Technologies for Observing and Monitoring Plastics in the Oceans

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Abstract— **Massive and rapidly increasing use of plastics in modern society with short average use times and poor reuse and recycling options has resulted in a global threat with potentially devastating impacts on human and non-human life. Knowledge on the impacts of plastics in all forms on the planetary life-support system is rapidly accumulating and it underlines the scale of the risk humanity is taking. While quantitative information on production and use of plastics is to a large extent available, the fate of plastics discarded or leaked into the environment is highly uncertain. In particular, knowledge of how much plastic at different scales down to micro and nano levels reaches the ocean and the trajectories of the plastic in the ocean remain poorly known. Based on the mounting evidence, the United Nations have recognized the threat and are coordinating the many efforts to limit the amount of plastic that enters the environment uncontrolled. However, the Earth observation community so far has not managed to establish a global tracking and information system that would provide quantitative information on where and how plastics move in the ocean and allow the identification of the points where marine plastic pollution could be reduced most effectively. There are a number of independent projects focused on better monitoring plastics in the environment, including the ocean. In particular, projects in the EU, USA, and Japan have participated in working groups initiated by UN Environment. These projects are focusing on the monitoring of marine litter and plastics, management of information and knowledge, risks assessments, exploitation of opportunities and synergies, and, as far as possible, estimation of relevant costs and benefits. Measurements proposed include satellite and airborne remote sensing, surface and underwater in situ measurements, and crowd-sourcing observations. The need for extensive data processing and the use of deep learning techniques is acknowledged. The sensors considered range from multi- and hyperspectral sensing or other optical sensing to radar imaging aiming at a wide geo-spatial coverage. There is a need to develop global coordination mechanisms to ensure that societal knowledge needs are met and decisions on reducing plastic pollution in the ocean are informed by this knowledge. OES in collaboration with the Blue Planet Initiative of the Group on Earth Observations (GEO) and the UN environment, is leading an initiative aiming at this coordination.**

Keywords—marine debris, plastics, remote sensing, tracking

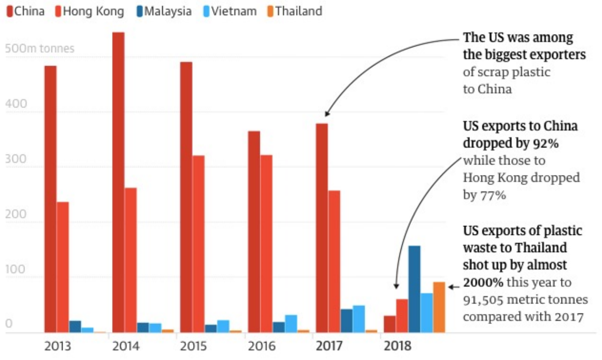
I. INTRODUCTION

Plastics are integrated in almost everything we produce, trade and use from the cloths we wear to the houses and buildings we live and work in, the way our food and on-line orders are protected, the infrastructure that provides services for water, power, sewage, communication, and transportation to us, and the many electronic tools we utilize. In 2015, an estimated 448 million tons of plastics were produced and of that 161 million tons had a use time of less than 6 months [1]. This massive production of plastics, along with an estimated average use time of 5 years [1] compared to a plastics life-time of between 500 and 5000 years has led to a steady and potentially catastrophic burden of plastics in all flows in the Earth's life-support system. And many of these flows in air and water transport plastics into the ocean. In fact, an estimated 10% to 12% of the plastics produced end up in the ocean. If the current trajectory continues, then by 2050 there would be more plastics than fish in the world's oceans [2]. Plastics have been found in the guts of marine megafauna and humans and in the tissues of fish. The mounting global challenge of plastic pollution [3,4,5,6,7] is impacting the marine biosphere [8,9,10] and the food web [11]. Over time, plastics in the environment break down into smaller pieces. Impacts of plastics on the biosphere including humans depend on the particle size and the additives incorporated during production. Macroplastics (larger than 5 mm) can physically hurt animals and clog the digestive systems if consumed. Microplastics (less than 5 mm) can accumulate in organism throughout the food web with health impacts currently not well understood. Nanoplastics (less than 1 μm in size) have been integrated at the cellular level in some organisms [12], and they can cross the blood-brain barrier [13].

