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Monitoring of Floating Marine Macro Litter

State of the art and literature overview

Vighi, M., Ruiz-Orejón, L. F., Hanke, G.

MSFD Technical Group on Marine Litter

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Authors: Vighi, M., Ruiz-Orejón, L. F., Hanke, G.

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Contact information
Name: Georg Hanke
Address: Via Enrico Fermi 2749, I-21027 Ispra (VA), Italy
Email: georg.hanke@ec.europa.eu
Tel.: +39-0332-785586

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Contents

Abstract

Marine litter is a recognised and major aspect of marine pollution, posing a direct threat to marine organisms and raising a global concern for its environmental and economic implications. Floating Marine Macro Litter (FMML) is the portion of marine litter comprising items larger than 2.5 cm that float in the surface layers of the water column and is considered a pertinent direct indicator of the pressure exerted by marine litter on marine ecosystems.

Indeed, being the mobile fraction of marine litter, FMML can provide indications of the main sources, sinks and pathways of litter in the marine environment, and allows the assessment of the effects of waste prevention measures. The monitoring and assessing of FMML is considered by the Marine Strategy Framework Directive (MSFD) and regional frameworks, and by the UN.

To this end, several methodologies have been proposed and tested across the globe for monitoring FMML. However, to guarantee that data collected within the monitoring programmes are representative and consistent, and to allow the assessment of trends and thus the evaluation of the effectiveness of mitigation measures, commonly agreed protocols for data collection and management need to be implemented. The present report has been developed by the MSFD Technical Group on Marine Litter (TG ML) to update the FMML monitoring guidance and support EU Member States (MS) in the implementation of monitoring programmes.

This technical report provides a summary of options for FMML monitoring retrieved from a detailed review of scientific literature and research projects developed for this purpose. It details the scientific and technical background that was used for specific guidelines for FMML monitoring.

Foreword

The Marine Directors of the European Union (EU), Acceding Countries, Candidate Countries and European Free Trade Association (EFTA) Countries have jointly developed a common strategy to support the implementation of Directive 2008/56/EC, the 'Marine Strategy Framework Directive" (MSFD). The main aim of this strategy is to allow the coherent and harmonious implementation of the Directive, focusing on methodological questions related to a common understanding of the technical and scientific implications of the MSFD. One of the objectives of the strategy is to develop practical documents that are not legally binding, on various technical issues of the Directive, such as this report.

To support and provide advice to the policy development and implementation process, the MSFD Technical Group on Marine Litter (TG ML) was set up as part of the MSFD Implementation Strategy. The TG ML acts through a mandate of the European Marine Directors. It is led by the Directorate-General for Environment (DG ENV) and chaired by the Institut Français de Recherche pour l'exploitation de la Mer (IFREMER) and the European Commission's Joint Research Centre (JRC). Members include EU Member State delegates, Regional Sea Conventions, other stakeholders and invited technical experts. The TG ML reviews scientific developments and prepares technical guidance and information documents to support EU Member States in implementing the MSFD. Further information can be found on the TG ML page of the JRC's MSFD Competence Centre website (http://mcc.jrc.ec.europa.eu/dev.py?N=41&O=434&titre_chap=TG%20Marine%20Litter).

The present technical report is part of a series of thematic reports issued by the TG ML providing guidance on specific topics related to marine litter, including *A Joint List of Litter Categories for Marine Macrolitter Monitoring* (Fleet et al., 2021), *A European Threshold Value and Assessment Method for Macro Litter on Coastlines* (van Loon et al., 2020), *Marine Litter Threshold Values* (Werner et al., 2020), *EU Marine Beach Litter Baselines* (Hanke et al., 2019), *Floating Macro Litter in European Rivers – Top Items* (González-Fernández et al., 2018), *Top Marine Beach Litter Items in Europe* (Addamo et al., 2017), *Identifying Sources of Marine Litter* (Veiga et al., 2017), *Harm Caused by Marine Litter* (Werner et al., 2017) and *Riverine Litter Monitoring – Options and Recommendations* (González-Fernández et al., 2016). These thematic reports are aimed at experts who directly or indirectly implement the MSFD in the European marine regions. This technical report provides information to support EU Member States in the implementation of monitoring programmes within the MSFD, and addresses marine litter experts and monitoring frameworks outside the EU.

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Authors:

Morgana Vighi, external collaborator – Instituto de Investigación de la Biodiversidad (Biodiversity Research Institute), University of Barcelona, Spain

Luis F. Ruiz-Orejón – Joint Research Centre (JRC), European Commission, Ispra, Italy

Georg Hanke – Joint Research Centre (JRC), European Commission, Ispra, Italy

1. Introduction

1.1. Background

Marine litter is defined as 'any persistent, manufactured or processed solid material discarded, disposed of, or abandoned in the marine and coastal environment' (UNEP, 2009) ([1]). Derived from either land-based or offshore sources, it is a major contributor to marine pollution, as its presence has been observed in all marine compartments, including the water column, the seafloor, the coastline and marine biota (Cheshire et al., 2009; Galgani et al., 2010). Marine litter is recognised by the EU and by regional and national initiatives as a worldwide concern, and its reduction is globally acknowledged as a major community challenge due to the significant environmental, economic, social, political and cultural implications of marine litter pollution (Cheshire et al., 2009; Galgani et al., 2010; Newman et al., 2015; UN Environment, 2017).

The Marine Strategy Framework Directive (MSFD) ([2]), the environmental pillar of the EU Maritime Strategy, is the European legislative framework for the protection of the sea, in place since 2008. It aims to maintain the Good Environmental Status (GES) of the European Seas or move them towards GES, through a cyclic set-up of monitoring, assessments and implementation of measures. After an initial assessment in 2012, the first reporting from monitoring programmes was done in 2014, the first programmes of measures were implemented in 2015, and updated reports on Assessment, GES and Targets were submitted by Member States (MS) in 2018–2020. Reporting on the different aspects is then updated periodically.

Within the MSFD, Marine Litter is addressed by Descriptor 10 (D10): properties and quantities of marine litter do not cause harm to the coastal and marine environment (Commission Decision 2017/848/EU). The MSFD Technical Group on Marine Litter (TG ML) is a formal part of the implementation strategy, consisting of delegates from all coastal EU MS, non-governmental organisation (NGOs), Regional Sea Convention (RSC) secretaries, stakeholders, etc., totalling more than 100 people. In 2017, the MSFD Commission Decision (2017/848/EU) was adopted following a revision process; its part about D10 was based on the TG ML recommendations, providing methodological standards for the different D10 criteria including beach, sea surface, seafloor, microlitter, ingestion and entanglement, which together provide the framework for marine litter assessments.

Floating Marine Macro Litter (FMML) is addressed by the first criterion of D10 (D10C1), which includes beach, floating and seafloor litter (excluding microlitter, which is addressed under D10C2), and sets as the overall provision for the GES that the 'composition, amount and distribution of litter on the coastline, in the surface layer of the water column, and on the seabed, are at levels that do not cause harm to the coastal and marine environment'. According to this criterion, EU MS should derive threshold values, and marine litter should be monitored in all the different compartments. The identification of baseline concentrations, as provided for beach litter (Hanke et al., 2019), is essential to assess the extent of the pollution problem and to assess its trends. The process of defining threshold values for marine litter started with beach litter (van Loon et al., 2020) and will subsequently also address seafloor and floating macro litter within MSFD D10C1.

Harmonisation of marine litter monitoring is supported through the guidance published by the TG ML in 2013 (Galgani et al., 2013). Considering the different degrees of maturity of the different monitoring approaches, this guidance provided a set of recommended methods and enabled improved comparability of resulting datasets across Europe. This guidance underwent an updating process in recent years, during which results from science and requirements from policy were gathered to reach a proposal to define common monitoring protocols for the different criteria and compartments of marine litter, and a joint list of items (Fleet et al., 2021) to be used for categorisation.

Following monitoring and assessment, the MSFD requires the implementation of measures against marine litter. The EU MS and the RSC Action Plans, developed by the Convention for the Protection of the Marine Environment of the North-East Atlantic (OSPAR), the Helsinki Convention on the Protection of the Marine Environment of the Baltic Sea Area (HELCOM), the Mediterranean Action Plan (MAP), the Black Sea Commission (BSC) and the Arctic Council's Protection of the Arctic Marine Environment Working Group (PAME), are identifying and implementing numerous actions to reduce litter input and impact (see Section 5). The periodic assessment of the state of the marine environment regarding this and other issues is a fundamental aspect of the adaptive management process within the MSFD and the RSC Action Plans.

([1]) UNEP (2009), Marine Litter: a global challenge, p. 13
([2]) https://ec.europa.eu/environment/marine/eu-coast-and-marine-policy/marine-strategy-framework-directive/index_en.htm

The European Zero Pollution Action Plan (European Commission, 2021) ([3]) is providing a cross-directive approach to environmental pollution, and a target for the reduction of Litter at Sea.

On a global scale, the scientific community identified the need to establish a global marine litter observatory (Maximenko et al., 2019), and marine litter was identified as one of the challenges under UN Sustainable Development Goal 14, 'Life below water', urging the need for global action. The Global Partnership on Marine Litter (GPML) is providing a framework for such actions on a global scale. RSCs have developed Regional Action Plans (RAPs) and monitoring schemes worldwide. In order to identify large-scale priorities and acknowledge that marine litter is a transboundary issue, comparable quantitative assessments must be provided across different policy frameworks and organisations at a large scale.

The United Nations Environmental Programme (UNEP) has prepared a report on assessment that includes FMML as one of the litter types considered (UNEP, 2021), and the Group of Experts on the Scientific Aspects of Marine Environmental Protection (GESAMP) provided a guidance document that includes recommendations for FMML monitoring (GESAMP, 2019). At the same time, the International Maritime Organization (IMO) has set up a dedicated group working on the issue of marine litter derived from the shipping sector, and is planning to discuss the litter generated by maritime transport, given that 811.2 million TEUs (20-foot equivalent units of litter) were handled in container ports worldwide in 2019, and an average of 1 382 containers a year were lost at sea from 2008 to 2019 (Unctad, 2020; WSC, 2020).

1.2. Scope of the report

The scope of this technical report is to compile the existing information regarding techniques and options for monitoring FMML, including an overview of available literature on the subject and on monitoring approaches.

The document provides a reference to FMML monitoring programmes developed within the RSC, scientific national and international projects developed by NGOs and research centres, and the most relevant scientific studies on FMML monitoring. It also provides an overview of recommendations on monitoring approaches and methodologies. The considerations provided herein are derived from the results of the testing activities performed across the EU marine areas, and the subsequent thematic discussion that took place within a dedicated joint workshop with relevant stakeholders held in Rome in February 2019.

The provision of sound assessments for policy implementation requires the consideration of scientific research results and knowledge of the latest state-of-the-art developments. It also requires information about the policy background, the data needs and options for the efficient use of assessments. It is, therefore, necessary to interface science and policy, enabling information exchange and communication among those involved.

While the monitoring of floating macro litter in the freshwater environment, lakes and rivers, is not specifically addressed here, it should be mentioned that there is a need for comparability of litter identification (through the Joint List of Litter Categories; Fleet et al., 2021) and that comparable approaches and metrics may enable the calculation of litter fluxes in rivers and streams, and thus also the estimation of litter inputs to the seas through riverine systems (González-Fernández and Hanke, 2017). The monitoring methods described here may therefore be also applicable, after adaptation, to the monitoring of floating macro litter in freshwater systems (González-Fernández et al., 2016).

This report should provide the scientific background for updating of existing guidance (Galgani et al., 2013) and protocols for monitoring FMML. It is also aimed at research-funding bodies in order to identify needs for further development, harmonisation and testing of methodologies.

([3]) https://ec.europa.eu/environment/strategy/zero-pollution-action-plan_en

2. Floating Marine Macro Litter (FMML)

FMML means any marine litter item larger than 2.5 cm in length that floats on the surface or in the surface layer of the water column (Galgani et al., 2013). FMML has been reported to cause severe injuries to marine organisms through entanglement, physical damage and/or accidental ingestion (e.g. Boerger et al., 2010; van Franeker et al., 2011; Domènech et al., 2019), and it is considered to be the major litter transportation pathway through marine ecosystems, as it contributes to both seafloor and beach litter; and, subject to weathering and degradation, it is the main source of secondary microlitter. The increased presence of FMML has been reported to facilitate the dispersal of marine organisms (Aliani and Molcard, 2003), including potential invasive species. Harmful implications of FMML can potentially also include the transport of persistent organic pollutants (POPs; Teuten et al., 2009) and the release of toxic compounds used in the manufacture of plastic materials (plasticizers, flame retardants, antimicrobials; e.g. Welshons et al., 2006; Hahladakis et al., 2018).

Owing to this ever-increasing pressure, regional, national and international policy frameworks have within the past decade been demanding an increase in monitoring efforts and the development of efficient and harmonised methods to systematically collect data on FMML abundance, distribution and trends. Coordinated monitoring actions would contribute to the identification of sources, areas of accumulation and temporal trends, which is necessary information for a better assessment of the magnitude of this threat and to plan and prioritise effective measures. Such data are also essential to enable modelling efforts for understanding pathways and predicting accumulation areas. Furthermore, information on FMML is needed to enable the evaluation of the effectiveness of implemented measures on waste reduction policies, for which macro litter is a pertinent and timely indicator.

2.1. Sources and pathways

Litter occurs in all marine and coastal environment compartments, all of which have their particular properties in terms of litter inputs, transportation, impacts and sinks. Floating litter plays a particular role in the environment, as it is the mobile fraction of marine macro litter and directly contributes to the pollution exposure of pelagic wildlife.

Macro litter in marine ecosystems can come from land-based sources from human activities, such as domestic (e.g. healthcare products, single-use plastic for food and beverage), agricultural (e.g. seed coatings, mulch, greenhouse covers) or industrial (e.g. paints, insulants) inputs. Other major sources of macro litter are direct discharges into or litter abandoned in marine ecosystems from maritime transport, tourism, aquaculture and the fishing industry, among other human activities (GESAMP, 2020; González-Fernández and Hanke, 2017; Lebreton et al., 2017).

Rivers are considered one of the main pathways for the transport of litter from land-based sources; moreover, occasional events such as storms, hurricanes or flooding may also contribute to the transport of macro litter (Crosti et al., 2018; Lebreton et al., 2017; Nizzetto et al., 2016a, b). Sewage systems can also facilitate the direct entry of various types of litter into marine ecosystems. However, the determination and prediction of fluxes and densities of litter released through these or other pathways are still challenging.

Furthermore, once floating litter enters marine ecosystems, it is subject to environmental exposure to currents, wind, waves and ultraviolet radiation, which contribute to weathering it and fragmenting it into smaller sizes (van Sebille et al., 2020), but also to other processes such as beaching, sedimentation and biological factors, which would play a secondary role in the transport of macro litter, limited to the size ranges that organisms can ingest, or be attached to.

2.2. Properties

2.2.1. Size of FMML items

Floating litter items persist in the marine environment in a wide range of sizes. The probability of detecting an item during monitoring decreases with its size and varies with the observation conditions, such as the observer's distance. As several platforms with varying characteristics can be used for monitoring, lower and upper size ranges of FMML should be set for each platform and technique used, provided the same classes are used for classification and the lower detection limit is specified to allow comparability of results. Comparability of results across different platforms and methodologies also requires compatible size ranges.

To account for the impossibility of measuring objects' sizes during observation, size range estimates, using the maximum length of the objects, are used as a proxy for litter size. In general, the size of a floating object can be roughly estimated by comparing it with the size of known objects (e.g. water bottles, lighters). For MSFD monitoring, the TG ML has recommended reporting the size of macro litter according to agreed size ranges in order to allow quantitative reporting and link to the assessments (Galgani et al., 2013):

- 2.5 – < 5 cm
- 5 – < 10 cm
- 10 – < 20 cm
- 20 – < 30 cm
- 30 – < 50 cm
- ≥ 50 cm.

These size ranges are also recommended for use in litter quantification in the different environmental matrices (Fleet at al., 2021).

Floating litter made by objects larger 50 cm typically cannot be monitored in a representative way from ships because they are scant and rarely spotted in traditional transect-based surveys. However, they are gaining increasing attention and thus require dedicated monitoring approaches. Satellite imagery, in theory, could provide a means to monitor large items or relatively large floating litter aggregations (e.g. Arias et al., 2021; Biermann et al., 2020), such as litter windrows. Although several promising proofs of concept have been published in the last few years, no practical application of such large-scale monitoring is in place yet.

2.2.2. FMML litter type categories

The quality of data collected in FMML monitoring relies on the unambiguous identification of litter type categories through commonly agreed-upon lists. Following a collaboration between experts from the TG ML, RSCs and researchers, a Joint List of Litter Categories (Fleet et al., 2021) has been developed and adopted by EU MS for marine litter monitoring under the MSFD. The list provides a hierarchical approach, which is backwards compatible with the lists that were in use earlier (e.g. OSPAR, UNEP MAP, the Baltic Marine litter project - MARLIN Baltic Sea). The Joint List enables the monitoring of litter category types linked to initiatives and policy measures, such as the Directive on the Reduction of the Impact of certain Plastic Products on the Environment (Directive (EU) 2019/904), to evaluate their efficiency.

