic entanglements on the Continuous Plankton Recorder	Use of volunteer ships, towed marine sampler	The data is publicly available
Mapping Marine Debris in the Main Hawaiian Islands **http://arcg.is/29tjSqk**	Beaches / Shoreline (Beach litter)	Main Hawaiian Islands	Size, category, and count of marine macro debris detected in comprehensive aerial shoreline surveys using orthorectified high-resolution imagery from 2015.	Aerial survey orthorectified high-resolution imagery	Data must be requested to State of Hawaii Department of Land and Natural Resources (dlnr.marine.debris@hawaii.gov). Imagery is publicly available here:

					http://geodata.hawaii.gov/arcgis/rest/services/SoH_Imagery/Coastal_2015/ImageServer All reuse of images must be credited to PICES/Government of Japan/DLNR.
Coastal Observation and Seabird Survey Team (COASST) **coasst.org**	Beaches / Shoreline (beach litter) Sources of Marine Plastic	Washington and Oregon, USA	Counts and item-specific characteristics (item type, colour, material, size, loops, floppiness, brands, logos, languages, shininess, biofouling, weathering, intactness etc.) of items observed during standardized beach surveys following specific protocols for sampling debris between 2.5mm and 2.5cm; 2.5cm and 50cm; and greater than 50cm, respectively.	Trained (over six hours) citizen science participants collect data following standard protocols developed by COASST.	Data available upon request. Raw data are not published but may be requested. Usually post-processing is preferred. A data use agreement is required to establish terms of use.
Observations of Litter Deposited in the Deep Waters of Isla del Coco National Park, Eastern Tropical Pacific **https://www.frontiersin.org/articles/10.3389**	Water Column Seafloor / Seabed	Isla del Coco National Park, Eastern Tropical Pacific	The data collected in this report sorts observed data by material, possible source, description, total number of items, the depth at which the litter was observed, and any macro-organisms the litter was in contact with	Images of marine debris were captured from videos taken with the deep-sea submersible. The site was surveyed over 2006 and 2015. When debris was observed, the camera recorded the objects for less than a minute. Marine debris was quantified from 365 dives at 17 different locations.	Copyright © 2018 Naranjo-Elizondo and Cortés. This is an open-access article distributed under the terms of the Creative Commons Attribution License (CC BY). The use, distribution or reproduction in other forums is permitted, provided the original author(s) and the copyright owner are credited and that the original publication in this journal is cited, in

/fmars.2018.00 091/full					accordance with accepted academic practice. No use, distribution or reproduction is permitted which does not comply with these terms.
LITTERBASE **https://litterbase.awi.de/**	Beaches / Shoreline (beach litter) Water Column Seafloor / Seabed Plastic ingested by biota Rivers, Lakes, Terrestrial	Global	-Quantitative geo-referenced data on aquatic and terrestrial debris, microplastic and nanoplastic from the peer-reviewed literature -Quantitative geo-referenced data on effects of marine debris, microplastics and nanoplastics on aquatic and terrestrial biota from the peer-reviewed literature (field studies) -Reports of impacts of marine debris, microplastics and nanoplastics on aquatic and terrestrial biota from the peer-reviewed literature (laboratory studies, species list).	Manual extraction of data from peer-reviewed articles following set criteria	Data is available on a case-by-case basis upon request.
Global Alert **www.globalalert.org**	Beaches / Shoreline (beach litter) Sources of Marine Plastic	Global coasts and waterways, inland waterways, and what they define as "hot spots"	They are not looking for individual pieces of trash but find the sources and waste hot-spots instead. Generally, an area that is at least 1 metre long (1 yard), and with “tens” of pieces qualifies as a trash site.	Marine litter is measured by using an app and citizen science. They ask that larger sizes of trash be reported. Inland sources of litter are identified.	The data is available with no restrictions. ORA, nor any of its software licensors involved in delivering the GA service, shall be responsible for the accuracy, timeliness, quality, integrity, and appropriateness of the data submitted by users.