Most of the plastic pollution entering the ocean today can be attributed to rivers. Estimates of the river contribution cover a wide range from the 20 top-ranking rivers contributing 67% [28] to the ten top-ranked rivers accounting for roughly 90% of the global river-borne load [14]. This large uncertainty emphasizes the urgent need for improved observations.

Most of the top-ranking rivers are located in Asia and Africa. Recognizing that much of this load results from the export of hard-to-recycle plastics from the richer to the poorer countries, the United Nations augmented on May 10, 2019 the Basel Convention with a legally binding framework to reduce this export significantly and makes exchange between member countries of the Convention and other countries illegal [15].

The rapidly changing regulatory and commercial context has a large impact on trajectories of plastics, including the flows into the ocean. Fig. 1 shows the change on export of plastics waste from the USA after China in 2017 drastically reduced the amount of plastic waste that could be exported to China. As a result of this change, the USA is exporting much more to Thailand, Vietnam, and Malaysia, where processing is very poor. The augmentation of the Basel Convention will no longer allow any trade of plastic waste between member (Thailand, Vietnam, and Malaysia) and non-member (USA) countries of the Convention, and this will again change significantly the global trajectories of plastics waste. However, there are no sufficient observations that would allow an assessment of the impact these changes have on the flows of plastics into the ocean.



The US was among the biggest exporters of scrap plastic to China

US exports to China dropped by 92% while those to Hong Kong dropped by 77%

US exports of plastic waste to Thailand shot up by almost 2000% this year to 91,505 metric tonnes compared with 2017

Guardian graphic. Source: Greenpeace

Figure 1. Export of plastic waste from the US. Note the sharp decrease of export to China and Hong Kong and increase of export to Malaysia, Vietnam, and Thailand after China changed the import regulations for plastic waste in 2017. Courtesy The Guardian [16].

There is a need of a more extended agreement on plastic pollution [17]. The development of such an agreement has to be informed by extensive observations of the sources and uses of plastics as well as the trajectories of plastics leaked into the environment.

New initiatives to extract plastics from the ocean for economic use are emerging at different levels (although in terms of amounts removed they are currently not more than the pro-verbal drop in the bucket), and all of these activities are in need of information on where to locate plastics in amounts that would make this extraction economically viable. Risk assessments and cost-benefit analyses are in need of quantitative information on plastics in the ocean as well as a better understanding of the full impacts of plastics at all scales on the marine biosphere. So far, impact assessments are extremely limited in scope and only available for a small range of spatial locations.

Promising efforts are made to monitor and quantify the flows of plastics into the ocean and to detect and quantify plastics in the ocean [18,19]. However, in order to fully explore the existing observation means for the detection, monitoring and quantifying of ocean plastics, a comprehensive strategy is need. The strategy for an Integrated Marine Debris Observing System (IMDOS) is discussed in [20]. It is important to note that this strategy should be aligned to the Sustainable Development Goal (SDG) 14 "Life Below Water," specifically the Target 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" and the associated Indicator 14.1.1 "Index of coastal eutrophication (ICEP) and floating plastic debris density." Work on developing this indicator has started [21]. The GEO Initiative "Oceans and Society: Blue Planet" is contributing to the development of this indicator. The current work plan for 14.1.1 [21] identifies four main indicators for plastics:

- Plastic debris washed/deposited on beaches or shorelines (beach litter);
- Plastics debris in the water column;
- Plastic debris on the seafloor/seabed;
- Plastic ingested by biota (e.g. sea bird).

Considering the flows of plastics into the ocean, there is also a need for indicators that characterize these flows. At a minimum, indicators are needed for:

- Plastic debris in rivers, including the mouths of rivers and estuaries
- Plastic debris from ocean activities (shipping, fishing, mining),
- Plastic debris flowing into the ocean as a result of coastal disasters.