The new list is a use-related list common to all marine compartments. It is organised in six levels, with a classification in increasing detail that goes from level 1 (classification by material) through levels 2 (classification by use), 3 (classification by general type), 4 (classification by type) and 5 (classification by specific type) to level 6 (classification by size class), with the highest level of detail including 220 specific categories.

To guarantee that the observers (including if they are volunteers) consistently classify items in accordance with the list, a field manual (Fleet et al., 2021) was prepared to provide explanations for using the list, with examples of each litter type and an online photographic guide with photos of the items organised by code (https://mcc.jrc.ec.europa.eu/main/photocatalogue.py?N=41&O=457&cat=all).

2.2.3. Subsurface floating litter

The surface layer of coastal and offshore waters has been identified as a FMML-monitoring matrix, with the depth of the layer depending on the environmental conditions. Besides the litter items' properties (size, colour), the visibility of litter is determined by parameters such as water transparency (algae, suspended sediment, turbidity), surface conditions (waves, foam) and light conditions (glint, sun elevation and direction). Under ideal conditions, objects can be seen down to a few metres, while in turbid waters even a few centimetres can prevent detection.

There have been no large-scale studies of deep suspended litter, although results from litter by-catch in longline fishery suggest the presence of macro litter in the water column, even if interception depth was unknown (Uhrin et al., 2020). While there is a need for research on quantities of mid-water floating litter and its pathways, this report considers the surface layer as the recommended practical compartment for FMML monitoring.

3. FMML monitoring in practice

Literature regarding the presence of floating litter in the sea has been produced for a few decades, but little attention was dedicated to monitoring techniques until the need to harmonise methodologies was unanimously stressed. A first compilation of existing survey methods to monitor the abundance of marine litter was published by Ryan et al. (2009), and periodical reviews have been done in this regard within MSFD, UN and regional reports.

Although the majority of scientific literature produced with results from FMML surveys still relies on visual observation methods, alternative methodologies, including aerial imagery, remote sensing and modelling approaches, have been developed within the past two decades and their implementation is gradually increasing.

The survey of scientific literature provided a selection of international scientific publications produced within the past two decades based on the application of different FMML-monitoring approaches, with a special, but not exclusive, focus on monitoring across the European Seas.

Further literature on FMML monitoring is listed within the following sections, specifically addressing methodologies based on image-based technologies and remote sensing techniques. However, a comprehensive review was recently published discussing how measurements of marine litter, remote sensing techniques and numerical simulations can elucidate the processes driving the transportation of floating marine litter in both the open ocean and the coastal zones, and their interactions across varying spatio-temporal scales (van Sebille et al., 2020).

3.1. Scope of FMML monitoring

Monitoring FMML can be generically intended to investigate the spatial or temporal changes in FMML density and composition that would answer specific questions related to local governance and large-scale legislative framework needs. This might include the identification of litter items in order to attribute them to sources and source activities. For this reason, methodologies can vary according to the specific purpose and scale of application of monitoring.

The MSFD, UNEP MAP and other RSCs provide the framework for the implementation of coordinated monitoring programmes intended to obtain the data needed to assess GES and related targets. Although guidelines and recommendations on FMML monitoring have been produced within both the EU and UN plans (e.g. Galgani et al., 2013; GESAMP, 2019), current protocols are mainly based on operationally defined parameters; in other words, results depend directly on the employed methodologies. However, using specific methodologies, research data acquisition does not always lead to comparable data. The requirements for the MSFD and the regional programmes should be aligned with the practical implementation of monitoring activities.

The harmonisation of methods must deal with the potential differences related to the various phases of the monitoring process, with the aim of obtaining comparable results. A commonly agreed-upon protocol is also needed to allow its large-scale implementation within the MSFD and beyond, eventually enabling comparable assessments.

This chapter provides an overview of the parameters that must be considered when planning a monitoring programme, and of the main characteristics of the different approaches that can be implemented, along with their advantages and disadvantages.

3.2. Sampling design

FMML density and distribution are dependent on multiple factors, including variability in inputs, currents, transportation and degradation processes. The amount of FMML is often higher in coastal areas, where its distribution depends on local inputs such as proximity to large cities or river mouths. On the open sea, in contrast, FMML patterns mostly depend on large-scale processes driven mainly by sea currents.

Thus, to design a monitoring programme that allows the detection of spatial and temporal variations, it is necessary to consider both its temporal and spatial scales of application, as well as the minimum sampling effort necessary to obtain a representative sample and the minimum number of replicates (i.e. the sampling frequency).

The strategy of FMML monitoring may require an initial exploratory phase, aimed at acquiring data that can then be used to develop a targeted approach. The effort of monitoring may also be shifted once gradients and patterns have been recognised. During the process, the selection of the scale and locations for monitoring longer time series is of particular importance.

3.2.1. Spatial and temporal scales

The selection of an appropriate monitoring scale depends on the question that needs to be answered, that is, the magnitude of variation to be detected: the extent of the investigated process determines the temporal/spatial scale of the monitoring plan. For this reason, all possible sources of variability should be listed and discussed previously (cities, proximity to coast, seasons, etc.), and they should be either excluded or compensated for by an appropriate sampling design.

To cope with spatial heterogeneity, sampling needs to be stratified according to the distribution of litter, and preliminary surveys should provide the basic information needed to plan the stratification of sampling. If these cannot be done, a basic stratification of the survey by coastal and open sea areas is recommended.

Given a known litter density distribution, the minimum area to be sampled that would provide a statistically representative estimation of FMML can also be estimated. If this information is not available, typical density values can be assumed for initial survey planning; the effort can be subsequently adjusted during the survey according to the situation encountered.

Regarding the frequency of sampling, as seasonal variations in oceanographic and anthropogenic factors may lead to temporal changes in the density and distribution of FMML, it is recommended to consider planning seasonal replicates.

3.3. Selection of monitoring platform and methodology

Various platforms and techniques can be used for FMML monitoring. This is the first aspect to consider within a given monitoring programme depending on its aim, as well as on practical limitations and resource availability.

According to the scientific literature, the most widely used technique for FMML monitoring is based on visual observations, which rely on competent and dedicated observers. While direct observations, especially if performed by adequately trained volunteers, need relatively few resources, this technique can be fraught with potential biases linked to the observation conditions and the type of platform. Small, medium-sized and large platforms have different ranges of speed and observation height, which consequently influence the ability of the observer to detect and identify floating items of different size classes or at different distances.

With the technological advances made in the last decades by remote sensing techniques, a wide range of potential applications of these methodologies have been proposed as valid options for detecting, quantifying, classifying and tracking floating items, as recently reviewed by Maximenko et al. (2019) and Martinez-Vicente et al. (2019). The automated photographic (or video) recording of FMML is made possible by recording systems specifically set to acquire images from any platform, starting from small ships or drones for small-scale monitoring, but also applicable to large vessels travelling along defined routes, such as the LITTERCAM system (Hanke and Piha, 2011), planes or satellite systems. However, while the visual observation of litter has reached a certain degree of maturity, image-based techniques are still in development and often in an experimental state. Automatic recording may in the future reduce the need for observers, as the item recognition is performed afterwards, and it may be further facilitated by automated algorithms and machine learning techniques (e.g. Garcia-Garin et al., 2021). The permanent record of images allows for subsequent analyses and provides for the exact identification of item location and size (Bryson and Williams, 2015); however, weather conditions may also affect the detectability of FMML through remote sensing.

3.4. Monitoring methods

3.4.1. Physical sampling of FMML

Physical sampling would be required to perform a detailed characterisation of litter, such as the determination of its origin, indicated by labelling or other information, and the analysis of polymer composition. The lack of litter collection hinders the identification of items, which can only occur in the short span of observation or through the acquisition of images, and the direct determination of their weight. However, the physical collection of macro litter samples at sea in a representative way is currently a challenge. Even in high-density areas, sampling should cover extensive surfaces of water. This would require a sampling set-up involving huge surface tow nets and potentially the use of two vessels.

While microlitter is frequently sampled with surface tow nets (e.g. manta trawls), their width and height apertures are small (typically 0.5–1 m and ≤ 0.3 m, respectively) and they are deployed for a short time to avoid clogging. Given the small openings and resulting limited survey areas, nets for microlitter monitoring, typically with < 1 m openings, cannot be expected to provide representative results on macro litter abundance and distribution. Macro litter surface tow nets need to be designed in terms of mouth opening and mesh sizes, with large coverage area and sampling time to allow for representativeness of the study area. While such approaches have been discussed (e.g. Morales-Caselles et al., 2021), they have been employed on limited occasions (Lebreton et al., 2018; Compa et al., 2019). Table 1 includes an overview of scientific studies applying the physical sampling of litter.

Table 1. Scientific studies of physical sampling cited for macro litter and their characteristics

Litter size	Type of litter sampled	Monitoring methods	Device opening dimensions and mesh size	Units	References
Micro (< 5 mm) to macro	Plastics	Manta trawl	0.90 m × 0.15 m; 0.5 mm mesh size	Items km^{-2}	Lebreton et al. (2018)
		Neuston trawls ('Mega trawl')	6 m x 1.5 m; 1.5 cm^2 mesh size	kg km^{-2}	
Macro	Litter	2 nets fixed to the sea-cleaning boat	0.80 m × 0.60 m; n.a.	kg km^{-2}	Compa et al. (2019)

n.a.: not available

In some cases, physical sampling is associated with coastal clean-up operations carried out in some regions or marine protected areas (MPAs) using sea-cleaning boats (e.g. operations in the Cinque Terre MPA, Italy; Balearic Islands, Spain, Compa et al., 2019).

Despite the technical and logistical challenges of the physical collection of litter, such experiments could also provide ground-truthing of observation methods. The performance of simultaneous monitoring combining visual observations and surface tow nets could allow complementary information to be acquired and the observer bias to be estimated in the identification and count of certain litter categories that are often missed (e.g. transparent film, small items). Furthermore, the collection of FMML would enable databases to be built for litter mass estimation, and the mass of plastics in each environmental compartment to be calculated.

3.4.2. Visual observation of FMML

Different platforms can be used for visual FMML monitoring. They can be classified based mainly on their height and speed, which are the main factors potentially affecting the detectability of FMML and thus the results of monitoring. Depending on the scope and scale of the monitoring, several platforms can be employed, ranging from small boats to aircraft, although the comparability of the lower size limit of detectable litter and the representativeness of the observations of larger litter objects need to be considered.

Monitoring FMML and biota synoptically can, in addition, highlight areas where the distribution of marine litter and sensitive fauna, such as sea turtles (Arcangeli et al., 2019; Atzori et al., 2021) and cetaceans (Gregorietti et al., 2021; Campana et al., 2022), overlap and there is therefore a significant danger of ingestion.

Ship platforms for visual observation

Ships have been traditionally used for visual observations of floating macro litter items (Figure 1). Large ships, such as ferries, offer a wide visual angle and, given their high speed, can be used for monitoring open sea areas (e.g. Suaria et al., 2020). Medium-sized vessels such as research and fishing vessels, where the observer height is approximately 4–6 m above sea level, can be used to monitor open sea and coastal areas (e.g. Suaria and Aliani, 2014). Small vessels (both motor and sailing boats), where the observer height is approximately 1–2 m above sea level (e.g. Curmi and Axiak, 2021; Currie et al., 2017) are instead used for monitoring coastal areas. In this sense, the observer height is defined as the vertical distance from the eyeline of the observer to the water surface (obtained as the height of the deck from the sea surface plus the height up to the eyes of the observer). The increase in the observer height may decrease the detectability of small litter items, and the speed of the vessel also influences the detectability of floating items (Ryan, 2013; Thiel et al., 2011).

Figure 1. Visual observation of FMML from the deck of a large ship (left). Observation distances marked on the window of the vessel (right).

Source: Interreg Mediterranean – MEDSEALITTER project.

However, Arcangeli et al. (2020) reported that the detectability of items larger than 20 cm from large vessels (e.g. ferries) did not vary over a wide range of speeds (tested up to almost 28 knots), presumably thanks to the relatively low density of items detected in high sea areas and the observer height from these platforms, which allows a good view over the observation strip. On the other hand, the litter density observed from small and medium-sized vessels, which are often used in coastal waters, significantly decreased when the vessel speed increased from 3 to 8 knots.

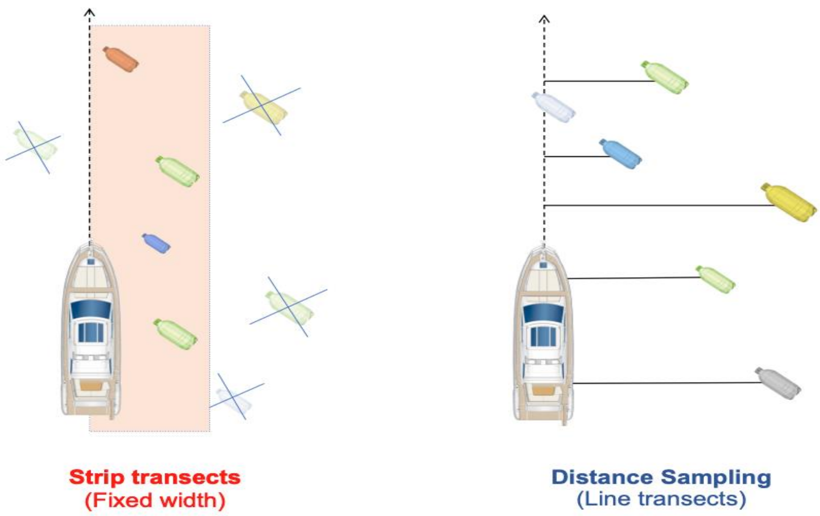
Interestingly, observations and counts performed between the hulls of catamarans or trimarans, even small ones, largely simplify the issue of the variable observation width during transects. According to tests performed on board research catamarans and those operated by NGOs (e.g. as part of the PlasticBusters project), the approach also makes it possible to observe FMML perpendicularly to the surface of the sea, and not laterally, avoiding parallax errors.

Even though observation parameters may vary substantially depending on the platform used, a range of monitoring conditions, such as the monitoring strip width and the categories used for litter classification, should be set to allow the collection of observations from different platforms in a consistent way.

— **Strip width and length for ship platforms**

Two main observation methods can be applied to FMML visual monitoring: the fixed-width strip transect method assumes that all items are detected within a predefined distance from the observer; the distance sampling method involves estimating the distance to each item to compensate for the decreasing detection probability with the increasing distance to the item (Figure 2).

Figure 2. Main visual observation survey methods for vessel-based FMML visual monitoring: fixed-width strip transects (left) and distance sampling (right).



Source: Global monitoring of FMML project – Institute of Marine Sciences of the Italian National Research Council – (CNR ISMAR); credit: Giuseppe Suaria.

The fixed-width transect method has been the most used in recent years (se also Annex I, Table S1), but the differences between platforms used and the size of the observed fixed-width strip may affect the detectability of floating items and thus lead to potential differences in density estimates. Arcangeli et al. (2020) recorded a higher proportion of items the narrower strip when assessing differences between subsectors corresponding to different distance ranges from the observer, and recommended a fixed-width strip of a maximum of 50 m from large, 5 m from medium-sized and 3 m from small vessels (which becomes 6 m if two observers participate, one at each side of the small vessel).

The distance sampling method has also been used as an alternative approach (e.g. Currie et al., 2017; Titmus and Hyrenbach, 2011; see also Annex I, Table S1). Various projects (e.g. Global monitoring of FMML – Institute of Marine Sciences of the Italian National Research Council (CNR ISMAR)) compared the two methods across a wide range of litter concentrations. Distance sampling was found to be responsible for a certain 'loss' of items, especially in high-density areas, where many small pieces were overlooked. At the same time, the diversity of litter in terms of sizes and typologies was better described using distance sampling techniques.

On the other hand, strip transect methods are easy to use, less time-consuming (in terms of data analysis) and likely to provide more realistic concentration estimates, especially for the smallest litter size fractions. Therefore, the method to be chosen should depend on the local abundance of floating litter, as the performance of distance sampling techniques seems to decrease in high-concentration areas, while the strip transect method appears to be less effective in detecting floating items in low-concentration areas. However, these two methods should not be considered entirely equivalent when analysing the results obtained.

The length of a transect based on the fixed-width method is often directly or indirectly derived from the observation duration of the surveys. The Burnham equation could provide the length of a transect needed to attain a given precision (Burnham et al., 1980). Results from Arcangeli et al. (2020) show that, in offshore areas with large vessels, a minimum sample size between 500–800 linear km per season with a strip width of 50 m is suggested. With small and medium-sized vessels in coastal areas, a minimum sample size of 83 linear km with a strip width of 5 m is recommended.

Literature on ship-based visual surveys

A brief overview of the main literature concerning ship-based visual surveys is provided in the following list.

González-Fernández et al. (2022): Floating marine macro litter on the Black Sea, compilation of results from visual surveys on the Black Sea.

Curmi and Axiak (2021): The article reported a seasonal study on floating litter in Malta's coastal waters using small vessels. The TG ML protocol was used for litter categories and size ranges. Observation height was 1.5 m and strip width was 6 m at the bow. It maintained a constant speed along each line transect, varying between 10 m s^{-1} and 50 m s^{-1} for different transects.

Pogojeva et al. (2021): Visual ship-based surveys, employing the JRC Floating Litter Monitoring App, have been used to study the distribution of FMML in relation to oceanographic characteristics in the Russian Arctic seas. The surveys provided the first data in an Arctic area that is difficult to access.