Southeast Atlantic Marine Debris Initiative (SEA-MDI) **http://marinedebris.engr.uga.edu/newmap/**	Beaches / Shoreline (beach litter)	Global: Indian Ocean, West and East Coast of the USA and Northern Canada/Arctic Region	Quantity of items seen sorted by type and item.	Citizen Science and cleanup events are used to collect data via the Marine Debris Tracker mobile app.	The raw data is available and there are no restrictions from the site. There is a data management system in place – submitted data are placed in a holding folder for vetting before being accepted into the database.
International Pellet Watch **http://www.pelletwatch.org/gmap/**	Beaches / Shoreline (beach litter)	Global, primarily focused on western European coasts and East Asian Seas and coasts	The concentration of organic pollutants found in plastic pellets. The database analyses regions for their pollution concentration.	In this project, participants collect plastic resin pellets on their nearby beaches and send them via air mail to Dr. Hideshige TAKADA. Pellets are collected using stainless steel tweezers. If users do not have tweezers, they can wash their hands with soap and collect the pellets with their bare hands (fingers). The laboratory needs 100-200 pellets from one location.	Data are available for public use after a year of processing time.
Global Ghost Gear Initiative **https://www.ghostgear.org/**	Open Ocean Ghost Gear, Entanglement	Global; US coasts, European coasts, Pacific Ocean near Australia	Types of "ghost gear" found are nets, lines, pots and traps. Total counts and location, dates, gear class.	Citizen science and cruises use a mobile app to upload the data. Bulk data uploads are also possible online.	Data are available to download, and more specific data are available upon request.

Heal the Bay's Marine Debris Database **http://sites.healthebay.org/MarineDebris/MDDB/**	Beaches / Shoreline (beach litter)	Los Angeles, California, USA	The database contains counts of the various pieces of trash that have been picked over the last 10 years at 19 of the most popular beaches in the Los Angeles area. Trash is categorized into 31 different "measures" (such as Styrofoam food containers, plastic bottle caps and rings or cigarette butts) and subtotalled into 7 groups (such as Recyclable Items, Styrofoam Items, or Medical and Hygiene Items).	All of the data in the database comes from information entered on Heal the Bay's Data Cards by volunteers during beach cleanups. It does not represent all the trash picked up at beaches by cities, counties, life guards, or other organizations and volunteers.	Data is publicly available.
Plastic Litter Projects (2018 and 2019) **https://mrsg.aegean.gr/?content=andnav=55** **https://mrsg.aegean.gr/?content=andnav=65**	detection from drones-satellites	Satellite images with artificial plastic targets, to be seen from satellites and drones in the Aegean Sea area	Large artificial plastic targets, drone images, multispectral data, satellite images	Scientific cruises, satellite observations	There are some restrictions to some high-resolution satellite images.
NOAA NCEI Marine Microplastics Database **https://www.ncei.noaa.gov/pro**	Open ocean and coasts	Global	This product is a publicly available collection of marine microplastics data from around the world. The database is a repository for multiple datasets of marine microplastics. The data are aggregated, archived, and accessible to users in a consistent and reliable manner.	Author submission of data from peer-reviewed articles following set criteria. Plastics < 5 mm	The Microplastics Application has information on the occurrence, distribution, and quantity of global microplastics. Data is available in CSV, NetCDF, and ArcGIS formats. A GIS-

ducts/microplastics			Contributors from various research cruises and field work provide the data.		based map shows the global distribution of data submitted. The map within the application allows users to download the entire dataset, or subset of data for a particular geographical region and time period.
Marine plastic litter mapping database (tentative)	Ocean surface microplastics	Global	The database is expected to launch in FY 2023. It is being developed under the "Global Marine plastic litter Monitoring Network Project" which is endorsed as a UN Ocean Decade project. The objectives of the database are the followings: (1) to bring together monitoring data of ocean surface microplastics from around the world, (2) to classify the data for better comparability in line with recommendations regarding data items and data collection by the "Guidelines for Harmonizing Ocean Surface Microplastic Monitoring Methods", (3) to visualize the distribution of survey sites and abundance (number of particles, weight) of ocean surface microplatics on global and local scale maps,	The database will compile monitoring data of ocean surface microplastics submitted by any entity including scientist, project, and organization who agrees to provide data to the database. Also, the data administrator of the database will collect data from published papers, reports etc. To enable data comparison, the following guidelines and data entry form are provided online. "Guidelines for Harmonizing Ocean Surface Microplastic Monitoring Methods" https://repository.oceanbestpractices.org/handle/11329/1361 Data Entry Form Sheet & Data List Sheet	Data will be made available to the public.

			(4) to make the information available to the public. (The database will contain over 10,000 data from the outset.)	https://www.env.go.jp/water/Data%20Entry%20Form%20Sheet%20%26%20Data%20List%20Sheet%28V01.17%29191.xlsm	