Ocean activities contribute significantly to the flow of plastics into the ocean. According to [22], derelict fishing gears account for 46% of the plastics currently in the ocean. Considering the amount of plastics used in the built environment, coastal disasters increasingly contribute large amounts to marine plastic debris [23].

Each of the above indicators requires different monitoring techniques operating at different spatial and temporal scales. In the following, we are focusing on macroplastics in the water column and on beaches and the flows of macroplastics into the ocean. There is an immediate need for assessments of the sources and presence of ocean plastics, as well as to detect plastics in the ocean through a range of observation means. Tracking the flows of plastics into the ocean and the circulation of plastics in the ocean provides a basis for quantitative assessments. Measurements of the type of plastics in the ocean are also needed for qualitative assessments and comprehensive risk analyses.

In order to overcome the many barriers for the use of scientific knowledge in the development of policies [24] it will be important to co-designing the research agenda with decision and policy makers and to co-create the knowledge. An important process to facilitate this is participatory modeling.

II. CHALLENGES TO MONITORING PLASTIC

There are many challenges to the remote sensing of plastic pollution in the coastal and marine environment. Most of the plastic items have sub-meter size and are dispersed in the ocean or along beaches. These individual pieces are difficult to image from existing space platforms, which typically have resolutions from 5 m up to 1 km. The fact that large-scale remote sensing instruments are not able to directly detect plastics is not only due to the size of plastic elements compared to the resolution but also the limited ability of high-resolution systems (optical, radar or hyperspectral sensors) to differentiate water-covered plastics from the surrounding water. In addition, fragmentation and decomposition reduces the size of the items over time, and thus further limits the possibility of detection. Airborne systems offer higher spatial resolution, but have limited temporal and spatial coverage. Ground-based systems such as HF radar can monitor coastal surface currents but will not see small plastic debris. The integration of multi-source remote sensing and in situ observation with models of surface currents appears to be necessary to generate an observational basis for the quantification of the indicators listed in the Introduction. For this quantification, inputs from other expert communities will be necessary in order to utilize knowledge of the lifecycle of plastics in the ocean. Moreover, an improvement of the methods and sampling systems is required, with calibrated and inter-comparable data. A standardized metadata description is also necessary.

For in situ observations, a combination of dedicated platforms, measurements of opportunity, networks of citizen scientists, and crowd sourcing has the potential to provide a sufficient database for estimations of both the quantity and types of plastics in the ocean. In situ platforms of observations should be developed or adapted with an emphasis on having them on-board ships, with real-time monitoring of measurements with a global satellite system (Internet of Ships). And data must be acquired on the whole globe.

To properly quantify the mass of plastic requires spatially distributed measurements of all size classes of debris at global scales, including the seafloor, which cannot presently be met with existing technology. Further complicating these aspects are the changes in depth, which affect detection, and disappearance through ingestion by wildlife for example. Thus, the only way to monitor and assess plastics in any quantifiable manner is through a set of well- defined proxy indicators.

III. TECHNOLOGIES

In the following, observation technologies are discussed based on a selection of the indicators and auxiliary information needs. The indicators considered are:

- Plastic debris washed/deposited on beaches or shorelines (beach litter);
- Plastics debris in the water column;
- Plastic debris in rivers, including the mouths of rivers and estuaries
- Plastic debris from ocean activities (shipping, fishing, mining),
- Plastic debris flowing into the ocean as a result of coastal disasters.

Auxiliary information discussed is for ocean surface circulation. Here, we are not considering observation approaches to the monitoring of impacts in detail. Potential impacts on wildlife can be mapped and quantified spatially by overlaying known trajectories of plastics, marine wildlife migration corridors, and habitats, although the depth distribution of each of these variables would have to be considered [25]. This of course requires good knowledge of wildlife habitats in space and time, which is often not available. The most visible and accessible evidence of impacts on wildlife is found at beaches, coral reefs and river mouths, while evidence from more remote location on the seafloor and in the open ocean is very sparse and less accessible. Importantly, an integrated information system should provide crowd-sourcing tools to collect information on plastic impacts on wildlife. Intelligent big data analyses should be used to extract observations from social media, the press, and published literature. Particularly susceptible bird species could be tagged and tracked for potential interactions with marine litter. Whales and other mammal species that are knowingly at risk to digest plastics might also be tagged to identify areas with plastic contents. Combining the information collected in the integrated information with models (see Section IV) would provide a tool for more detailed and comprehensive assessments of the impacts.