Garcia-Garin et al. (2020): This study compared results from visual and drone surveys to validate the drone methodology for FMML monitoring along the Catalan coast (Spain). A sailing catamaran was used for visual observations at a constant speed of 5 knots and a 10-m fixed strip. Two different commercial drones were used for drone surveys, equipped with a 12-megapixel camera. Flight height was set between 45 and 65 m to guarantee a ground sampling distance of 2 cm per pixel.

González-Fernández et al. (2020): Anthropogenic litter input through rivers to the Black Sea was estimated through visual counting from vantage points (e.g. bridges) by trained observers to register the number and identity of floating macro-litter items (> 2.5 cm) passing by in the river water surface layer. The observations were performed using the JRC Floating Litter Monitoring App from 2016 to 2020 as part of the Improving Environmental Monitoring in the Black Sea (EMBLAS) project.

Pogojeva et al. (2020a): Visual observations were performed from a research vessel in 2019 using the JRC Floating Litter Monitoring App, covering the potential accumulation areas of FMML in the Barents Sea.

Pogojeva et al. (2020b): Visual observations from ships of opportunity were performed during 2016–2019 using the JRC Floating Litter Monitoring App as part of the EMBLAS project. This was the first multinational integrated assessment of FMML pollution of the Black Sea and it used a harmonised MSFD approach for the first time.

Suaria et al. (2020): Ship-based visual survey of floating macro litter in the Southern Ocean around the Antarctic continent. Teams of one to three observers equipped with binoculars recorded floating debris while the ship was steaming at 10–14 knots. Observations were made from the bow of the ship (elevation 8–9 m above the waterline) when weather permitted, or from the ship's bridge or flying bridge (20–22 m). Litter densities were estimated for items within 50 m of the ship's track, except south of 60 ° S, where no items were observed within 50 m of the ship. Density estimates assumed all items within 50 m of the ship were detected, whereas extrapolated densities used simple size-specific detection functions to estimate the proportion of items not detected at 10-m distance bands from the ship.

Campanale et al. (2019): A visual survey of floating natural and anthropogenic macro litter (> 2.5 cm) was performed in the central Mediterranean Sea during a campaign on board the ship *Amerigo Vespucci*. Observations were performed with the naked eye from the bow of the vessel (9 m above sea level) at a speed of 7.28 knots; every item was assigned to one of six size classes (2.5–5 cm, 5–10 cm, 10–20 cm, 20–30 cm, 30–50 cm, > 50 cm) and to either anthropogenic or natural marine litter. The survey effort was split into 30-min transects; only data taken in good visibility conditions (wind speed < 21 knots, wave height < 2 m) were retained and analysed.

Palatinus et al. (2019): Floating macro litter (> 2.5 cm) was surveyed in Croatian waters from a 15-m sailing boat sailing at 2–3 knots. Observations were made simultaneously with floating microlitter samplings (manta trawls) to evaluate the correlation between macro and microlitter. The cumulative height of the vessel and the observer was about 2.2 m and the density of litter items was estimated using a 7-metre strip transect method.

Rothäusler et al. (2019): Seasonal observations were done from a ferry between Finland and Sweden between spring 2012 and spring 2013. Observations were performed from one side of the ship, the port side close to the bow, and from the lowest outdoor deck, situated 11 m above the sea surface. Two or three dedicated observers recorded all floating marine debris items passing the ship during the cruises. Floating marine debris densities (items per square kilometre) were calculated as the number of items recorded along the 5 km transects within the transect width of 50 m. All observations were made under conditions of good visibility and calm sea state, in a range of speed between 8 knots in the archipelagos and 20 knots in the more open sea regions.

Arcangeli et al. (2018): A 3-year survey was performed from ferries along five fixed transborder transects in the Mediterranean basin. Observations were done from the bridge (17–25 m) close to the bow, at < 3 on the Beaufort scale, at a speed of 19–25 knots. Only items larger than 20 cm were recorded, within a fixed strip of 25–100 m.

Campana et al. (2018): Visual FMML monitoring was performed from ferries across the western Mediterranean Sea from 2013 to 2016 by dedicated observers at < 3 on the Beaufort scale, using the fixed-width strip method. Items were classified by material, and information on source, industry, size classes and colour was included.

Constantino et al. (2018): FMML surveys were conducted on board the R/V *Ramform Hyperion* during a 3D seismic programme. Surveys were carried out daily, across transects, in summer 2017, covering morning and afternoon periods, by the same observer. Each monitoring episode lasted on average 15 min. Items were counted and classified according to the categories defined by the MSFD. Macro litter density (D, items per square kilometre) was estimated as $D = N/(W \times L)$, where N is the number of items of plastic litter observed, W is the maximum distance perpendicular to the transect (0.05 km) and L is the total length of the transect (km).

Ourmieres et al. (2018): FMML and stranded debris were sampled in 2006–2008 along the French Riviera with specific protocols to describe the litter's spatial distribution in semi-quantitative terms. FMML data were collected for the MSFD initial assessment, including 801 counts performed along 67 transects. Items larger than 5 cm were counted using the strip transect method (50 m strips at both sides), with at < 3 on the Beaufort scale, speed 6 knots.

Zeri et al. (2018): Abundances of macro- and microplastics were determined in the Adriatic Sea following the TG ML protocol. Studied areas included populated gulfs, river outlets and offshore waters in five Adriatic countries. The use of medium-sized ships (observation height < 3.2 m) and a 10-m strip made it possible to detect small plastics (2.5–5 cm). Observations were always conducted from one side of the ship, by two observers without binoculars, who rotated to avoid fatigue, and under low wind speed conditions (< 4 knots).

Campanale et al. (2017): Visual FMML observations were collected during a dual-use campaign on board the Italian Navy ship *Amerigo Vespucci* circumnavigating Italy during May–June 2016. The distribution, abundance and composition of floating marine debris were assessed using a 10-m fixed-width strip transect method.

Carlson et al. (2017): Observations of FMML in the Adriatic Sea were used to define initial conditions (number of particles, location and time) in a Lagrangian particle-tracking model. Time, date, position, abundance and typology of floating macro litter were recorded during three visual ship surveys performed in the Adriatic Sea in May 2013 and March, November and December 2015. Items larger than 2.5 cm were recorded along short transects of ~ 30 min (mean length 7.7 ± 2.6 km) during daytime navigation and under good visibility conditions (i.e. wind speed < 20 knots). FMML abundances were expressed as items per square kilometre.

Currie et al. (2017): Line transect surveys were conducted across lines perpendicular to the depth contours in the region of Maui, on board a 26-foot research vessel sailing at a speed of 15 knots, at ≤ 3 on the Beaufort scale and Douglas sea state ≤ 3. Two observers, one on the port and one on the starboard side, scanned the water from the bow to 90º on either side. All sightings were logged by a data recorder. Litter sighted was collected if possible, and global positioning system (GPS) location and type of material were recorded. If the item was not collected, it was photographed and recorded. Items were classified into plastic, metal, glass, rubber, clothing/fabric and processed lumber. Plastics were further classified into subcategories. To determine sources, items were divided into three categories: general, land and ocean. To help quantify the risk to cetaceans, debris was divided into two categories: entanglement risk (net, rope and/or line) and ingestion risk, defined as the remaining debris void of any trailing/entangling gear.

Di-Méglio and Campana (2017): Visual FMML surveys were conducted from sailing vessels along the French coast between 2006 and 2015, simultaneously with surveys of cetaceans. Sampling was carried out in standard conditions at a speed of 6 (± 0.5) knots and ≤ 2 on the Beaufort scale with three observers standing at the bow of the boat, 3 m above sea level, continuously scanning the 180° ahead, and reporting litter sightings to a fourth person, who recorded the time, type, size and number of objects seen. Information on sea state, light conditions and wind force was noted, and a GPS continuously recorded the position. Only anthropogenic marine litter was recorded, classified into plastics (bags, bottles, cans, other), extruded polystyrene and other items.

Fossi et al. (2017): This article investigated the possible overlap between floating microplastic, mesoplastic and macro litter accumulation areas and the fin whale feeding grounds in in a pelagic Specially Protected Area of Mediterranean Importance (SPAMI): the Pelagos Sanctuary. Models of ocean circulation and fin whale potential habitat were merged to compare marine litter accumulation with the presence of whales. In addition, field data on microplastics, mesoplastics and macro litter abundance and cetacean presence were simultaneously collected. Visual FMML surveys were conducted from a medium-sized vessel (R/V *Astrea*) at a speed of 3–5 knots, at ≤ 3 on the Beaufort scale and Douglas sea state ≤ 3.

Bergmann et al. (2016): Ship- and helicopter-based observer surveys of FMML were done in the Barents Sea and Fram Strait (Arctic). Ship surveys were based on 30-min transect counts of items larger than 20 cm from the bridge 18 m above sea level at a speed of 4.7–12.7 knots. Observations from helicopters were done at a mean altitude of 53–249 m and a mean speed of 109–182 km h^{-1}.

Sá et al. (2016): Visual FMML surveys were performed with vessels travelling at 10 knots along predefined linear transects in 2011 in offshore continental Portuguese waters. Observer height was 6 m above sea level. Four size classes were used (< 2.5 cm, ≤ 10 cm, ≤ 100 cm, > 100 cm), and detection functions were obtained for each class, assuming that items on the line are always detected, that they are detected at their initial location, and that distances and angles are measured accurately with personalised measuring sticks.

Miranda-Urbina et al. (2015): Seabirds and floating litter were surveyed during 16 days in the central South Pacific Ocean, aboard a Chilean navy patrol vessel. Data were collected in daylight from the vessel bridge, 12 m above the sea surface, with a vessel speed of 20 km h^{-1}. All FMML sightings were georeferenced using a handheld GPS; type, number and distance of each item were recorded. Sizes of items and perpendicular distance to the vessel were estimated in accordance with Thiel et al. (2013). To estimate the total density of marine litter, the strip transect method was used, whereby density was calculated as $D = N / ((W / 1\,000) * L)$.

Suaria et al. (2015): A ship-based visual survey of FMML was performed in the north-west Black Sea. With a vessel speed of 7 knots, the observer surveyed from the bow (~ 4 m above sea level) and recorded the size, type, position and perpendicular distance of all debris larger than 2 cm.

Eriksen et al. (2014): Twenty-four expeditions (2007–2013) were performed conducting surface net tows (N = 680) and visual survey transects of items larger than 20 cm. Items were classified into nine categories: four were fishing-related (buoy, line, net and other) and five were other plastics (bucket, bottle, foam, bag/film or mix).

Ryan (2014): Research cruises were performed in the South Atlantic 'garbage patch' in 2013, with observers positioned 12–15 m above sea level and 50 m from the ship's bow, along transects of 50 km, covering 2.5 km^2 each. Distance from the ship was assigned to one of seven categories: 0–10 m, 11–20 m, 21–30 m, 31–40 m, 41–50 m, 51–100 m and > 100 m. Items were assigned to one of the size classes < 5 cm, 5–15 cm, 15–30 cm and 30–60 cm, > 60 cm. Categories included packaging, fishery-related plastic, other plastic user items (e.g. buckets, shoes, gloves) and other plastic pieces (e.g. fragments). Non-plastic categories included glass jars/bottles, light bulbs, tins/aerosols, cardboard/paper and wood.

Suaria and Aliani (2014): Visual FMML surveys were performed from the R/V *Urania* in 2013 in the Mediterranean Sea, at a speed of 10 knots, 5 m above sea level, at < 5 on the Beaufort scale. FMML was classified into the size classes < 10 cm, 10–50 cm, 50–100 cm and > 100 cm, and into anthropogenic marine litter (extruded polystyrene, plastic, others) and natural marine debris. Simplified distance sampling was used: perpendicular distance of objects estimated knowing that the distance from an item when abeam equals the distance travelled by the ship between two consecutive bearings of the same object at 45° and 90° to the bow. Items were assigned to eight distance categories (0–10 m, 10–20 m, 20–30 m, 30–40 m, 40–50 m, 50–60 m, 60–100 m, > 100 m) and the software DISTANCE was used for analyses.

Goldstein et al. (2013): During 2009–2010, concurrent plankton net tows and visual observations by an observer at 10 m height were performed in the north-east Pacific Ocean. Standardised line distance methods were used: litter distance was determined using a handheld range finder and assigned to predetermined distance bins based on perpendicular distance from the ship (0–10 m, 10–50 m, 50–100 m, 100–200 m, 200–300 m, 300–600 m and > 600 m). Size classes were used: small (2–10 cm), medium (10–30 cm) and large (> 30 cm). Visually detected macroplastic broadly correlated with net-tow-caught microplastic, but they did not necessarily correlate on smaller (10 km) scales.

Luperini et al. (2013): Visual FMML surveys were performed along the Livorno–Bastia ferry route in the Pelagos Sanctuary in the Tuscan Archipelago by a dedicated observer located on a ship deck, monitoring a 100-m-wide strip, in which all items larger than 30 cm were detected (sea state < 2). Samplings were categorised according to the OSPAR guidelines.

Ryan (2013): A size- and distance-based technique was used to assess the distribution, abundance and composition of floating marine debris in the Indian Ocean. Floating marine debris was counted during a research cruise aboard the R/V *Marion Dufresne* in June 2012.

Thiel et al. (2013): Seasonal sampling was conducted during 2002–2005 to determine the composition of FMML in the coastal system of Coquimbo (Chile). A ship transect method was used, with a maximum distance perpendicular to the transect of 10 m to each side of the vessel. Density was calculated as $D = N / (2 \times (W / 1\,000) \times L)$.

Thiel et al. (2011): FMML ship-based visual surveys were performed in the German Bight in 2006–2008. Observers were positioned ~ 11 m above sea level and ~ 20 m behind the bow. Vessel speed ranged from 5 to 12 knots. The strip (ranging 20–70 m) transect method was used, and density was calculated as $D = N/(2 \times (W/1\,000) \times L)$.

Titmus and Hyrenbach (2011): Visual surveys were performed along a 4 400 km cruise track using line and strip transect methods to monitor FMML and marine birds in the north-east Pacific Ocean. Observers were 10 m above sea level, and recorded the perpendicular distance between items and the ship's track in seven distance bins using a hand-held range finder: 0–10 m, 10–50 m, 50–100 m, 100–200 m, 200–300 m, 300–600 m and > 600 m. Items' colour, description and size (classes: small (2–10 cm), medium (10–30 cm) and large (> 30 cm)) were recorded.

Topcu et al. (2010): FMML sightings were recorded from a cruise in the Aegean Sea during August 2008 by an observer with a handheld GPS tracker and binoculars. The strip transect method, with a fixed strip width of 60 m, was used to determine FMML abundance.

Hinojosa and Thiel (2009): FMML ship surveys were performed in fjords, gulfs and channels of southern Chile during 2002–2005 from the bridge of ships travelling at 10 knots, 4 m above sea level. A fixed strip of 20 m was used, according to the strip transect method, and densities were calculated as $D = N / ((W / 1\,000) \times L)$, where N = number of items observed, W = strip width and L = transect length. Seven FMML categories were distinguished: styrofoam, plastic fragments, plastic bags, lines, food sacks, wooden tables and others. The same vessel and method were also used by Hinojosa et al. (2011), who extended the survey to central and southern fjords of Chile.

Pyle et al. (2008): FMML visual surveys were performed during at-sea observation programmes in west coast national marine sanctuaries (USA) using vessels of various sizes, at a speed of 7 knots. Strip widths measured 50–100 m; litter was classified in 11 categories, derived by simplifying the codes used for beach surveys. Size categories used were small (< 2.5 cm), medium (≥ 2.5 and ≤ 10 cm), large (> 10 and ≤ 1 m) and extra large (> 1 m).

Aliani et al. (2003): Visual sightings of FMML were performed in the Ligurian Sea, north-west Mediterranean, during the summers of 1997 and 2000, from large research vessels sailing along transects (50-m strip) and at fixed stations (200-m radius). Densities found in 1997 and 2000 ranged from 15 to 25 and from 1.5 to 3 objects km^{-2}, respectively.

Thiel et al. (2003): Visual FMML surveys were performed in the coastal waters of the south-east Pacific (Chile), on fishing boats and research vessels, with observation height of 1 m, speed of 4–10 knots and the strip transect method using a strip width of 10 m on either side of the vessels.