Annex B: Data Layers for Related Sustainable Development Goals

Related Sustainable Development Goal (SDG)	Data Layer Name	Data Provider	Geo-coverage	Description
SDG 6	Macro Plastic Litter Load in Rivers	DHI	Global	This data layer assesses macroplastics found in freshwater pathways: plastic transport and deposition in freshwater pathways are monitored on a global scale.
SDG 6	Main Global Drainage System 2016	United Nations Environment Programme (UNEP), Global Environment Facility (GEF)	Global	This data layer is derived from the TWAP River Basins indicator data portal (2016), which covers all of the world's 286 transboundary river basins. It allows users to view results of around 15 key indicators and subindicators, for the baseline assessment of relative risks in these basins (2010), and projections in 2030 and 2050.
SDG 6	Plastic Pollution Along Mekong and Ganges Rivers	United Nations Environment Programme (UNEP), CounterMEASURE	Regional	This data layer indicates plastic pollution along the Mekong and Ganges Rivers, specifically in Phnom Penh, Vientiane, Chiang Rai, Ubon Ratchathani, Can Tho, Agra, Haridwar, Allahabad and Mumbai.
SDG 6.3.2	Water bodies with good ambient water quality	United Nations Environment Programme (UNEP)	Global	Data on the proportion of open water bodies that have good ambient water quality. Ambient water quality refers to natural, untreated water in rivers, lakes and groundwaters and represents a combination of natural influences together with the impacts of all anthropogenic activities.
SDG 11	Marine Litter Hotspots	United Nations Human Settlement Programme (UN-Habitat)	Global	This data set contains available municipal solid waste management data that are compatible with inputs from SDG indicator 11.6.1, and with local geological and meteorological factors to identify hotspots.

		and University of Leeds		
SDG 11.6.1	Municipal solid waste collected and managed in controlled facilities	United Nations Human Settlement Programme (UN-Habitat); United Nations Statistics Division (UNSD)	Global	These data indicate the performance of a city's municipal solid waste management. The following parameters, which are essential to plan and implement sustainable Municipal Solid Waste (MSW), are quantified: Total MSW generated in the city (tonnes/day); Total MSW collected in the city (tonnes/day) c) Proportion of population with access to basic MSW collection services in the city (%); Total MSW managed in controlled facilities in the city (tonnes/day); and, MSW composition.
SDG 12.4.1	Parties meeting their Multilateral Environmental Agreement's (MEA) obligations on chemicals and waste	United Nations Environment Programme (UNEP)	Global	This data set refers to the number of parties that have ratified, accepted, approved or accessed the following Multilateral Environmental Agreement (MEA): the Montreal Protocol on Substances that Deplete the Ozone Layer, the Rotterdam Convention on the Prior Informed Consent Procedure for Certain Hazardous Chemicals and Pesticides in International Trade, the Stockholm Convention on Persistent Organic Pollutants, and the Minamata Convention on Mercury.
SDG 12.5.1	Electronic waste recycling	United Nations Environment Programme (UNEP)	Global	This data set consists of the quantity of electronic waste material recycled in a country, plus the quantities exported for recycling out of the total waste generated in the country, minus materials imported intended for recycling. Note that codigestion / anaerobic digestion and composting / aerobic process fall within recycling, but not controlled combustion (incineration) or land application.

SDG 14	World Atlas of Mangroves	United Nations Environment Programme (UNEP), World Conservation Monitoring Centre (WCMC)	Global	This data set shows the global distribution of mangroves and was produced as a joint initiative of the International Tropical Timber Organization (ITTO), International Society for Mangrove Ecosystems (ISME), Food and Agriculture Organization of the United Nations (FAO), UN Environment Programme World Conservation Monitoring Centre (UNEP-WCMC), United Nations Educational, Scientific and Cultural Organization's Man and the Biosphere Programme (UNESCO-MAB), United Nations University Institute for Water, Environment and Health (UNU-INWEH) and The Nature Conservancy (TNC). Major funding was provided by ITTO through a Japanese Government project grant; the project was implemented by ISME.
SDG 14	Global Distribution of Coral reefs	United Nations Environment Programme (UNEP), World Conservation Monitoring Centre (WCMC)	Global	This data set shows the global distribution of coral reefs in tropical and subtropical regions. It is the most comprehensive global data set of warm-water coral reefs to date, acting as a foundation baseline map for future, more detailed work. This data set was compiled from a number of sources by the UNEP World Conservation Monitoring Centre (UNEP-WCMC) and the WorldFish Centre, in collaboration with WRI (World Resources Institute) and TNC (The Nature Conservancy). Data sources include the Millennium Coral Reef Mapping Project (IMaRS-USF and IRD 2005; IMaRS-USF 2005) and the World Atlas of Coral Reefs (Spalding *et al*. 2001).
SDG 14	Global Distribution of Seagrasses	United Nations Environment Programme (UNEP), World	Global	This data set shows the global distribution of seagrasses; it is composed of two subsets of point and polygon occurrence data. The data were compiled by UN Environment Programme