Sea bottom plastic monitoring is only possible via remotely operated vehicles such as submarines or manned submarines which can view seabed plastic, or take core or surface samples to detect presence of microplastics [32].

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

Baseline surveys should summarize the standing stock, abundance, distribution and composition of litter on beaches with consistent monitoring protocols and standards. Beaches should also be characterized by physical characteristics that make them prone to have plastic: location (rural or urban), presence of regular cleaning (resorts), tides, or exposure, or storms [29, 30]. These characteristics would indicate areas most likely to collect plastic. Combined with observations of litter to determine, they would aid targeting clean-up efforts.

Observations of beach debris can be collected using crowdsourcing, citizen scientist programs, autonomous monitoring tools (e.g., webcams, robots), and airborne surveys (drones). Citizen science programs could focus on mapping plastic types and amounts on beaches. Global citizen scientist programs exists that could be utilized here. For example, the Global Learning and Observations to Benefit the Environment (GLOBE) program (see https://www.globe.gov) is a worldwide science and education program, in which many high school students engage in observations. Developing a standard procedure and app for plastic at beaches (and in the environment) could rapidly increase the information available on global scale. Using drone or aerial surveys would likely cause large costs and should address priority areas.

Currently, standards for the collection, storing and processing of observations of plastics at beaches and other coastal locations are lacking. There is a need to develop templates and tools for the collection of information on beach debris. Importantly, intelligent algorithms to identify and quantify plastics in images are needed, and artificial intelligence (AI) approaches to pattern recognition are a promising avenue.

III.2 Plastics debris in the water column

Observation of plastic in the water column can be done in several ways. Concentration of plastic particles can be determined via in situ samples collected at the water surface or in the water column. The samples can be analyzed to determine the statistics of the debris size as well as the types. It appears necessary to establish a globally coordinated program to collect and analyze such samples along carefully selected transects. These transects should be determined based on extensive model studies (see Section IV).

The presence and movements of plastic could potentially be monitored by satellites, particularly for plastic at or near to the water surface. Satellite observations are limited in spatial and temporal resolution. Therefore, drones or blimp surveys should be used in selected accessible areas to increase resolution as needed. Both, drones and blimps are limited in terms of timing and spatial coverage, and their use should be guided by model studies. Fixed-wing drones are increasing the distance and duration of drone flights. Blimps have the advantage of longer stable flights.

Multi-spectral satellite remote sensing of plastic in the water column is currently only possible for larger elements on or close to the water surface, and under good atmospheric conditions (no clouds). Commercial high-resolution satellite data are available for purchase but have low temporal resolution. In all cases cloud cover and sea surface conditions affect the detection of debris no matter the resolution.

As the plastic elements sink or decompose, the likelihood of detection with remote sensing methods decreases significantly. There are some promising methods looking at anomalies or particular signatures to identify ocean plastic. For example ESA's Sentinel-3 satellite has an ocean color imager that is potentially detecting unique signatures or large agglomerations of plastic. However, this sensor only images at 300 m resolution, and even with a revisit rate of almost every 2 days, it will not detect most plastic of interest. Commercially available hyperspectral sensors such as HyMap may be more suited for detecting plastics [33, 34].

Synthetic Aperture Radar (SAR) provides high-resolution information on parameters of the ocean surface such as topography, roughness, surface waves, winds and currents, which can be correlated with the movement of marine debris, or used for the identification of convergent fronts where floating debris collects. Larger objects, which float at the surface can be detected directly with SAR or through secondary surface wave patterns, although false alarms remain a significant obstacle [18,35].