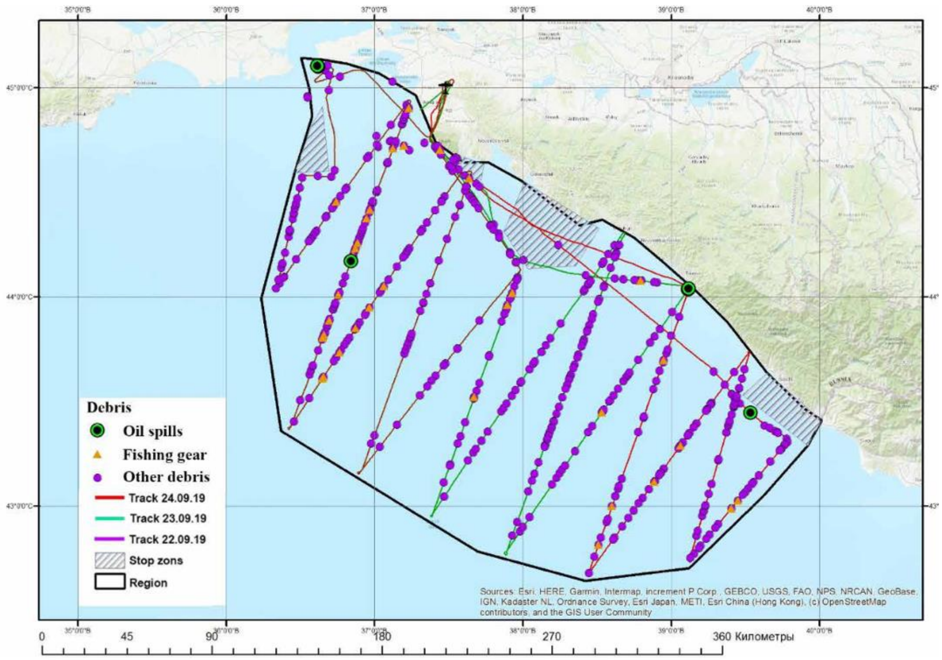
Visual observations from aeroplanes

Aircraft surveys have been used to locate floating litter aggregations and to detect spatial variations in the amounts of litter (e.g. Pichel et al., 2007; Unger et al., 2014) (Figure 3). The aircraft's high speed and flying altitude enable the monitoring of wide areas, but from these platforms a human observer may only detect items larger than 30 cm. Therefore, they are recommended for large-scale monitoring programmes (Figure 4).

Figure 3. Aircraft for monitoring FMML (left). Observer at one side of the plane measuring the observation angle with a clinometer (right).

Source: Interreg Mediterranean – MEDSEALITTER project.

Figure 4. Example of tracks and visual observations recorded from aircraft La-8 realised in partnership ACCOBAMS, CeNoBS, IEE RAS and International Ecological Fund 'Clean Seas' – The Aerial survey of cetaceans of the north-eastern Black Sea September 2019.



The selection of the observation method used in aerial surveys follows the same fundamentals as those used from vessels (i.e. the height of the observation, weather and light conditions, etc.). The observation height is commonly set at around 180 m (e.g. ACCOBAMS, 2021a; Lambert et al., 2020; Darmon et al., 2017) and the speed at approximately 90–100 knots (e.g. ACCOBAMS, 2021a; Darmon et al., 2017). Fixed-width transects are the predominant method of observation from aeroplanes, with transect widths between 200 and 300 m, but distance sampling methods have been also used in large-scale campaigns (see Annex I, Table S1).

A number of the large-scale surveys that were performed on marine mammals also included the recording of floating litter items in the documentation. Such surveys have been done over the Mediterranean Sea (Lambert et al., 2020) and the Black Sea (BSC, 2009; see also Figure 4).

However, the implementation of remote sensing techniques through the application of high-resolution sensors can substantially improve the performance of these platforms. Drones, or similar remote-controlled devices, are also used as platforms for remote sensing techniques (see Section 3.4.3). Depending on their endurance and characteristics, they can be used to monitor FMML at different spatial scales, allowing surveys to reach remote areas and be replicated over time with relatively reduced costs. However, the operating range of the most commonly used drones does not currently allow surveying in offshore locations and remote oceanic areas.

Literature on visual observation from aeroplanes

A brief overview of the main literature concerning visual surveys from aeroplanes is provided in the following list.

ACCOBAMS (2021a): Aerial surveys to support MSFD implementation in the Black Sea through establishing a regional monitoring system of cetaceans were conducted during daytime with good weather conditions (< 4 on the Beaufort scale) at an altitude of 183 m and a speed of 100 knots. Data on marine litter were also collected in collaboration with other projects and institutions following the line transect distance sampling methodology.

ACCOBAMS (2021b): Large-scale aerial surveys were conducted during the summers of 2018 and 2019 in the Mediterranean Sea, complemented by ship-based visual and acoustic distance sampling surveys (Agreement on the Conservation of Cetaceans of the Black Sea, Mediterranean Sea and Contiguous Atlantic Area (ACCOBAMS) Survey Initiative, ASI). Floating marine litter items larger than 30 cm (mega litter) were recorded at a mean altitude of 183 m and 100 knots.

Lambert et al. (2020): Two large-scale surveys were conducted during 2012 and 2018 to provide the first large-scale estimation of floating mega-litter in the Mediterranean Sea. All litter larger than 30 cm in size present in a 200-m strip on either side of the aircraft was recorded at 180 m altitude and 90 knots.

Garcia-Garin et al. (2019): Concurrent observer-based and photographic-based monitoring of FMML and marine macrofauna were performed from aircraft flying at 180 m altitude and 90 knots over the coast of Catalonia (Spain).

Lebreton et al. (2018): Surveys of litter items > 50 cm have been made from a C-130 aeroplane in the Eastern Pacific Ocean.

Bergmann et al. (2016): Ship- and helicopter-based observer surveys of FMML were done in the Barents Sea and Fram Strait (Arctic). Ship surveys were based on 30-min transect counts of items larger than 20 cm from the bridge 18 m above sea level at a speed of 4.7–12.7 knots. Observations from helicopters were made at a mean altitude of 53–249 m and mean speed of 109–182 km h^{-1}.

Darmon et al. (2017): Aerial surveys were performed in the English Channel, Atlantic and Mediterranean regions in winter and summer 2011–2012, to assess exposure areas and magnitude of risk for marine turtles in terms of spatial overlap, encounter probability and density of surrounding debris at various spatial scales. Observations were performed from a plane equipped with two side ‘bubble’ windows flying at 183 m above the sea surface at a constant speed of 90 knots, along linear transects. Two observers noted the location and number of sea turtles and litter items. Data were recorded by a third person. Transects were homogeneously distributed in zigzag over four types strata: the coastline strata; the neritic strata, corresponding to the continental shelf; the continental slope strata; and the oceanic strata beyond the 2 km isobath. Data on marine debris were collected following a strip transect methodology, recording all items larger than 30 cm sighted in a 200-m-wide strip. FMML was differentiated into macro litter, such as plastics, wooden pallets and other types, and fishing debris.

Mace (2012): The Ghost Net Project developed and tested procedures for using models, satellite observations and aircraft to observe debris. Extending procedures to airborne radar as a final search stage, followed by visual detection from small unmanned aerial systems, low-altitude aircraft or ship, is the most likely refinement for this approach to be successful.

Pichel et al. (2012): The goal of the Ghost Net project is to detect derelict nets at sea through the use of weather and ocean models, drifting buoys and satellite imagery to locate convergent areas where nets are likely to collect, followed by airborne surveys with trained observers and remote sensing instruments to spot individual derelict nets. Once located, potential areas of accumulation were observed using satellite remote sensing imagery and measurements to assess oceanic features. Crewed instrumented aircraft were then flown over areas of convergence to document litter items and their general distribution in the targeted areas.

Pichel et al. (2007): Ocean circulation models, satellite remote sensing data and aircraft observations were used to detect derelict nets and other debris in the open ocean within the North Pacific Subtropical Convergence Zone.

Lecke-Mitchell and Mullin (1997): Data on FMML were collected during two types of aerial surveys of cetaceans in the US Gulf of Mexico. Line transect methods were implemented, and the program DISTANCE was used to determine density estimates (items per square kilometre).

Observation parameters influencing detectability on visual observations

Different visual observation methodologies can be used to monitor FMML, which can be applied from diverse platform types (see Annex I, Table S1). However, to guarantee that the basic data needed for a consistent and harmonised assessment of FMML (namely geographical position and time, number, litter type category and size of items) are collected, a series of parameters should be considered and some standards must be respected.

The parameters that can influence the detectability of FMML can be classified into operational, which are mainly related to the technique and platform used for monitoring; environmental, which depend on weather and visibility conditions; and those related to the properties of litter, such as its size and composition.

— **Weather and visibility conditions**

Various aspects related to environmental conditions could affect the detectability of FMML, including the effects of wind, sun reflection and general weather conditions (fog, rain, etc.).

In published scientific surveys, observations are generally performed in relatively good sea and weather conditions (i.e. wind < 21 knots, wave heights < 0.6 m), and data are not collected in poor visibility conditions (i.e. wind > 21 knots, wave height > 2 m), when the detection probability within the transect width is severely compromised. Results of monitoring conducted from small and medium-sized vessels showed a decreasing trend in the densities of marine litter recorded as the sea state on the Beaufort scale increased (Arcangeli et al., 2020), with values recorded at 3 on the Beaufort scale significantly lower than those recorded in lower sea state conditions, and values recorded at 2 on the Beaufort scale significantly lower than those recorded at 1.

— **Observer conditions**

The experience and conditions of the observers could influence the capability to detect and identify FMML, potentially leading to inconsistent results. There are some factors that should be taken into consideration.

- **Training**

Monitoring protocols should include minimum standards regarding the observers' qualification, expertise and training, which are fundamental for the quality assessment and quality control of data. Preliminary training of observers can substantially reduce the bias related to previous monitoring experience.

Results from a concurrent monitoring experiment performed by Arcangeli et al. (2020) showed that, from large vessels, non-expert observers detect on average 30 % fewer items than expert observers. This difference was larger in high-density areas and decreased in low-density areas (high sea compartment). Less experienced observed also tended to look farther from the vessel and focus only on larger items. Differences in detection rates related to the experience of the observers were also detected from small and medium-sized vessels, although they were less pronounced. Here, the detection ability of non-experienced observers was between 4 % and 11 % lower than that of experienced ones, and no relationship with FMML densities was observed.

- **Observer fatigue**

The maximum survey period during which observers can maintain focused attention is 60 min (Arcangeli et al., 2020), depending on the observation conditions. However, other studies reduced this time to 15–30 min to avoid considerable loss of information about smaller-scale heterogeneity and accumulation features and patterns (e.g. Campanale et al., 2019; González-Fernandez and Hanke, 2017).

- **Citizen science**

While voluntary non-scientific observers play an important role in beach litter monitoring, it has been emphasised that training and joint experiences and quality assurance / quality control (QA/QC) measures are crucial to provide sufficient data quality. Data quality must also be assured for FMML monitoring, which in principle could be performed by non-experts in 'citizen science' programmes. The availability of apps and a data collection protocol alone are not sufficient to ensure the production of useful and comparable data, as data used for compliance checking or to support management decisions should be acquired in accordance with minimum quality standards.

3.4.3. Image-based monitoring

FMML surveys can be done not only by trained observers, but also by using images obtained from different platforms, such as fixed structures, ships, drones or aeroplanes (Veenstra and Churnside, 2012). The use of camera-based observations has great potential for harmonising visual observations of FMML performed from different platforms. The permanent recording of images allows their subsequent analysis, and the information contained in the image metadata allows the exact determination of the geographical location of FMML observations and the precise measurement of the size of floating items. The introduction of high-resolution georeferenced images for wildlife-monitoring purposes has offered a high-quality tool for automated FMML monitoring. This approach is now implemented from various recording systems and platforms by several research projects and monitoring programmes worldwide.

Currently, most progress in the remote sensing of FMML has been made using sensors within the RGB visible range and in the short-wave infrared spectrum, mostly applied from unmanned aerial systems such as drones, or small aeroplanes. However, once again the selection of the best sensor and monitoring platform depends on the scope of monitoring (e.g. drone monitoring for coastal areas, and sensors mounted on large vessels or aircraft for large-scale monitoring), providing that appropriate sensors are selected according to the height of the monitoring platform to guarantee a minimum standard of image resolution.

In image-based monitoring, the analysis and object recognition tasks are performed afterwards: FMML can be identified using visual recognition, either by trained observers or by automated processing systems developed through machine learning techniques. While this new approach has seen rapid development for beach litter monitoring (e.g. Martin et al., 2018, 2021), algorithms for the automatic recognition of FMML are still improving, in response to the challenges posed by the marine surface, whose properties may vary substantially according to many environmental factors (sun glare, wind, hour of the day, etc.).

Spectral analyses are an alternative approach to detecting FMML in aerial imagery, mainly regarding plastics. Studies highlighting the effectiveness of remote sensing spectroscopic near-infrared (NIR) imaging were published over two decades ago (e.g. Huth-Fehre et al., 1995; Wienke et al., 1995; van den Broek et al., 1996), suggesting that identification systems based on NIR spectroscopy can sort plastics from other materials. More recent studies have reported promising findings suggesting that optical sensing in the visible to short-wave infrared spectrum can potentially detect and identify floating and slightly submerged plastic litter thanks to the unique spectral reflectance properties of plastics (e.g. Goddijn-Murphy et al., 2018; Garaba et al., 2018). Spectral remote sensing would further improve if associated with complementary measurements based on different sensing technologies; for example, manned and unmanned platforms equipped with light detection and ranging (LIDAR) and thermal infrared (TIR) imaging have potential applications in the remote sensing of floating plastic debris (Pichel et al., 2012; Veenstra and Churnside, 2012; Maximenko et al., 2019; Salgado-Hernanz et al., 2021). In comparison with RGB sensors, the resolution of such sensors will be a constraining factor in their applicability.

Ship-based imagery

Obtaining images at high resolution is crucial in order to ascertain the identification of the objects as litter. High-resolution cameras mounted on the bows of ships have been used to monitor FMML across large temporal and spatial scales. Within the JRC Sealittercam project, started in 2010, a camera was mounted on the bow on cruise ships at a height of 16 m, recording rectangular images unattended, at a frequency of four images a second (Figure 5). The same approach was also tested from bridges for river monitoring. Further development stages, including a portable system, have been tested on different ships, for example in 2019 from the R/V *Mare Nigrum* in the Black Sea.

Figure 5. Images of FMML obtained through a camera with a telephoto lens from the bows of vessels during the JRC Sealittercam project.

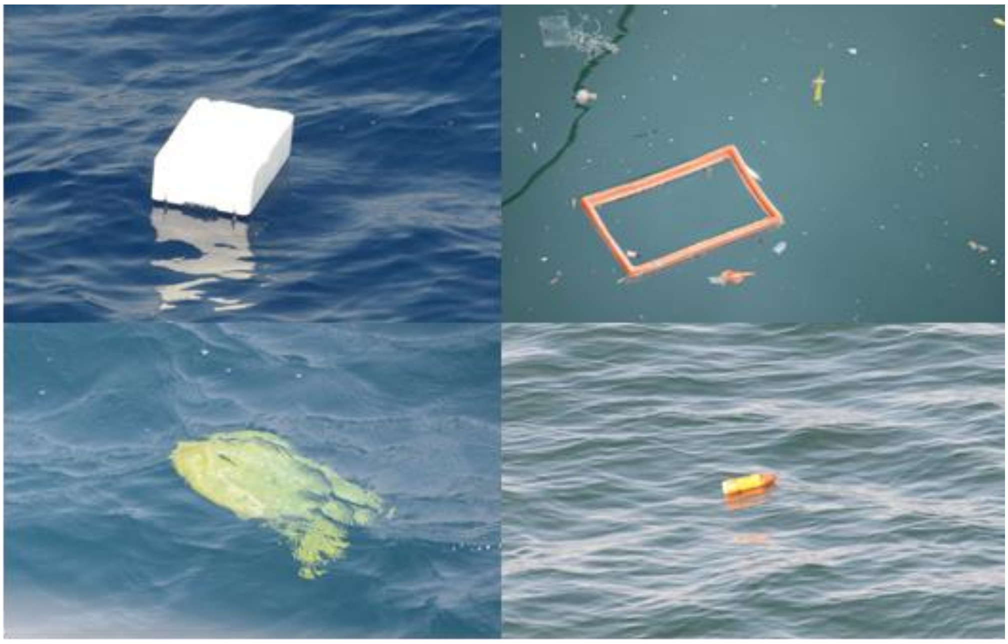


Image recognition software (e.g. eCognition), with a stepwise approach, have been tested to select candidate litter items and validate them. The recognition system could also be applied automatically to video recordings, but some problems related to the video resolution may occur and the final confirmation of litter items should be done by a human operator. The greatest challenge within this approach is identifying items and excluding false negatives; however, other approaches based on machine learning (e.g. Kylili et al., 2019) are evolving rapidly but they are not applicable yet for standardised and systematic FMML-monitoring programmes.

In a different application, an upward-looking camera was mounted below a Wave Glider and tested to monitor marine litter on the surface and in the mid water layers. Wave Gliders are a kind of surfboard propelled by wings underwater that, thanks to a solar panel system, can travel for weeks at sea (Galgani et al., 2019).

Literature on ship-based imagery

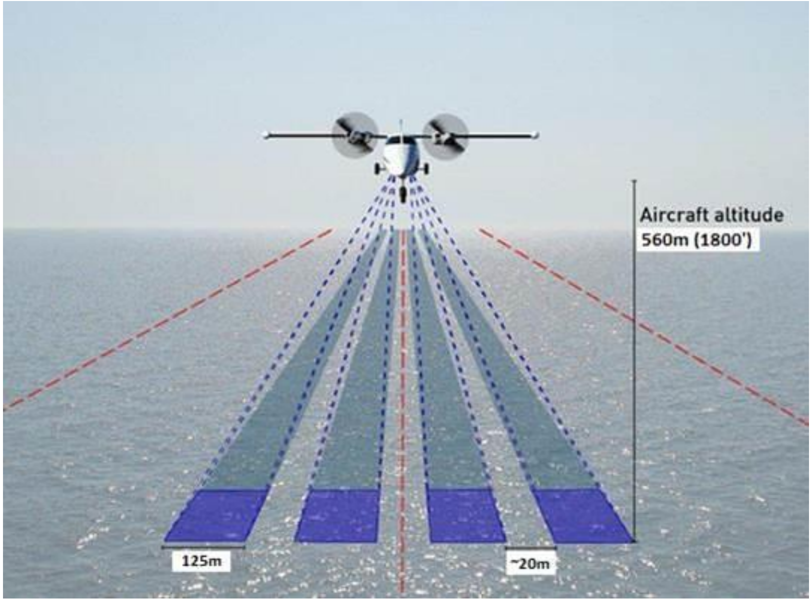
de Vries et al. (2021): quantification of macroplastics larger than 50 cm using of action cameras placed on vessels of opportunity. Macroplastic density is estimated through a twofold approach based on object detection and training object detection models. This study compared the distributions of macroplastics with concentrations of micro- and mesoplastics collected with manta trawl nets.