		Conservation Monitoring Centre (WCMC)		World Conservation Monitoring Centre in collaboration with many collaborators (such as Frederick Short, of the University of New Hampshire), organizations (such as OSPAR), and projects (such as “Mediseh”, the European project on Mediterranean Sensitive Habitats), across the globe.
SDG 14	Global Distribution of Saltmarsh	United Nations Environment Programme (UNEP), World Conservation Monitoring Centre (WCMC)	Global	This data set displays the distribution of saltmarshes globally, drawing from occurrence data (surveyed and/or remotely sensed). The data set was developed to provide a baseline inventory of the extent of our knowledge regarding the global distribution of saltmarshes, which are ecosystems located in the intertidal zone of sheltered marine and estuarine coastlines. These ecosystems comprise brackish, shallow water with salt-tolerant plants such as herbs, grasses and shrubs, and are commonly found at temperate and high latitudes.
SDG 14	Habitats Affected by Plastics	United Nations Environment Programme (UNEP), World Conservation Monitoring Centre (WCMC), Grid Arendal	Global	Geographic data layers of mangroves, reefs, saltmarshes, and seagrass habitats located in proximity of rivers emitting plastics.
SDG 14	Index for Coastal Eutrophication	Harmful Algal Event Database (HAEDAT)	Global	The Index for Coastal Eutrophication Potential (ICEP) is an indicator for the potential of riverine nutrient export to sustain new production of non-diatoms phytoplankton biomass; it is calculated by comparing the N, P and Si loading to the Redfield ratios expressing the requirements of marine diatoms growth.

SDG 14	Eutrophication and Hypoxia	World Resources Institute (WRI)	Global	The Interactive Map of Eutrophication and Hypoxia represents 762 coastal areas impacted by eutrophication and/or hypoxia. These data were compiled using a literature search conducted by Dr. Robert Diaz of VIMS and WRI staff.
SDG 14	Nutrient Pollution 2013	Bren School of Environmental Science and Management, University of California	Global	This data layer combines estimates of pollution coming from commercial shipping and from ports. It is a combination of the shipping and port volume data layers, with the port volume data plumed to estimate pollution from commercial ports (with exponential decline in intensity from the port). Ocean-based pollution is assumed to derive from commercial and recreational ship activity. No data on global recreational ship activity currently exist, and therefore the authors modelled this driver using a combination of commercial shipping traffic data and port data.
SDG 14	Ocean pollution from Shipping Lanes and Ports Pressures 2013	Bren School of Environmental Science and Management, University of California	Global	This data shows the ocean-based pollution from stressor data after adjusting for habitat/pressure vulnerability.
SDG 14	Global Ocean Litter Model	Florida State University	Global	Global ocean mismanaged plastic waste distribution calculated using a state-of-the-art Lagrangian ocean analysis tool, analysing the source and fate of pollution broken down by country.
SDG 14	Marine Litter and Plastic Pollution Regional Action Plans	United Nations Environment Programme (UNEP)	Global	This data set maps the indicators in Regional Action Plans across the world.

SDG 14	Marine Litter and Plastic Pollution Resources	United Nations Environment Programme (UNEP) and the Global Partnership on Marine Litter (GPML)	Global	A compilation of marine litter and plastic pollution action plans, initiatives, technical resources, financing resources, technologies and initiatives hosted on the GPML Digital Platform.
SDG 14.1.1	Beach litter count per square kilometre	United Nations Environment Programme (UNEP)	Global	Marine litter is any persistent, manufactured or processed solid material which is lost or discarded and ends up in the marine and coastal environment. It constitutes an increasing risk to ecosystem health and biodiversity while entailing substantial economic costs through its impacts on public health, tourism, fishing and aquaculture. National efforts to collect data on beach litter can be supported by campaigns to engage members of the public as volunteers in beach cleanups; the current data set is derived from citizen science activities reported through beach cleanup campaigns.
SDG 14.5.1	Coverage of protected areas in relation to marine areas	United Nations Environment Programme (UNEP)	Global	This data layer consists of the coverage of protected areas in relation to marine areas (Exclusive Economic Zones) (%), protected marine area (Exclusive Economic Zones) (square kilometres) and average proportion of Marine Key Biodiversity Areas (KBAs) covered by protected areas (%)
Complementary Data	Population Density 2020	Center for International Earth Science Information Network (CIESIN)	Global	The Gridded Population of the World (GPW) collection, now in its fourth version (GPWv4), models the distribution of human population (counts and densities) on a continuous global raster surface. Since the release of the first version of this global population surface in 1995, the essential inputs to GPW have been

		Columbia University		population census tables and corresponding geographic boundaries. The purpose of GPW is to provide a spatially disaggregated population layer that is compatible with data sets from social, economic, and Earth science disciplines, and remote sensing. It provides globally consistent and spatially explicit data for use in research, policy-making, and communications.