Direct tracking of plastic or floating pieces can be achieved more reliably with debris tagged with GPS tags and transmitters. Trajectories of ocean plastic can be compiled to reconstruct the path of plastic from source to fate. These trajectories would provide important data for the assimilation in the model discussed in Section IV. Tracking can be achieved with Argos tracking sensors, or GPS devices, which may however remain too expensive to implement widely. The upcoming Kineis constellation from CLS, or a low-tech solution such as PandaSat proposed by WWF could provide more affordable solutions in 2021. These do however come with the caveat of introducing electrical trash into the environment. For areas close to shore, cheaper, accurate IoT (internet of things) technology can be deployed using conventional 3G networks, or Lora systems to provide better coverage where mobile data is lacking. Iridium satellite connectivity is prohibitively expensive to be deployed into the sea.

III.3 Plastic debris in rivers, including the mouths of rivers and estuaries

Main sources of marine litter entering the ocean through rivers are due to improperly managed plastic waste, including failed recycling, inadequate sewage systems, and inadequate disposal [4]. A combination of an intensive 2-week in situ sampling program with hydrological data showed that the Saigon river, Vietnam, carried macroplastic loads at least four times higher than previously estimated [26]. This underlines the importance of case studies in those rivers that knowingly contribute significantly to the flow of plastic into the ocean.

There are various technologies to estimate riverine sources directly with varying levels of effort, scale and accuracy. Drone or field surveys of river mouths can assess accumulated plastic. A standard methodology for drone-based surveys of plastic is being developed by DRONET [27].

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

In addition to estimates of plastics at river mouths and in estuaries, it would be important to map the input of plastic into the rivers. Variables such as watershed population, sources of waste and leakages into the environment, management practices, and runoff would be important auxiliary data to harvest from existing sources.

III.4 Plastic debris from ocean activities (shipping, fishing, mining)

Many sea-based activities contribute to marine debris. Important contributions come from fishing and aquaculture, shipping (e.g., transport, tourism), offshore mining and extraction, and illegal dumping at sea. As most sea-based sources of plastic come from ship presence or traffic, the comprehensive available Automatic Identification System (AIS) data provides a valuable database. 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. This would allow determination of ship size, type, and flag country to identify the most likely polluters.

Knowing where the most important fishing areas are at any given one point in time (e.g., using the such as with Global Fishing Watch, https://globalfishingwatch.org) would help to detect major potential sources and locations of ghost gear. Aquaculture is also a known source of lost fishing gear and apparatus. Locations of these activities can be detected reliably with high-resolution imagery [31] and they can also be harvested from publicly available data sources.

III.5 Plastic debris flowing into the ocean as a result of coastal disasters.

The modern built environment includes a large fraction of plastic material. In 2015, 72 million tons of plastic went into building and construction (with an average use time of 35 years) [1]. Considering the migration of the global population, a large fraction of this is located in the coastal zone or in flood zones and thus exposed to hydro-meteorological hazards. This rapidly increasing exposure of the built environment to floods and storms has increased the likelihood of plastic and other debris entering the ocean. The risk is further exacerbated by the likely increase of the frequency and intensity of hydro-meteorological hazards due to modern climate change.

Information on the amount of marine debris resulting from coastal disasters is urgently needed. Databases compiled by insurances, real-estate companies and municipalities could be harvested to estimate and map the plastic integrated the built environment. Overlaying this information with disaster assessment would provide a basis to quantify the amount of plastic and other debris washed into the ocean during major hazardous events.

III.6 Ocean surface currents

A very important auxiliary input for modeling the trajectories of plastics in the ocean are ocean surface currents. The output of regional and global Ocean General Circulation Models (OGCM) can be used to map and predict past and future trajectories of marine plastic. This can assist in identifying sources and accumulation locations [40]. The data used to generate these models include wind speed and direction, mapped sea level anomaly (MSLA), and sea surface temperature, which are available almost daily. These models can be fine-tuned using data from buoys, or GPS tracked plastic pieces [37, 38]. Three-dimensional modeling of marine plastic is also being developed, for example by the TOPIOS project (http://topios.org/).