Kylili et al. (2019): The Convolutional Neural Network (CNN) approach is able to train itself on images of plastic objects larger than a few centimetres and automatically predict the class of new images of macro plastic objects floating at sea. With the aid of a camera mounted on board a marine vessel, the system would scan the sea surface, and detect and recognise litter. The system was trained on three categories of plastic marine litter (bottles, buckets and straws) and the classifier was able to recognise these types of floating objects at a success rate of ~ 86 %.

<u>Aerial aeroplane and drone imagery</u>

Similarly to ship-based imagery, high-resolution cameras have been installed on aircraft to monitor FMML. Typically, during these surveys, floating litter was recorded opportunistically during marine mammal monitoring (e.g. ASI, HiDef project). The use of high-resolution video cameras for marine litter detection has also been tested in the Baltic Sea, and along the Catalan coast of Spain (Garcia-Garin et al., 2019). This approach usually uses one or more digital video cameras mounted on an aircraft to detect litter (Figure 6). The image resolution to detect FMML is typically set at 2 cm per pixel (e.g. HiDef project).

Figure 6. Example of flight operation and transects scheme using four digital video cameras mounted on an aircraft.



Source: HiDef project —BioConsult SH/HiDef Aerial Surveying Ltd.

Drone systems provide an alternative to the use of aircraft for floating marine litter monitoring (Figure 7). Two experiments were performed to validate the results obtained from image-based monitoring of FMML. Concurrent image-based and visual-based observations were performed from a small aircraft, and results highlighted that the densities of FMML detected by aerial photography were higher than those detected through the observer-based method (Garcia-Garin et al., 2019). A similar experiment performed visual observations from a sailing catamaran and drone monitoring over the same area. Results showed that similar densities of FMML were detected through the two methods, suggesting that aerial photography can provide a valid contribution to the assessment of FMML density and distribution, and represent a valid alternative to traditional observer-based methods (Garcia-Garin et al., 2020).

Figure 7. Drone operation to detect FMML (left). Example of camera set-up (right).

Source: Interreg Mediterranean – MEDSEALITTER project; credit: Alex Aguilar.

Long-range drones are currently being developed (e.g. SolarXOne, DeltaQuad Pro), which could provide a significant advantage to the use of aircraft, particularly in relation to operational limits and deployment costs. Such drones are usually equipped with RGB, multispectral and thermal/infrared cameras and sensors, and may have flight times of more than 100 minutes.

Finally, results from image analyses (through linear discriminant methods) based on pixel characteristics performed on selected images indicated good discrimination between floating items and water. RGB and multispectral images gave similar results, while the resolution of thermic cameras was too low to detect FMML. The main limitation highlighted of image-based monitoring was found to be the sun glare effect, which should be limited or masked in the images before their processing. The identification of floating items can be automated through machine learning techniques based on XBOOST analysis or CNN (e.g. Garcia-Garin et al., 2021).

In the future, camera-based large-scale observations may become possible with the use of long-range autonomous drones covering up to 300 km in one survey (e.g. SolarXOne).

Literature on aerial aeroplane and drone imagery

Garcia-Garin et al. (2021): FMML in aerial images were detected using deep learning models based on an algorithm that uses CNNs capable of learning from unstructured data. This model was implemented in an application to detect and quantify marine litter in the images.

Garcia-Garin et al. (2020): Two combined methods to detect floating macro litter, visual observations and drone surveys, were compared. Both methods proved equally effective at detecting FMML. Two different commercial drones were used for drone surveys, equipped with a 12-megapixel camera. Flight height was set between 45 and 65 m to guarantee a ground sampling distance of 2 cm per pixel.

Garaba et al. (2018): RGB and hyperspectral short-wave infrared (SWIR) imagery were captured with equipment mounted on a C-130 aircraft surveying the great Pacific garbage patch at a height of 400 m and a speed of 140 knots. Position, size, colour and type (container, float, ghost net, rope and unknown) were recorded for every plastic piece identified in the RGB mosaics, and then the top 30 largest items within each plastic type category (0.6–6.8 m in length) were selected to investigate SWIR spectral information obtained with a SASI-600 imager (950–2 450 nm). Analyses revealed unique SWIR spectral features common to plastics, with some variability probably influenced by differences in the objects' optical properties, water submersion and the atmosphere. Simulations confirmed that the plastics' absorption features have potential applications in detecting and quantifying ocean plastics from spectral information obtained from airborne images.

Kako et al. (2012): Low-altitude remote sensing methods were used to monitor marine and beach litter with a remote-controlled digital camera suspended from a balloon filled with helium gas, suspended at 0–500 m above sea level. Photographs were taken at various angles, and images were processed to identify litter using colour differences between target objects and the background in the CIELUV colour space. With the balloon suspended at 150 m, a pixel represented an area of 100 cm^2.

Satellite-based imagery

The potential use of satellite images to monitor FMML is currently under investigation and development (e.g. Topouzelis et al., 2021; 2019). Some satellite missions have varying geospatial and spectral capabilities and can produce imagery with a very high resolution (e.g. Maxar Technologies WorldView missions can attain a pixel size of ~ 0.3 m × 0.3 m). Although this is an extremely high resolution considering the distance from which images are taken, the detection of individual litter items has not been achieved from the captured imagery, and to date it has been possible to observe only very large items. The remote detection of floating marine litter is currently limited by inherent restrictions of the specifications of the available sensors, and it has been shown that the methodological processing chain can significantly affect the future accuracy of plastic detection from space (Topouzelis et al., 2021). On the other hand, satellite-based imagery has also been used to detect marine litter on the shoreline above the tidal line (e.g. Martinez-Vicente et al., 2019; Acuña-Ruz et al., 2018), but also presents challenges in terms of a higher reflectivity on the full spectrum and potentially higher complexity in terms of discrimination of materials and objects.

The European Space Agency (ESA) recently launched a call for ideas on remote sensing of plastic marine litter within its Discovery element through the Open Space Innovation Platform (OSIP). Twenty-five projects of public and private institutions are assessing the feasibility of remote sensing, also by using existing satellites for litter monitoring in ESA projects ([4]) supported by robust ground truthings. Images are acquired from satellites, and spectra are classified following a series of steps that involve enhancing the image (contrast, etc.); separating the background; identifying regions of interest; and extracting features (e.g. Basu et al., 2021; Biermann et al., 2020; Themistocleous et al., 2020). Final image recognition is usually done through artificial intelligence programs and machine learning techniques are often applied for classifying the detected spectral/spatial anomaly.

The concept of 'litter window' has recently been defined as aggregations of floating litter, usually shaped as stripes up to a few kilometres long, generated from wind formed Langmuir cells. Other fronts formed after severe pollution events (e.g. coastal floods) and currents, also offer the opportunity to use space-borne sensors, aerial surveys or other platforms for the detection and monitoring of such accumulation features (Cózar et al., 2021). Moreover, it has recently been shown that windrows and sea-slicks can be used as a proxy to detect aggregations of marine litter from space, with some promising results (see, for example, Cózar et al., 2021; Arias et al., 2021).

In principle, current satellite imagery can detect floating litter which contain plastics (e.g. Biermann et al., 2020; Topouzelis et al., 2019, 2020), but this requires a very high plastic density in the observed cells for non-fit-for-purpose instruments (e.g. pixels of 10 m × 10 m resolution need to be filled with at least 30–50 % of plastic bottles or fishing gear in order to be detected with the Sentinel-2 satellite). Therefore, its application is limited at present and not fit yet for most routine uses, but the detection limit may be reduced under ideal conditions and if the right signal-to-noise ratio is achieved.

The discussion about the maturity and applicability of these technologies is still open; however, they are not ready yet for standardised and systematic FMML-monitoring programmes, although they may be useful for instance in the design of monitoring programmes and in combination with other sampling methods, especially if the in situ sampling targets remote-sensing relevant information and in supporting adaptive sampling in routine monitoring.

Literature on satellite-based imagery

Basu et al. (2021): Novel supervised and unsupervised clustering algorithms were developed to identify floating plastics using *in situ* validated Sentinel-2 images with different size of deployed plastic targets (10 m × 10 m, 5 m × 5 m and 1 m × 10 m). Three different sets of bands and indices were employed to develop the attributes for the classification process. The best-performing method, Support Vector Regression (SVR)-based supervised classification, had an accuracy in the range of 96.9–98.4 %.

Kremezi et al. (2021): This study explores for the first time the use of satellite hyperspectral PRISMA (Hyperspectral Precursor and Application Mission) images to detect floating marine plastic litter. Thirteen pansharpening methods and denoising preprocessing techniques were employed (e.g. Bayesian, deep learning, component substitution) along with three novel indices to detect floating plastic targets with a low number of false positives.

Biermann et al. (2020)*:* Satellite technology was employed to investigate the feasibility of monitoring marine surface floating plastic litter in coastal areas.

Kikaki et al. (2020): High-resolution multispectral satellital images from Landsat-8, Sentinel-2 and Planet satellite missions and *in situ* observations were employed to study the sources and trajectories of floating marine plastic litter in the Bay Islands of Honduras (Caribbean Sea). The determination and discrimination of floating litter was carried out manually by photo interpretation experts.

Topouzelis et al. (2020): A spectral signature for the polyethylene terephthalate(PET) targets was produced by modifying the US Geological Survey PET signature, using an inverse spectral unmixing calculation to perform matched filtering processing on the Sentinel-2 images. The results provide evidence that, under suitable conditions, pixels with a PET abundance fraction of at least as low as 25 % can be successfully detected.

Themistocleous et al. (2020): Sentinel-2 satellite images were combined with multispectral aerial images acquired from an unmanned aerial vehicle to determine if plastic litter on the sea surface can be detected using

([4]) Open Space Innovation Platform (OSIP) Campaign 'Remote Sensing of Plastics Marine Litter': https://www.esa.int/Enabling_Support/Preparing_for_the_Future/Discovery_and_Preparation/The_Discovery_Campaign_on_Remote_Sensing_of_Plastic_Marine_Litter an artificial plastic target (3 m × 10 m). Images were processed using two newly developed indices, the plastic index and the Reversed Normalised Difference Vegetation Index (RNDVI).

Topouzelis et al. (2019): This study explored the application of unmanned aerial systems and open-access satellite imagery in remote detection of floating plastics in natural seawater, through a dedicated aquatic environment experiment using a set of three artificial floating plastic targets placed in the coastal zone.

Acuña-Ruz et al. (2018): WorldView-3 images were combined with anthropogenic marine debris hyperspectral laboratory characterization to detect large and highly reflective plastic items on beaches. A spectral library for the implementation of a digital classification method applied to WorldView-3 satellite images was generated by collecting litter samples from the Chiloé Islands beaches (Chile) and assessing their spectral signature.

3.4.4. Monitoring litter ingested by biota as a proxy for FMML

Monitoring the ingestion of litter by biota has been proposed as a proxy for FMML. The digestive tract contents of marine organisms, mainly seabirds and fishes (e.g. Bond et al., 2014; van Franeker et al., 2011; van Franeker, 1985; Markic et al., 2020), but also other marine species (e.g. Matiddi et al., 2017; Bravo Rebolledo et al., 2013), have been monitored since around the 1980s.

The size range of litter items potentially ingested by marine organisms is limited by the particles that the organism can detect, select and ingest; however, the potential for the use of this information for the assessment of FMML is under discussion. OSPAR has implemented the system of the Ecological Quality Objectives (EcoQO's) for the North Sea considering the plastics ingested by fulmars as an ecological indicator (OSPAR, 2010). It is suggested that the range of size and the amounts of plastic particles ingested by fulmars reflect the amount of floating plastic particles within a marine subregion (e.g. the south-east North Sea), and are ecologically relevant data because they reflect the risk of ingestion of plastic particles by marine biota in general. However, the litter ingested by these seabirds is predominantly in the micro and meso size range (e.g. Bravo Rebolledo, 2011; van Franeker, 2019), and the grinding effect produced on the ingested particles by the muscular stomachs of these birds may hinder the determination of the original particle size in the environment (Bravo Rebolledo, 2011).

An overview of the assessment tools used for the monitoring of FMML ingestion by fulmars, including a threshold value, is given by van Franeker et al. (2021).

Literature on FMML marine litter ingested by biota

van Franeker et al. (2021): The study provides potential tools for policymakers by assessing the proportion of litter ingested by North Sea fulmars and analysing the trend in the mass of litter ingested over the last 10 years of data.

Matiddi et al. (2017): This project collected 120 dead loggerhead sea turtles to monitor the amount and composition of litter ingested. A total of 85 % of the individuals had ingested an average of 1.3 g of litter or 16 items each. The results provide evidence that the loggerhead is a good indicator of the trends in the amount and composition of litter ingested by marine animals.

van Franeker and Law (2015): The study evaluates trends and compositions of stomach contents of fulmars and trends in the composition of plastics in the North Atlantic Gyre. Similar trends were confirmed between stomach contents and the North Atlantic Gyre in abundance of plastics and the composition in relation to plastic pellets.

Trevail et al. (2015): Plastic ingestion was quantified in 40 northern fulmars from Svalbard, in an area with potential for future shipping routes in the high Arctic. Thirty-five individuals had plastic particles in their stomach contents, averaging 15.3 pieces per individual.

Bravo Rebolledo et al. (2013): All 107 stomachs and 100 intestines of 107 harbour seals, and an additional 125 scats were examined for ingested debris. Analysis revealed that 12.2 % of the seals had ingested plastics (stomachs and intestines); however, no evidence of plastics was found in the scats.

van Franeker et al. (2011): Long-term monitoring programmes were performed during 2003–2007 to analyse the stomach contents of 1 295 northern fulmars. In total, 95 % of individuals contained plastic items. The study suggests that fulmars continuously reflect litter levels in their environment.

3.4.5. Monitoring floating marine mesolitter

Litter items between 5 mm and 2.5 cm, known as mesolitter, also constitute large fraction of floating marine litter (e.g. Cózar et al., 2015; Ruiz-Orejón et al., 2016), which is considered within criterion D10C1 of D10 under the MSFD. As size distribution of marine litter in the environment is continuous, to avoid knowledge gaps regarding the biologically relevant size ranges that may be ingested by wildlife, monitoring programmes should ideally consider all size ranges.

In terms of monitoring, visual observations are not appropriate for effectively detecting debris smaller than 2.5 cm. However, based on surface trawl nets, some approaches derived from the physical collection of macro- and microlitter (Lebreton et al., 2018) may facilitate the monitoring and assessment of floating mesolitter. Thus, the methodology for microlitter sampling by surface tow nets might be used for mesolitter monitoring, provided that the sampled surface area enables representative sampling.

Trawl nets have been the most widely used tool for sampling mesolitter items. However, the variability in the methodology employed and the different configurations of the tools (e.g. Law et al., 2010; Ruiz-Orejón et al., 2016; Caldwell et al., 2019; Carretero et al., 2022), including the opening and mesh size of the nets (Table 2), may hinder the subsequent comparability and harmonisation of data. Furthermore, while the use of these tools is widespread in some regions, the operational limits of trawl nets (i.e. sea conditions, etc.) are still a challenge to their deployment in others.

Table 2. Characteristics of mesolitter sampling methods and relative studies applying them

Type of net	Speed	Time of deployment	Device opening dimension and mesh size	References
Manta trawl	~ 3 knots	10 min	n.a.; 333 µm	Carretero et al., 2022
Bongo net	2 knots	10 min	0.6 m diameter; 500 µm	Liu et al., 2020
Manta trawl	1.5–3 knots	15–30 min	40 cm × 70 cm; 335 µm	Compa et al., 2020
Manta trawl	1.5–3 knots	30–60 min	16 cm × 61 cm; 333 µm	Caldwell et al., 2019
2 nets fixed to the sea-cleaning boat	~ 2 knots	~ 4.5 h	0.8 m × 0.6 m; n.a.	Compa et al., 2019
Manta trawl	2.0–3.4 knots	15 min	0.6 m × 0.25 m; 333 µm	Ruiz-Orejón et al., 2019
Manta trawl	0.7–6.8 knots	0.35–4 h	0.90 m × 0.15 m; 0.5 mm	Lebreton et al., 2018
Neuston net	0.7–6.8 knots	0.35–4 h	6 m x 1.5 m; 1.5 cm	Lebreton et al., 2018
Manta trawl	~ 3–4 knots	15–30 min	0.6 m × 0.25 m; 333 µm	Ruiz-Orejón et al., 2018
Manta trawl	2 knots	20 min	0.6 m × 0.25 m; 333 µm	Gündoğdu and Çevik, 2017
Manta trawl	~ 2.5 knots	~ 60 min	0.6 m × 0.20 m; 333 µm	Pedrotti et al., 2016

Manta trawl	~ 3.14 knots	15–30 min	0.6 m × 0.25 m; 333 μm	Ruiz-Orejón et al., 2016
Neuston net	2–3 knots	~ 15 min	1.0 m × 0.5 m; 200 μm	Cózar et al., 2015
Manta trawl	3.7 m s^{-1}	45–90 min	0.6 m × 0.15 m; 333 μm	Faure et al., 2015
Neuston net	0.5–2 m s^{-1}	15–60 min	n.a.; 333 μm	Eriksen et al., 2014
Neuston net	2–3 knots	10–15 min	1.0 m × 0.5 m; 200 μm	Cózar et al., 2014
Neuston net	2 knots	30 min	1.0 m × 0.5 m; 335 μm	Law et al., 2014
Neuston net	2 knots	30 min	1.0 m × 0.5 m; 335 μm	Law et al., 2010

n.a.: not available

Literature on floating marine mesolitter monitoring

Carretero et al. (2022): This study analysed the seasonal cycle of micro- and mesoplastics in the surface coastal waters of the Ría de Vigo (Spain). Results showed high seasonal variability but a similar distribution between micro- and mesoplastics, and suggested that mesoplastics cannot be estimated.