IV. EVALUATING RISKS AND ASSESSING POTENTIAL FUTURES

Currently, no thorough assessments are available for the current and future impacts of plastics on the marine biosphere and potential feedbacks to the land-based biosphere, including humans. Integrating the observations discussed in Section III with a system model of the ocean capturing plastics and its known impacts would provide a versatile assessment tool. A global box model could be used to model ocean plastics and the impacts. Each of the boxes would represent a stock-and-flow model capturing all aspects of plastics in this box.

Land-based sources (rivers, coastal disasters) and sinks (beaches) could be accounted for. The major land-based sources of marine plastic include land-fills, floodwaters, industrial outfalls, discharge from storm water drains, untreated municipal sewerage, and littering of beaches and coastal areas from tourism and other activities. Information on these sources could be harvested from existing databases, social media and public documents.

The integrated information and model system would provide a basis for risk assessments. For example, a candidate for assessing the risk of seafood contamination from ocean plastics is the functional dependency network analysis [39], which this model system would support. Likewise, the model system would facilitate cost-benefit analyses for mitigation means.

This integrated system also would allow for a scenario-based exploration of possible futures. After careful validation and calibration, this model could be used to assess future trajectories for ocean plastics based on scenarios of plastic production, waste management, recycling and reuse practices, as well as efforts to remove plastics from the ocean. Desirable futures could then be connected back to transformative policies that need to be implemented to ensure such futures.

V. CONCLUSIONS

The growing plastic pollution in the ocean comes with a high risk for the marine biosphere and with unknown risk for humanity. Information on the quantity of plastic in the ocean and its impacts on marine life and beyond is limited. There is an urgent need to establish an integrated information system that meets the societal knowledge needs for decision and policy making addressing this global challenge. While there are many promising observation techniques and approaches for in situ and remote sensing, many of these techniques need to be adapted and improved to provide useful observations. A wide range of sensor-based, harvested, and crowd-sourced observations need to be integrated with a global modeling system. IEEE/OES in collaboration with the Blue Planet Initiative of the GEO and UNEP is leading an initiative aiming to bring together experts and social agents to co-develop the information and modeling system.

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REFERENCES

[1] Parker, L., 2018. We made plastic. We depend on it. We're drowning in it. *National Geographic*, June 2018 issue.

[2] World Economic Forum, Ellen McArthur Foundation, and McKinsey & Company, 2016. The New Plastics Economy – Rethinking the future of plastics. http://newplasticseconomy.org/assets/doc/EllenMecArthurFoundation_TheNewPlasticsEconomy_Pages.pdf.

[3] Law, K. L., & Annual, R., 2017. Plastics in the Marine Environment. *Annual Review of Marine Science*, **9**, 205-229.

[4] Jambeck, J. R., Geyer, R., Wilcox, C., Siegler, T. R., Perryman, M., Andrady, A., Narayan, R., Law, K. L., 2015. Plastic waste inputs from land into the ocean. *Science*, **347**(6223), 768–771. doi:10.1126/science.1260352

[5] Nash, A. D., 1992. Impacts of marine debris on subsistence fishermen – an exploratory study. *Marine Pollution Bulletin*, **24**(3), 150-156.

[6] Peeken, I., Bergmann, M., Gerdts, G., Katlein, C., Krumpen, T., Primpke, S., & Tekman, M., 2018. Microplastics in the Marine Realms of the Arctic with Special Emphasis on Sea Ice. Arctic Report Card: Update for 2018. Retrieved from https://arctic.noaa.gov/Report-Card/Report-Card-2018/ArtMID/7878/ArticleID/787/Microplastics-in-the-Marine-Realms-of-the-Arctic-with-Special-Emphasis-on-Sea-Ice.

[7] Villarrubia-Gomez, P., Cornell, S. E., & Fabres, J., 2018. Marine plastic pollution as a planetary boundary threat - The drifting piece in the sustainability puzzle. *Marine Policy*, **96**, 213-220.

[8] Green, D. S., Colgan, T. J., Thompson, R. C., & Carolan, J. C., 2019. Exposure to microplastics reduces attachment strength and alters the haemolymph proteome of blue mussels (Mytilus edulis). *Environmental Pollution*, **246**, 423-434.

[9] Nel, H. A., Hean, J. W., Noundou, X. S., & Froneman, P. W., 2017. Do microplastic loads reflect the population demographics along the southern African coastline? *Marine Pollution Bulletin*, **115**(1-2), 115-119.

[10] Taylor, M. L., Gwinnett, C., Robinson, L. F., & Woodall, L. C., 2016. Plastic microfibre ingestion by deep-sea organisms. *Scientific Reports*, **6**.

[11] Provencher, J. F., Vermaire, J. C., Avery-Gomm, S., Braune, B. M., & Mallory, M. L., 2018. Garbage in guano? Microplastic debris found in faecal precursors of seabirds known to ingest plastics. *Science of the Total Environment*, **644**, 1477-1484.

[12] Mattsson K, Hansson L-A, Cedervall T., 2015. Nano-plastics in the aquatic environment. *Environmental Science: Processes& Impacts*, **17**(10):1712–1721. doi:10.1039/c5em00227c

[13] Mattsson, K., Johnson, E. V., Malmendal, A., Linse, S., Hansson, L.-A., Cedervall, T., 2017. Brain damage and behavioural disorders in fish induced by plastic nanoparticles delivered through the food chain. *Scientific Reports*, **7**, Article number 11452, DOI 10.1038/s41598-017-10813-0.

[14] Schmidt, C., Krauth, T., & Wagner, S., 2017. Export of Plastic Debris by Rivers into the Sea. Environmental Science & Technology, **51**(21), 12246-12253.

[15] United Nations Environment Programme, 2019. Draft decision BC-14/[]: Amendments to Annexes II, VIII and IX to the Base Convention. NNEP/CHW.14/CRP.40, 10 May 2019.

[16] McVeigh, K., 2018. Huge rise in US plastic waste shipments to poorer countries following China ban. *The Guardian*, Oct. 5, 2018. https://www.theguardian.com/global-development/2018/oct/05/huge-rise-us-plastic-waste-shipments-to-poor-countries-china-ban-thailand-malaysia-vietnam.

[17] Borrelle et al Borrelle, S. B., Rochman, C. M., Liboiron, M., Bond, A. L., Lusher, A., Bradshaw, H., & Provencher, J. F., 2017. Why we need an international agreement on marine plastic pollution. *Proceedings of the National Academy of Sciences of the United States of America*, **114**(38), 9994-9997.

[18] Davaasuren, N., Marino, A., Boardman, C., Ackermann, N., Alparone, M., & 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.

[19] Garaba, S. P., & 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.

[20] Maximenko, N., Corradi, P., Law, K., Van Sebille, E., Garaba, S. P., Lampitt, R. S., Galgani, F., Martinez-Vincente, V. … Wilcox, C., 2019. Towards an Integrated Marine Debris Observing Systems. *Frontiers in Marine Sciences*, in press.

[21] UNEP, 2018. Goal 14, Target number 14.1, Indicator Number and Name 14.1.1. Workplan for Indicator 14.1.1., available at https://unstats.un.org/sdgs/tierIII-indicators/files/Tier3-14-01-01.pdf.

[22] Lebreton, L., Slat, B., Ferrari, F., Sainte-Rose, B., Aitken, J., Marthouse, R., Hajbane, S., Cunsolo, S., Schwarz, A., Levivier, A., Noble, K., Debeljak, P., Maral, H., Schoeneich-Argent, R., Brambini, R., and Reisser, J. (2018). Evidence that the Great Pacific Garbage Patch is rapidly accumulating plastic. Scientific Reports. DOI:10.1038/s41598-018-22939-w.

[23] Murray, C. C., Maximenko, N., & Lippiatt, S. (2018). The influx of marine debris from the Great Japan Tsunami of 2011 to North American shorelines. Marine Pollution Bulletin, 132, 26-32.

[24] Kirchhoff, C.J., Lemos, M.C., Dessai, S., 2013. Actionable knowledge for environmental decision making: Broadening the usability of climate science, *Annual Review of Environment and Resources*, **38**, 393-414.