Liu et al. (2020): This looked at seasonal variation in floating micro- and mesoplastics in Jiaozhou Bay (Yellow Sea). The hydrodynamic and meteorological processes influenced the distribution pattern of floating plastics in Jiaozhou Bay.

Caldwell et al. (2019): This studied micro- and mesoplastic in the Ligurian and Tyrrhenian Seas. The predominant polymer types were polyethylene, polypropylene and polyamide, and the morphology of the plastic particles was dominated by fragments (65 %). Thirty-four surface samples were collected using a manta trawl net.

Compa et al. (2019): Spatiotemporal analysis of coastal floating marine litter from sea-cleaning boats showed a heterogeneous distribution of plastics in the coastal areas of the Balearic Islands. Two nets, one fixed to each side of the sea-cleaning boats were deployed to monitor floating litter.

Ruiz-Orejón et al. (2019): This research determined the distribution of floating plastic litter (micro and meso) throughout different periods of the year in the MPA of the Menorca Channel (Spain). High-resolution and particle distribution models were employed to corroborate the floating plastic distribution and the influence of the oceanographic variables in the different seasons.

Lebreton et al. (2018): This assessed the plastic accumulation zone in the great Pacific garbage patch. Data from multivessel and aircraft surveys were used to calibrate the model. Manta trawl and neuston nets were deployed to collect floating litter in the size ranges from micro to macro.

Ruiz-Orejón et al. (2018): The study analysed the floating plastic litter in the coastal waters of the Balearic Islands (Spain), including micro and meso size ranges. It found a higher accumulation of floating plastics in the north and north-west of the islands.

Gündoğdu and Çevik (2017): This recorded preliminary results of micro- and mesoplastic surveys on the coasts of Turkey. The results found similar densities of microplastics to the other regions of the Mediterranean Sea.

Pedrotti et al. (2016): Floating plastic abundance, composition and size distribution were analysed in relation to distance to land in the Ligurian Sea. Fragments less than 2 mm were more abundant within the first kilometre of coastal water, suggesting the rapid fragmentation of the plastic items in coastal areas.

Ruiz-Orejón et al. (2016): Floating plastic litter was surveyed during two research campaigns throughout the central and western Mediterranean Sea. Samples were collected with a manta trawl net for periods of 15–30 minutes. A total of 16 719 microplastics, 691 mesoplastics and 85 macroplastics were found, and a general abundance of 1 455 tonnes of floating plastic litter was estimated for the entire Mediterranean Sea.

Cózar et al. (2015): Floating plastic litter was measured throughout the Mediterranean Sea. Neuston nets were employed during the surveys to assess the density of floating plastics. The study found a concentration of 1 item per 4 m^2 and estimated that the Mediterranean basin accumulates between 1 000 and 3 000 tonnes of floating plastics.

Faure et al. (2015): This study analysed the distribution, abundance and characteristics of floating micro- and mesoplastics in the western Mediterranean Sea.

Cózar et al. (2014): This study assessed the abundance and distribution of floating plastic litter worldwide using data from the Malaspina 2010 circumnavigation.

Eriksen et al. (2014): An estimation of floating plastic litter was based on data from global scale from 24 expeditions during 2007–2017. Floating plastics were collected using neuston nets for periods of 15–60 minutes at 0.5–2 m s^{-1}.

Law et al. (2014): An extensive survey from more than 2 500 neuston net tows was carried out between 2001 and 2012, to determine the distribution of surface plastic litter in the eastern Pacific Ocean.

Law et al. (2010): This analysed the floating plastic distribution, abundance and temporal variability in the North Atlantic Ocean and the Caribbean Sea from 1986 to 2008. Significant variability was not observed in the concentration of floating plastic litter over the dataset.

3.4.6. Comparison of methodologies

The selection of a given monitoring approach must take several factors into account, including its scale of application, cost, and requirements in terms of experience and equipment, which should be consistent with the monitoring needs and the general scope of monitoring. When selecting the best methodology to detect and assess long-term trends, it is also necessary to allow some freedom in the choice of the monitoring technique and platform, provided the above factors are considered.

The observation parameters (e.g. height, resolution) can vary according to the methodology; therefore, it is fundamental that minimum standards be guaranteed and that data collection be performed using a standardised method in accordance with common protocols and data collection forms.

To guide the selection of the most appropriate methodology for any given situation, a general table was prepared based on the one proposed within the TG ML monitoring guidelines (Galgani et al., 2013), highlighting the benefits and limitations related to each platform and technique, along with relative indicative costs (with the proviso that they may vary considerably between countries and seasons), and requirements in terms of technical equipment, expertise and possible personnel (Table 3).

However, as recommended by the MSFD and regional programmes, the selection of a given approach within monitoring should consider the available equipment and expertise and any possible opportunity to reduce costs.

Table 3. Overview of the different approaches that can be used for FMML monitoring.

Variable	Large vessels; visual transect survey (≥ 50 m fixed width)	Small/medium-sized/large vessels; visual transect survey (fixed width adjustable to purpose)	Ship-based imagery	Aerial survey (visual)	Aerial (aircraft) photography	Aerial (UAV) photography	Satellite-based imagery	Monitoring litter ingested by biota	Macro- and mesolitter physical monitoring
Level of technical equipment	L	L/M	H	H	H	M	M/H	M	H/M
Expertise	L/M	L/M	H	M/H	H	H	H	M/H	H
Possible personnel	V; C/A; S	V; C/A; S	C/A; S	C/A; S	C/A; S	C/A; S	C/A; S	C/A; S	C/A; S
Costs (sampling; analysis; equipment)	L/H; M; L/H Overall: L/M	M; M; M Overall: M	M; M; M Overall: M	H; M; H Overall: M/H	H; M; very H Overall: H	M/H; M; M/H Overall: M/H	L/M; M/H; M/H Overall: M/H	L/M; M; L/M Overall: L/M	M; M; M/H Overall: M
Detail generated	M (size > 20 cm)	H (size > 2.5 cm)	M/H (depending on height and resolution)	L (size > 30 cm)	L/M (depending on height and resolution)	M/H	L	L	M/H
Spatial scale of applicability	H	M	H	H	H	L/M	H	L/M	H
Benefits and opportunities to reduce costs	Wide coverage. Can be integrated with vessels' ongoing operations and/or coupled with marine fauna-monitoring programmes to allow replicated surveys over seasons and years. Trained volunteers can be	High detail of observations; can be adapted to necessities of sampling (specific areas/seasons); allows precise assessments at local scales. Can be coupled with marine fauna	Can produce extremely high detail of observation and allows FMML assessment over large areas. Automation of analyses can further reduce costs.	Allows FMML assessment over large areas and correlations with potential sources (shipping/fisheries). Can be coupled with marine fauna monitoring or other ongoing monitoring	Large area coverage and high detail of observations. Recorded images can be used for several subsequent analyses. Automation of analyses can	Can produce extremely high detail of observation. Basic platforms and sensors can be easily adopted for routine low-cost monitoring of small coastal areas. Automation	Wide coverage. Open-access satellite imagery can be adopted to reduce costs. Automation of analyses can reduce the overall cost and time dedicated to analyses.	Allows potential assessment of trends in litter ingested by organisms and the relation to the abundance in the environment.	Wide coverage and high detail of data and assessments. Can be integrated in vessels' ongoing operations.

	employed to reduce staff costs.	monitoring, and trained volunteers can be employed to reduce costs.		activities to reduce costs.	reduce the overall cost and time dedicated to analyses.	of analyses could further reduce costs.			
Limitations	Items smaller than 20 cm are usually not considered. Observations are affected by weather and sea conditions. Very expensive if performed on dedicated platforms.	Observations are affected by the weather; strong temporal variations; can be expensive if dedicated platforms are used.	Observations are affected by weather and sea conditions. Unless automated, the process of analysis can be time-consuming.	Items smaller than 30 cm are not considered and the discrimination among types is limited. Observations are affected by weather and sea conditions. Expensive.	Observations are affected by weather and sea conditions. Expensive. Unless automated, the process of analysis can be time-consuming.	Observations are affected by weather and sea conditions. Unless automated, the process of analysis can be time-consuming.	Very high densities of particles are usually needed. Detection of marine litter limited to sensor specifications. Unless automated, the process of analysis can be time-consuming.	Limited to trend information. The process of analysis can be time-consuming. Limited comparability and harmonisation of data across regions.	Requires a high level of training and experience in the handling of the sampling tools. Environmental and weather conditions may condition sampling.

C/A, consultants and agencies; H, high; L, low; M, medium; S, scientists; V, volunteers.

3.5. Databases and data repositories

The availability of harmonised datasets is being improved by the development and implementation of monitoring schemes. However, appropriate data repositories, databases and portals need to be set up to ensure the accessibility of the data, provide a complete set of metadata and facilitate the identification of further harmonisation needs.

Therefore, it is crucial that large-scale monitoring efforts (i.e. going beyond scientific research) feed data into a common portal so that it is fit and available for use, such as for the assessment of transboundary litter transport and the modelling of litter transportation pathways. Currently, FMML data are housed in individual project-based or national data repositories.

The Alfred-Wegener-Institut Litterbase (https://litterbase.awi.de/) provides a repository of data extracted from scientific publications, including FMML data.

The European Marine Observation and Data Network (EMODnet; www.emodnet-chemistry.eu) is a data portal that provides access to marine data through seven thematic portals. Its chemistry module also includes data on marine litter (Molina Jack et al., 2019). EMODnet made a preliminary study to manage FMML datasets, enlarging their scope from beach, seafloor and microlitter to FMML. To this end, a consolidated data format and set of metadata must be developed and agreed upon. Harmonisation efforts are underway in the MSFD TG ML.

Outside the EU, Regional Sea Conventions and other international organisations may provide IT infrastructure for collecting, hosting and managing FMML and other litter data. However, it should be emphasised that only a common data format, structure and metadata can provide comparability of data and interoperability of databases.

3.6. Floating Litter Monitoring app

The Floating Litter Monitoring (FLM) app is a scientific tool developed by the JRC to facilitate data acquisition during litter monitoring at sea and on rivers. It was developed starting in 2014 during the Policy-oriented marine environmental research in the southern European seas (PERSEUS) project and was subsequently applied within the Environmental Monitoring in the Black Sea (EMBLAS) II project and the Riverine and marine floating macro litter monitoring and modelling of environmental loading (RIMMEL) project.

An observer can use this application by standing on an elevated position on a vessel or bridge in the case of rivers, select the observation area, record the position and categorise the macro litter objects passing through the observation area according to the Joint List of Litter Categories (Fleet et al., 2021). A new version is currently being developed that will be available for Google's Android and Apple's iOS platforms (Figure 8).

The data acquired through the app will be stored on a server-based database but can also be kept locally by the owner. Data points consist of geographical coordinates, sampling date and time, and the litter type category along with size information. To manage datasets separately, data can be labelled with a project code. A web portal will provide a simple viewer for observed transects and observing locations (Figure 9).

Figure 8. Litter categories menu in the mobile FLM app.

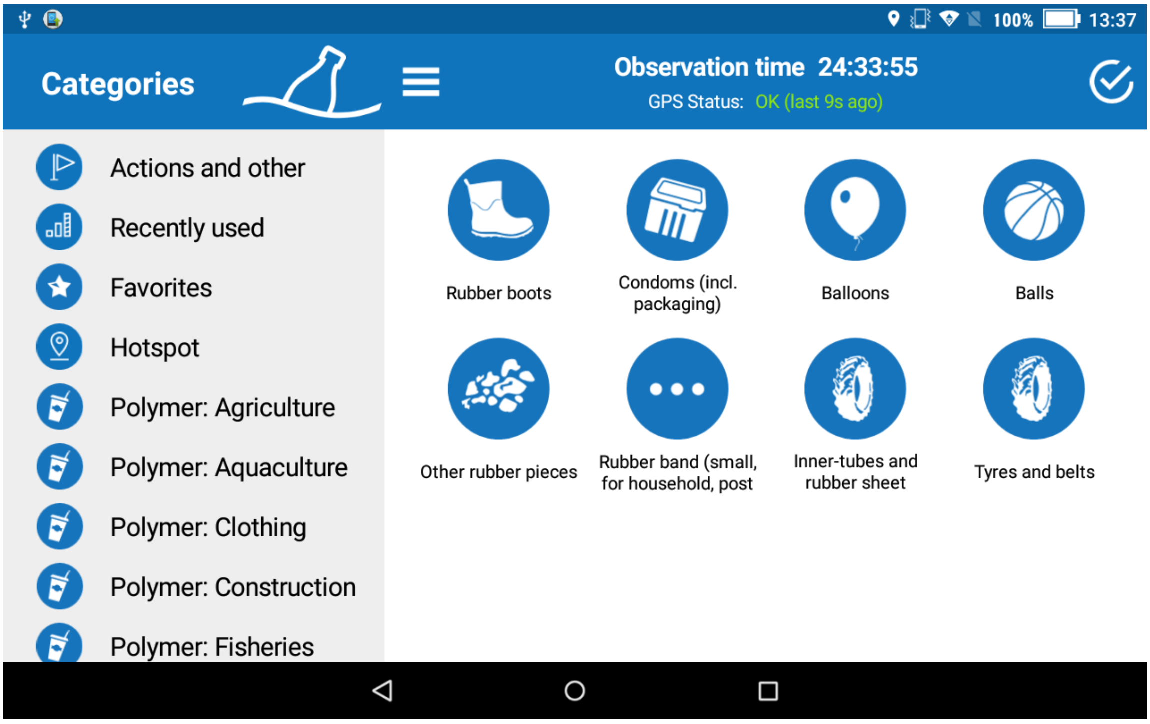


Figure 9. The main options on the FLM app web portal.

4. Modelling of FMML

The availability of FMML data is crucial for feeding oceanographic models, which can provide scenarios for litter transportation through currents, winds and wave action. Models can also be used to predict accumulation areas and thus indicate priority monitoring areas, and guide policy actions for the mitigation of marine litter impacts. Marine litter models are now becoming a widespread tool for answering specific questions, such as those related to transboundary litter transportation (Macias et al., 2021), and efforts towards large-scale coherent modelling are under way ([5]). To make the best use of monitoring data and to enable the use of models for the development of sampling strategies, the parties involved need to collaborate closely on the collection of standardised and comparable data. Since the publication of the first paper on FMML and ocean modelling by Aliani and Molcard (2003), a number of relevant scientific works have been produced.

Macias et al. (2021): A combination of hydrodynamic and Lagrangian models of the Mediterranean Sea was used in order to understand the origin of coastal litter. Simulations show that the amount of transboundary litter in Mediterranean countries could be as large as 30 %, although regional and seasonal differences could be significant.

Tsiaris et al. (2021): An 8-year simulation was used to identify micro- and macroplastic accumulation patterns in the surface layer, in the water column, on the seafloor and on the beaches of the Mediterranean Sea.

Soto-Navarro et al. (2021): A methodology was developed to assess the risk of marine litter pollution in the Mediterranean Sea by estimating the hazard component, using a state-of-the-art 3D modelling system, which allows the simulation of floating and sinking marine litter particles. The exposure component, based on biodiversity estimates and species vulnerability, is related to marine litter ingestion rates of each species.

Miladinova et al. (2020): The distribution and accumulation patterns of floating marine debris in the Black Sea were studied using a 3D hydrodynamic model with a particle-tracking model. Simulations showed that the accumulation zones are more abundant in summer along the south-eastern and eastern coasts.

Macias et al. (2019): The surface water circulation in the Mediterranean Sea was studied, using the general estuarine transport model within the marine modelling framework, to determine its implications for the seasonally changing patterns of floating litter accumulation.

Liubartseva et al. (2018): The drift of floating litter in the Mediterranean was studied with a 2D Lagrangian model with stochastic beaching and sedimentation of plastics. Virtual particles were tracked from anthropogenic sources (coastal cities, rivers, shipping lanes) to environmental destinations (sea surface, coastlines, seabed), considering daily analyses of ocean currents and waves provided by the Copernicus Marine Environment Monitoring Service as factors forcing the plastics.

Pereiro et al. (2018): A Regional Ocean Modelling System (ROMS), in conjunction with a particle-tracking model, was used to study the distribution of floating litter in northern Iberian waters.

Zambianchi et al. (2017): The largest available set of historical Lagrangian data gathered in the Mediterranean Sea (the Mediterranean Drifter Data Base) was used to estimate the probability of litter particles reaching different subareas of the basin, and identify possible retention areas.

Carlson et al. (2016): Surface drifters and virtual particles were used to investigate observed and modelled surface Lagrangian transport between coastal regions in the Adriatic Sea, starting from observed FMML densities.

Liubartseva et al. (2015): Sea surface concentrations of plastics and their fluxes onto coastlines in the Adriatic Sea were simulated over 2009–2015. Calculations were based on combining data of terrestrial and maritime plastic litter inputs.

Mansui et al. (2015): An ocean general circulation model was coupled with a particle-tracking model to model the transport and accumulation of floating marine litter in the Mediterranean basin.

([5]) https://mcc.jrc.ec.europa.eu/main/dev.py?N=simple&O=456&titre_chap=%C2%A0&titre_page=MEME%20-%20Network%20of%20Experts

5. FMML monitoring in the EU context

As the attention given to marine litter issues rapidly increased during the last decades, several marine litter research and monitoring projects were developed and implemented across Europe.

To this end, research institutions, MPAs and NGOs have been carrying out projects aiming to develop, test and implement harmonised methodologies for the assessment of FMML abundance, distribution and composition. Several methodologies have been applied, and different guidelines have been proposed and published. These approaches include the use of ships as platforms of opportunity, aerial surveys, dedicated vessels, drone-based observations, satellite-based imagery, and predictions of marine litter density and distribution based on modelling exercises. This chapter summarises the monitoring activities and reports produced through RSCs, national activities, research projects and NGOs within the recent period.

5.1. Regional Sea Conventions

Given the transboundary nature of the marine litter issue, RSCs provide international, regional approaches, where needed, and promote international collaboration beyond the EU's borders across the marine waters shared with numerous other countries. Links across conventions are provided within the overlapping areas, as the EU MSFD includes countries from five regional initiatives (OSPAR, HELCOM, MAP, Black Sea Commission (BSC), Arctic Council), and close collaboration is needed to address the transboundary transportation of floating litter. The review of the monitoring approaches used by the MSFD and the RSCs to assess plastic pollution revealed a strong commitment to providing common monitoring elements. However, the implementation of such approaches is recent and remains subject to significant knowledge and data gaps (González-Fernández and Hanke, 2020). Here, an overview of how RSCs within the EU's shared basins consider floating litter is given.

Convention for the Protection of the Marine Environment of the North-East Atlantic (OSPAR)

OSPAR has been working with other RSCs and the European Commission to develop assessment tools, such as indicators of the state of the marine environment. In 2014, OSPAR agreed to develop a RAP and an implementation plan for marine litter, to achieve the objective of significantly reducing amounts of marine litter. The RAP focuses on both sea-based and land-based sources of litter, and currently assesses beach litter, seabed litter, and plastic particles in fulmar stomachs or in turtle guts and faeces (ingestion indicator). However, to date, it does not consider FMML as an indicator as part of its monitoring and assessment programme. The ingestion of litter by the northern fulmar is mentioned as a proxy for litter at sea. However, OSPAR is currently also working to develop new indicators, and some of the contracting parties are performing FMML-monitoring activities.

Helsinki Convention on the Protection of the Marine Environment of the Baltic Sea Area (HELCOM)

HELCOM was adopted in 1992. In June 2017, the 'Second HELCOM Holistic Assessment of Ecosystem Health in the Baltic Sea' was published under the title *State of the Baltic Sea* (http://stateofthebalticsea.helcom.fi/), providing information on the overall environmental status of the Baltic Sea and pressures on it, including consideration of beach litter but not of FMML. HELCOM does not consider FMML as an indicator, and no coordinated monitoring of floating marine litter currently exists in the HELCOM region. National monitoring programmes concerning marine litter are in place, depending on the contracting party. Indicators regularly undergo thorough updating processes, and plans exist for the future development of indicators on litter.

United Nations Environment Programme / Mediterranean Action Plan (UNEP/MAP)

The Barcelona Convention (the Convention for the Protection of the Marine Environment and the Coastal Region of the Mediterranean) was adopted in 1995 and is implemented through the UNEP MAP. The MAP addresses FMML within the Integrated Monitoring and Assessment Programme of the Mediterranean Sea and Coast (IMAP) Ecological Objective 10 (Marine and coastal litter do not adversely affect the coastal and marine environment) and Common Indicator 23 (Trends in the amount of litter in the water column including microplastics and on the seafloor). The preliminary baseline values defined for floating litter within the action plan were defined as three to five items per kilometre, and targets were set as statistically significant decreases in percentage.

The UNEP MAP 2015 report includes an assessment of marine litter composition and distribution in all marine compartments, presenting the most abundant litter items found in the different marine compartments. The report on the quality of the Mediterranean Sea also addresses marine litter, including background information, assessment methods, results, trends and best practices for all compartments (UNEP MAP, 2015, 2017).

Med Pol (the marine pollution assessment and control component of the MAP) is working on an information system for the standardisation of monitoring data and for the quality assessment and quality control of data.

Bucharest Convention – Black Sea Commission (BSC)

The Bucharest Convention for the Protection of the Black Sea was adopted in 1992 and is implemented through the BSC. An RAP for the management of marine litter in the Black Sea was adopted during the 34th regular meeting of the BSC in October 2018; it considered performing regular activities during 2019. In December 2019, the BSC Permanent Secretariat hosted the 'Regional verification workshop to support the establishment of the Black Sea Marine Litter Monitoring Programme and streamline the implementation of the Regional Action Plan on Marine Litter Management in the Black Sea', held in the framework of a bilateral collaboration between the UNEP MAP Barcelona Convention Secretariat and the BSC Permanent Secretariat. It served as a platform for the consideration of drafting marine litter monitoring guidelines for the Black Sea and for discussing the implementation of the marine litter RAP and related activities. While the BSC has not yet approved a monitoring programme, the EMBLAS project has performed large-scale surveys of FMML in the Black Sea basin.

Arctic Council – Arctic Monitoring and Assessment Programme (AMAP)

Activities of the Arctic Council against marine litter are addressed through the Protecting the Arctic Marine Environment (PAME) programme. PAME is currently developing an RAP on marine litter, which is co-led by Canada, the Kingdom of Denmark, Finland, Iceland, Norway, Sweden, the United States, the Aleut International Association (AIA) and OSPAR in close collaboration with other working groups. The RAP for the Arctic will address both sea- and land-based activities, focusing on Arctic-specific marine litter sources and pathways. The RAP will be validated twice a year to address new and emerging information and priorities. The Arctic Monitoring and Assessment Programme supports this RAP, focusing on the monitoring aspect, and an expert group is currently working on developing a comprehensive monitoring plan and technical guidelines for monitoring the Arctic. Currently, FMML is addressed in the draft plan, but a comprehensive monitoring plan for FMML is not operative yet.

5.2. National monitoring activities

Over the last few years, EU MS have been carrying out several national activities based on general, social and/or policy interests. An overview of the MS currently involved in FMML monitoring is provided below in protocol order.

Bulgaria (BG)

FMML has been monitored in Bulgaria through visual observations based on the fixed-width strip transect method. Six monitoring surveys were carried out between 2017 and 2019, at an average speed of 5.5 knots. Observations were fixed to 30 min under low wind-speed conditions (≤ 5 m s^{-1}). In this initial assessment of FMML in the Bulgarian Black Sea waters, a total of 1 320 items of litter were identified in the 288 transects conducted, with densities ranging from 0 to 1 750 items per square kilometre (Slabakova et al., 2020).

Germany (DE)

Floating litter has been surveyed using the aerial video surveying method HiDef. The system comprises four digital charge-coupled device video cameras mounted on a Partenavia P68 aircraft, recording four strips with a combined width of 544 m at a resolution of 2 cm per pixel from a survey altitude of 550 m. Four surveys were chosen as representatives for this feasibility study. Reviewers classified all objects based on the recommendations for remotely observed litter by Cheshire et al. (2009). In total, in all four surveys, 4 550 objects were classified as litter. 'Other litter' was the largest group by far, with 2 693 objects, followed by pieces of plastic (578) and foil (529). Spatial and seasonal patterns could be detected, and results from different years were significantly different. These results agree with those from the German environmental agency's previous research and development project, in which visual observations from plane and ships were tested, and the use of ships was discarded as an option for potential long-term monitoring.

During testing, FMML visual observations were carried out during aerial surveys aiming to estimate the abundance and density of harbour porpoises in the North Sea and the Baltic Sea. The data generated are based on standardised aerial line transect surveys conducted regularly since 2002. Areas of the German exclusive economic zone (EEZ) in the North Sea, such as Borkum Reef Ground and Sylt Outer Reef, are surveyed annually, while the complete German EEZ and adjacent Danish waters in the Baltic Sea are surveyed every second year. Aggregated data were categorised into sightings of total floating litter, floating fishing-related litter and floating litter without fishing-related litter (residual litter). The information on the exact coordinates made it possible to determine the distribution and estimate the amount of floating marine litter. Further analysis enabled the identification of hotspots of marine litter, and annual and seasonal differences. The data on marine litter collected from 2010 to 2012 were analysed and evaluated to investigate possible annual trends and seasonal changes. After the records of floating litter were evaluated as described above, data were further analysed to combine information about floating litter with litter on the seafloor. In a next step, aggregated data about these three categories were interpolated applying orthogonal isotropic Kriging procedures.

Spain (ES)

A pilot programme is currently being tested in cooperation with observers of marine mammals and seabirds.

Data on floating litter are obtained during acoustic surveys of fisheries carried out by the Instituto Español de Oceanografía (IEO). These multidisciplinary surveys obtain information on pelagic fish distribution and abundance using acoustic methods, following a sampling grid consisting of parallel transects perpendicular to the coastline, separated by 8 nautical miles.

Observers work in teams of two and, together with information on marine mammal, seabird and fish presence, also record the presence of floating litter (position, abundance, composition, etc.). Observers work during daylight while the ship is surveying a transect at a constant speed of ~ 10 knots. Two observers, placed on the ship bridge, located 16 m or 12 m above sea level, depending on the vessel used, scan the 180° ahead of the vessel (90° each observer). At the start of each observation period, observers record the meteorological conditions and additional information that can affect visibility.

With the aim of avoiding the bias introduced by different weather conditions (e.g. reduction of visibility and consequently the possibility of sightings), the Beaufort scale is used to filter the database. Distance sampling methodology (Buckland et al., 2015) is used to estimate floating litter density.

France (FR)

The French Office for Biodiversity, in charge of the implementation of several Descriptors of the MSFD under the French Ministry of the Environment, funds monitoring programmes from aerial platforms and opportunistic surveys during fishery scientific campaigns and from ferries. Standard protocols are applied, based mainly on the report of the MSFD TG ML. In France's Mediterranean waters, the collection of data from ferries is based on the MEDSEALITTER standards: transborder fixed transects are realised over three different routes, with a frequency of two surveys per season. Dedicated and experienced observers record data in optimal weather conditions (< 3 on the Beaufort scale) from large vessels travelling at a maximum speed of 28 knots, within a fixed strip of 50 m. The effort is automatically recorded and all litter items are georeferenced and classified in accordance with the JRC Joint List of Litter Categories (Fleet et al., 2021). Analyses of amount, distribution and composition are performed by the Institut Français de Recherche pour l'exploitation de la Mer (IFREMER).

Croatia (HR)

FMML has been systematically monitored since 2017. Before that, monitoring activities were carried out within the Derelict fishing gear management system in the Adriatic region (DeFishGear) project in 2014–2015. FMML monitoring is currently carried out twice a year, during March–May and October–November, at 21 stations that cover a significant area of the eastern coast of the Adriatic Sea. The employed methodology follows the TG ML guidelines.

The survey area is defined by the transect width and length. Depending on the boat used, the observation level of the surveyor for a predefined ship speed of 2.5 knots is 3 m above the sea, the observation width is approximately 8 m (4 m from each side of the boat), and the duration of each transect survey is 1 hour. Observations are made from the bow of the boat, parallel to the forward movement, and from the side without glare from the sea to maintain favourable visibility conditions. The length of the transect is determined based on the latitude and longitude of the start and end points of the transect obtained by GPS.

All litter items larger than 2.5 cm are monitored, and recorded based on the type of material and size. Identification of recorded items is made in accordance with the methods described by Vlachogianni (2015a,b), and litter is quantified as the number of items per square kilometre.

Italy (IT)

The Ministry for Ecological Transition and the National System for Environmental Protection (SNPA) coordinate and implement the MSFD monitoring programme on D10 for three subregions: western Mediterranean; central Mediterranean and Ionian Sea; and Adriatic. Three monitoring programmes are implemented: in coastal areas, in offshore areas and at the mouths of rivers.

In coastal areas, FMML monitoring is performed every 2 months along the fixed monitored transects identified by the 'Decreto Legislativo' 152/2006 (implementing Directive 2000/60/CE, the Water Framework Directive, WFD), perpendicular to the coastline from 3 to 12 nautical miles, and homogeneously distributed along the Italian coastline. Monitoring is performed in optimal weather conditions (< 3 on the Beaufort scale) by dedicated and experienced observers from small/medium-sized boats at a speed of 4–6 knots, within a fixed strip of 5 m (observed from the front of small boats, or from the side of medium-sized boats).

In offshore areas, FMML monitoring is performed in five surveys per season (20 surveys per year) along transborder fixed monitored transects. Dedicated and experienced observers perform monitoring in optimal weather conditions (< 3 on the Beaufort scale) from large boats at a maximum speed of 28 knots, within a fixed strip of 50 m. The effort track is automatically recorded and all litter items are georeferenced and classified according to the JRC Joint List of Litter Categories (Fleet et al., 2021). Analyses of amount, distribution and composition are performed, stratifying data by subregion, area and season.

At the river mouths, monitoring is carried out through visual census over at least half the width (the observation strip) of the river and from a height not exceeding 10 m, from a bridge or the river bank. Five surveys per season are performed on 12 different rivers, within the three marine subregions established by the MSFD Directive, for a total of 120 hours of monitoring on rivers per season. The methodology is the one developed within the JRC's RIMMEL project, with the following adaptations: items are classified in accordance with the Joint List of Litter Categories for Marine Macrolitter Monitoring (Fleet et al., 2021) and, for rivers wider than 40 m, multiple observation strips are designed, with the sampling station close to the river mouth.

Cyprus (CY)

Cyprus is in the process of testing methods for collecting FMML data. A pilot study was conducted in 2018 to identify plastic targets on the sea surface using remote sensing techniques with Sentinel-2 data, in combination with an unmanned aerial vehicle (UAV) equipped with multispectral cameras (Themistocleous et al., 2020).

Cyprus is also developing a monitoring method using drones, based on the one used to detect turtle traces on beaches to monitor their nests.

Malta (MT)

The Office of the Prime Minister (which is in charge of the implementation of the MSFD), the Malta Environment and Planning Authority and Transport Malta coordinate the programme of monitoring marine litter in the water column. Two monitoring methodologies are implemented based on visual observations: visual surveys from beaches and visual surveys of litter at sea by volunteers and/or from boats of opportunity. Visual surveys from beaches use the same stretch of coastline monitored within the beach litter monitoring programme to count any floating litter observed within a stretch of 10 m from the foreshore. Two duplicate counts are taken by repeating the count while walking back to the starting point. Visual surveys at sea are undertaken on boats moving at cruising speed for 6 km, and the observer (dedicated or volunteer) records any floating litter detected within a designed strip from the boat. The distance travelled is recorded using GPS readings at the start and end of the survey.

The FMML-monitoring programme in Malta is currently being revised.

Poland (PL)

Floating litter monitoring is carried out once a year during a monitoring cruise performed in June, through observations at six stations and two transects in the Polish EEZ. All types of floating litter are recorded.

Portugal (PT)

Continental Portugal does not have a monitoring programme for floating litter. Opportunistic monitoring is carried out during research cruises and as part of the programme 'A Pesca por um Mar Sem Lixo', in which fishermen from various regions of mainland Portugal collect floating litter during their fishing activities; after they arrive in port, the collected litter is deposited in dedicated disposal places. This programme is currently carried out in 18 ports.

In the Azores, macro litter monitoring on the surface of the water column is carried out in accordance with the guidelines on marine litter monitoring in the European seas (Galgani et al., 2013). Data collection takes place annually between May and October. The methodology is applied by observers on board tuna-fishing vessels included in the programme for the observation of fisheries in the Azores. Data are collected during visual transects of 10 minutes, performed six times a day, every 2 hours. Floating litter larger than 2.5 cm is observed from a height of 8 m above sea level, within a 100-m fixed-width transect.

Madeira is going to start a floating litter monitoring programme in 2022, planning to monitor four marine areas adjacent to the beaches of Praia Formosa, Seixal, Maiata and Prainha. In Porto Santo, the areas adjacent to the beaches of Calheta, Vila and Docas will be monitored. Aerial images of the coastline will be collected through drone flights equipped with a multispectral camera. Transects of approximately 1 km will be carried out parallel and perpendicular to the coastline, and images of accumulation zones will also be collected.