[25] Vegter, A. C., Barletta, M., Beck, C., Borrero, J., Burton, H., Campbell, M. L., … Hamann, M. (2014). Global research priorities to mitigate plastic pollution impacts on marine wildlife. Endangered Species Research, 25(3), 225–247. https://doi.org/10.3354/esr00623.

[26] Van Emmerik, T., Kieu-Le, T.-C., Loozen, M., van Oeveren, K., Strady, E., Bui, X.-T., … Tassin, B. (2018). A Methodology to Characterize Riverine Macroplastic Emission Into the Ocean. Frontiers in Marine Science, 5, 372. https://doi.org/10.3389/fmars.2018.00372

[27] The Plastic Tide, 2018. Launching the Marine Litter Dronet. https://www.theplastictide.com/blog-1/2018/4/22/launching-the-marine-litter-dronet.

[28] Lebreton L C. M., Joost van der Zwet, Jan-Willem Damsteeg, Boyan Slat, Anthony Andrady & Julia Reisser, 2017. River plastic emissions to the world's oceans. Nature Communications volume 8, Article number: 15611.

[29] Moy, K., Neilson, B., Chung, A., Meadows, A., Castrence, M., Ambagis, S., & Davidson, K. (2018). Mapping coastal marine debris using aerial imagery and spatial analysis. Marine Pollution Bulletin, 132, 52–59. https://doi.org/10.1016/J.MARPOLBUL.2017.11.045.

[30] Ryan, P. G., Moore, C. J., Van Franeker, J. A., & Moloney, C. L. (2009). Monitoring the abundance of plastic debris in the marine environment. Philosophical Transactions of the Royal Society B: Biolog.

[31] Trujillo, P., Piroddi, C., & Jacquet, J. (2012). Fish farms at Sea: The ground truth from Google Earth. PLoS ONE, 7(2), e30546. https://doi.org/10.1371/journal.pone.0030546.

[32] Thompson, R. C., Woodall, L. C., Sanchez-Vidal, A., Canals, M., Paterson, G. L. J., Coppock, R., … Narayanaswamy, B. E. (n.d.). The deep sea is a major sink for microplastic debris. https://doi.org/10.1098/rsos.140317.

[33] Garaba, S. P., Aitken, J., Slat, B., Dierssen, H. M., Lebreton, L., Zielinski, O., & Reisser, J. (2018). Sensing Ocean Plastics with an Airborne Hyperspectral Shortwave Infrared Imager. Environmental Science and Technology, acs.est.8b02855. https://doi.org/10.1021/acs.est.8b02855.

[34] Goddijn-Murphy, L., Peters, S., van Sebille, E., James, N., & Gibb, S. (2017). Concept for a hyperspectral remote sensing algorithm for floating marine macro plastics. Marine Pollution Bulletin, 126, 255–262. https://doi.org/10.1016/j.marpolbul.2017.11.011.

[35] Davaasuren, N., Marino, A., Ackermann, N., Alparone, M., Nunziata, F., & Boardman, C. (2018). Detecting microplastics pollution in world oceans using SAR remote sensing. In 2018 IEEE International Geoscience and Remote Sensing Symposium.

[36] Sudre, J., & Morrow, R. A. (2008). Global surface currents: A high-resolution product for investigating ocean dynamics. Ocean Dynamics, 58(2), 101–118. https://doi.org/10.1007/s10236-008-0134-9.

[37] Havens, Z. W. (2018). The Remote Sensing of Marine Plastics. University of Virginia. Retrieved from: https://libraetd.lib.virginia.edu/downloads/5h73pw50c?filename=1_Havens_Zane_2018_MA.pdf

[38] GESAMP. (2019). Guidelines for the Monitoring and Assessment of Plastic Litter in The Ocean. Report and Studies 99, GESAMP. Retrieved from http://gesamp.org.

[39] Pinto, C. A., Garvey, P. R., 2013. Advanced Risk Analysis in Engineering Enterprise Systems. CRC Press, Taylor&Francis Group.

[40] van Sebille, E., England, M. H., Froyland, G., 2012. Origin, dynamics and evolution of ocean garbage patches from observed surface drifters. Environmental Research Letters, 7(4), DOI: 10.1088/17489326/7/4/044040.