Slovenia (SI)

FMML has been systematically monitored in the DeFishGear project. The first assessment of pollution from floating marine litter was carried out in 2011 and the sampling method was harmonised with other Adriatic countries within the Instrument for Pre-Accession Assistance (IPA) Adriatic project – DeFishGear. In 2019, Slovenia improved the methodology by harmonising the sampling transects with the classification of water bodies in the Slovenian sea according to the WFD (Directive 2000/60/EC). Pilot monitoring of floating macro litter was financed by the Ministry of the Environment and Spatial Planning and was carried out by the Institute for Water of the Republic of Slovenia in 2014, 2015, 2017, 2019 and 2020.

In 2020, Slovenia performed pilot sampling and analysis of FMML during the four seasons at five monitoring stations. Floating litter observations were carried out from the bow of a boat travelling at 2.5–3 knots, while items were collected with a net mounted on a telescopic pole. After collection, litter items were dried in a laboratory, weighed, photographed, categorised and measured for classification by size. The survey area was defined by the transect width (3.5 m – the length of the sampling pole) and length (defined by the start/end GPS coordinates and time of sampling, which was 30 minutes). Sampling was carried out in a straight line towards the planned end GPS coordinates. Because of the currents and speed of the boat, the end coordinates were usually different and were written again in the data sheets at the end of the sampling.

Identification of recorded items was done according to the methods described by Vlachogianni (2015a,b), in line with the TG ML recommendations.

Litter was quantified as the number of items per square kilometre and mass (kg) per square kilometre. All data were presented per season in order to detect any seasonal fluctuation.

5.3. Research projects and institutions involved in FMML monitoring

Triggered by research needs, policy demands and public interest, a number of research initiatives at national, regional and EU levels have been carried out in recent years. Here a non-exhaustive list of projects and institutions, including FMML activities, is provided as an overview.

Agreement on the Conservation of Cetaceans of the Black Sea, Mediterranean Sea and Contiguous Atlantic Area (ACCOBAMS Survey initiative)

ACCOBAMS implemented the ASI to establish a baseline for cetacean abundance and distribution, covering the entire Mediterranean Sea during summer 2018. The partners agreed to include FMML monitoring in the surveys. The Mediterranean Sea was divided into blocks to have equivalent coverage probability across the surveyed areas. Forty countries were involved. More than 11 000 litter items were detected, and the minimum information collected included the number and type of items. The data from this first international basin-scale survey of the Mediterranean Sea were used to provide the first abundance estimate of floating mega-litter (> 30 cm) and map its distribution over the entire Mediterranean Sea. The total number of floating mega litter items was estimated to be ~ 2.9 million. As items larger than 30 cm represent only a quarter of the complete load of anthropogenic marine litter larger than 2 cm in the Mediterranean, the estimate is scaled up to 11.5 million floating items, with the highest densities observed in the central Mediterranean and the lowest in the eastern basin (Lambert et al., 2020). A similar survey was performed in 2019 on the Black Sea.

Actions for Marine Protected Areas (AMARE)

The Actions for Marine Protected Areas (AMARE) project, financed by the transnational European cooperation programme for the Mediterranean area (Interreg MED) between 2016 and 2019, aimed to develop shared methodologies and geospatial tools for multiple stressor assessment, coordinated environmental monitoring, multicriteria analyses and stakeholder engagement, and to develop concrete pilot actions and coordinated strategies in selected MPAs to resolve hotspots of conflicts affecting marine biodiversity and the services it provides.

Within this Interreg project, a guideline was produced to provide advice and practical guidance for establishing programmes to monitor and assess the distribution and abundance of marine litter in all marine compartments within MPAs (Galgani et al., 2019). Moreover, during the project, a field experiment was performed using a Wave Glider to monitor the subsurface marine litter through a camera system acquiring images every 7 seconds, covering 12.4 m in width. The system allowed the collection of 45 000 images, from which the density of marine litter in the layer between the surface and 4.5 m below, was estimated to be six items per square kilometre. These results showed the possible long-term and large-scale utilisation of the Wave Glider as a monitoring tool, as it is suitable to monitor surface litter over large coastal or oceanic zones, despite some constraints related to marine traffic.

CleanAtlantic

The CleanAtlantic project, financed by the Interreg Atlantic Area, envisages monitoring beach litter and FMML in the coastal zone and open ocean under work package 5 (Monitoring the presence of marine litter in the marine environment). With this purpose, an overview of new and improved marine litter monitoring methods for the seabed, water surface and coastal compartments in the Atlantic area have been developed. New technologies and applications have been tested for their potential use in marine litter monitoring. Satellite data, drones and high-frequency radar coupled with the use of imagery identification gadgets have been improved for this purpose.

Coastal management and monitoring network for tackling marine litter in Mediterranean Sea (COMMON)

The European Neighbourhood Instrument cross-border cooperation project Coastal management and monitoring network for tackling marine litter in Mediterranean Sea (COMMON) is a 3-year project started in 2019 that applies the integrated coastal zone management (ICZM) principles to address the challenge of marine litter, improving knowledge of the phenomenon, enhancing the environmental performance of five pilot coastal areas in Italy, Lebanon and Tunisia, and engaging local stakeholders in marine litter management. The methodologies applied to monitoring FMML and floating micro-litter are those developed in previous projects (e.g. MEDSEALITTER, PlasticBusters MPAs).

Derelict fishing gear management system in the Adriatic region (DeFishGear)

The DeFishGear project, financed between 2013 and 2016 by the IPA Adriatic cross-border cooperation programme, aimed to facilitate efforts towards integrated planning to reduce the environmental impacts of litter-generating activities and ensure the sustainable management of the marine and coastal environment of the Adriatic and Ionian seas. Within the project, partners developed a monitoring protocol and guidelines in cooperation with the TG ML, based on the MSFD guidance (MSFD TG ML, 2013) and the National Oceanic and Atmospheric Administration (NOAA) recommendations for monitoring marine litter (Lippiatt et al., 2013). The monitoring techniques were tested in collaboration with the Adriatic and Ionian Sea countries. A geographic information system database on marine litter was developed as well as an e-learning module on FMML. A report was published in 2017 summarising the results from the DeFishGear monitoring activities, performed through visual observation from small ships during 2014–2015 along 66 transects, and from large vessels (ferries) along 91 transects (Vlachogianni et al., 2017). Results, showing high variability of densities and higher densities of FMML and litter fragments in areas closer to the coast and inshore areas, were published by Zeri et al. (2018).

Environmental Monitoring in the Black Sea (EMBLAS)

The EMBLAS project, funded by the Directorate-General for Neighbourhood and Enlargement Negotiations, aims to help improve the protection of the Black Sea environment through technical assistance on environmental monitoring. Marine data collection and small-scale actions for public awareness and education are among its goals. While Georgia, Russia and Ukraine are project partners, the project is working closely with other Black

Sea countries. The State Oceanographic Institute of Russia was involved in the project to monitor FMML, to assess the exposure of the Black Sea to marine litter accumulation. Strip transects were applied in accordance with the MSFD guidelines, and observations were classified using the joint master list and the JRC Floating Litter mobile application. Visual observations were performed in 2016, 2017 and 2019 using research vessels and platforms of opportunity. The average litter density observed was 90 items per square kilometre. The second phase of the project, EMBLAS II, and subsequently EMBLAS Plus, addressed the need for support in protecting and restoring the environmental quality and sustainability of the Black Sea, and aimed to improve the availability and quality of data, and the monitoring capacity of the countries involved.

European Space Agency (ESA)

The European Space Agency (ESA) has funded several projects to develop remote sensing methods to monitor FMML. Following two initial studies (OPTIMAL and RESMALI) in 2017 – 2018, to conduct a first assessment of the feasibility of using remote sensing, and in particular the current satellites, for marine litter detection, as well as to lay out the basis for a future dedicated Earth Observation mission, new initiatives were launched in ESA starting from 2018 – 2019: the large Discovery Campaign on Remote Sensing of Plastic Marine Litter ([6]), the "EO Science for Society" projects (e.g. EO Tracking of marine debris in the Mediterranean Sea and MIREIA), or the "Plastic-less Society" initiative.

Other projects such as the ESA Plastic Litter Project (PLP) develops experimental reference targets made of polymers commonly found in FMML to calibrate remote sensing detection, and support algorithm development for satellite detection, and Windrows As Proxies (WASP) focuses attention on using remote sensing to monitor FMML accumulations at ocean convergences. More recently, at the ESA Living Planet 2022 has been presented the first mission concept with an ad-hoc instrument for marine litter detection. The scope of this proposed mission is the detection of FMML at sea along the principles of windrows detections and with significant inputs from ESA RESMALI project, including plastic quantification, the acquisition of shoreline plastic litter, and the detection and monitoring of dumping sites close to rivers.

European quality controlled harmonisation assuring reproducible monitoring and assessment of plastic pollution (EUROqCHARM)

The EU Horizon 2020 project European quality controlled harmonisation assuring reproducible monitoring and assessment of plastic pollution (EUROqCHARM) is coordinated by the Norwegian Institute for Water Research and includes 15 partners across Europe. The overall objective of the project is to develop optimised, validated and harmonised methods for the monitoring and assessment of plastics in the environment (including floating macro litter), as well as blueprints for standards and recommendations for policy and legislation. To do so, the project plans to evaluate, with rigorous quality control, the existing methodologies for plastic pollution assessments, and to reinforce Europe's monitoring capacities based on the analysis of guidelines. It will critically review the state-of-the-art analytical methods and, taking harmonisation one step further, will validate them through interlaboratory comparison and certified reference materials. EUROqCHARM will bring together stakeholders from industry, governing bodies, regulators and standards bodies, among others, to cooperate and participate in the dialogue, the decision-making process and the implementation of solutions woven throughout the project. Through the planned work, the project will improve the understanding of the methods required for monitoring plastic pollution and, ultimately, contribute to the establishment of national, EU and global monitoring standards that will be applicable for future policies for mitigation of plastic pollution. The recommended harmonised methods will improve the capacity to acquire relevant and standardised knowledge of plastics in the global environment, and of the effects on biota, that can be efficiently compared.

Institute of Marine Sciences of the Italian National Research Council (CNR-ISMAR)

CNR ISMAR currently leads the Scientific Committee on Oceanic Research working group project Floating litter and its oceanic transport analysis and modelling, which focuses on the near-surface ocean dynamics of litter, and aims to improve modelling capabilities to predict marine litter behaviour, and to use remote sensing technologies (from space, aircraft, etc.) to address the marine litter issue. FMML is also addressed within Horizon 2020 and ESA-funded projects. Between 2013 and 2017, large-scale sampling was carried out in the Mediterranean using distance sampling methods, and results highlighted spatial, seasonal (higher density in summer) and interannual variability of litter density. More than 90 % of litter found was plastic, and most objects were smaller than 50 cm. These data were used to feed oceanographic models. In 2016 a monitoring survey was undertaken around Italy on board the Italian navy vessel *Amerigo Vespucci* and a large-scale monitoring transect was performed from Germany to Cape Town. Results showed an increase of litter in the

([6]) https://esamultimedia.esa.int/docs/preparing_for_the_future/Discovery_marine_litter_results.pdf intertropical latitudinal band off the coast of Africa, again highlighting that most of the items were plastic. During the survey, the distance sampling method was compared with the fixed-strip method. Finally, a survey was performed during the Antarctic circumnavigation showing that the circumpolar current could be a barrier to litter, as higher concentrations were found over the subtropical front. Most of the items were fishing related. Preliminary results from a recent survey carried out under projects funded by ESA and Italian Research Projects of National Relevance provided the first quantifications of the capability of the frontal system to accumulate FMML locally.

International Ocean Colour Coordinating Group (IOCCG)

The IOCCG Task Force on Remote Sensing of Marine Litter and Debris ([7]) is an important initiative in support to the international coordination and standardization in the field of Remote Sensing of Marine Litter, which has the overarching goal to coordinate the advancement of current and future remote sensing technologies and techniques that have potential to provide observations of marine plastic litter over all aquatic environments, including their interfaces with land (e.g. coasts, shores, river/lake banks), and land areas in proximity with potential leakage path to water bodies.

Italian Institute for Environmental Protection and Research (ISPRA)

The Italian Institute for Environmental Protection and Research (ISPRA), which acts under the vigilance and policy guidance of the Italian Ministry for Ecological Transition, is involved in monitoring and carrying out research on FMML both in marine water (coastal and high sea waters) and at the mouths of rivers. Under the mandate of the Ministry for Ecological Transition, together with the Italian Regional Environmental Agencies, ISPRA coordinates and implements the MSFD monitoring programme on D10, FMML, within the National System for Environmental Protection.

The European Commission Joint Research Centre (JRC)

The European Commission Joint Research Centre (JRC) is the science and knowledge service of the European Commission. It provides support for MSFD implementation and for international activities beyond the EU. It co-chairs the TG ML, which was set up to provide technical guidance and information to support EU MS in the implementation of the MSFD regarding marine litter. The JRC is leading the efforts of the TG ML to provide an overview, harmonise FMML monitoring and work towards baselines on marine litter in the different environmental compartments. The JRC has (co-)organised two workshops on FMML, led the RIMMEL project, and developed the Floating Litter Monitoring app and the LITTERCAM system.

Marine litter in Europe seas: Social awareness and co-responsibility (MARLISCO)

The Marine litter in Europe seas: Social awareness and co-responsibility (Marlisco) project, financed between 2012 and 2015 by the European Union's seventh framework programme, aimed to raise public awareness, facilitate dialogue and promote co-responsibility among the different actors towards a joint vision for the sustainable management of marine litter across all European seas. Within its activities, the project produced a report summarising the methods for marine litter monitoring and providing general advice for its assessment (Maes and Garnacho, 2013).

Conservation of marine protected species in mainland Portugal (MARPRO)

The Life+ project Conservation of marine protected species in mainland Portugal aimed to define future areas of conservation for cetaceans and seabirds within the Portuguese EEZ. It performed surveys on the Portuguese EEZ from ships using the linear distance sampling method to estimate density and distribution of FMML. Results indicated an average FMML density of three items per square kilometre in the area. The project is currently monitoring beach litter and FMML in the coastal zone and their impacts on marine fauna. Preliminary results indicated that most of the litter observed was made of plastic.

MEDSEALITTER

The MEDSEALITTER project, financed by the Interreg MED programme, started in 2016 with the aim of defining standardised methodologies to monitor marine litter at different spatial scales in the Mediterranean Sea. Within the project, two working groups were formed to focus specifically on litter ingestion (aiming to define sampling and analysis protocols, and indicator species for marine vertebrates and invertebrates) and FMML. The FMML working group put in place several field experiments across the Mediterranean Sea to test and define the parameters needed for the implementation of FMML-monitoring protocols at both large open sea scale (using

([7]) https://ioccg.org/group/marine-litter-debris/

aerial surveys and large vessels) and small coastal/MPA scale (using small and medium-sized vessels, and drones). The results of this testing phase were discussed in a joint workshop with representatives of TG ML and other stakeholders in February 2019, which aimed to define commonly agreed methodologies for FMML monitoring. The common monitoring protocol for marine litter (Medsealitter consortium, 2019) was published and disseminated at the end of the project in summer 2019 (Arcangeli et al., 2020).

National Aeronautics and Space Administration (NASA)

The Interagency Implementation and Advanced Concepts Team (IMPACT) from NASA, part of the US federal government, develops different projects for the detection of marine plastic litter through machine learning on data from the NASA's Cyclone Global Navigation Satellite System (CYGNSS). In 2020, NASA also launched the Research Opportunities in Space and Earth Science (ROSES) call including request for projects on the topic of remote detection, quantification and analysis of marine litter, where three projects directly related to marine litter were funded. Two new ROSES calls in 2021 and 2022 have been published for funding research projects.

National Oceanic and Atmospheric Administration (NOAA) marine debris programme

The NOAA marine debris programme is the US federal government's lead scheme for addressing marine debris. It started in 2006 as the result of an act by the US congress. It includes a series of activities focused on prevention and outreach; removal; and science and research. The most developed programme is the coastal one, which started after the Japanese tsunami of 2011 and moved to a citizen science programme. Guidelines were developed and included in a report (Lippiatt et al., 2013), mainly focused on coastal litter but also giving some recommendations on vessel monitoring. A fishery observer programme started in 2014 to check for by-catch species, and marine litter was found to be a common by-catch in the North Pacific. Litter was mainly caught by Hawai'ian fisheries, which use long lines mainly in deep waters in the subtropical gyre. The marine debris programme joined the fishery observer programme to collect data about litter recovered by long-line fishery. Being opportunistic (i.e. needing minimal investment apart from the observers' training), it allows a great temporal and spatial coverage. The main problems of this programme relate to its non-systematic nature, and the fact that litter is not the priority of observers. Experienced observers are needed to overcome the difficulties in discriminating among items, and avoid biases in results.

PlasticBusters

PlasticBusters MPAs is a 4-year-long Interreg MED project aiming to contribute to maintaining biodiversity and preserving natural ecosystems in pelagic and coastal MPAs, by defining and implementing a harmonised approach against marine litter. The project started in 2018 with the aims of assessing the amount, sources, pathways, distribution and convergence areas of marine litter, and its effects on biota, and of mitigating and reducing its impacts on the MPAs of the Mediterranean Sea.

It consolidates Mediterranean efforts against marine litter by assessing the impacts of marine litter on biodiversity in MPAs and identifying marine litter 'hotspot' areas; defining and testing tailor-made marine litter surveillance, prevention and mitigation measures in MPAs; and developing a common framework of marine litter actions for Interreg Mediterranean regions towards the conservation of biodiversity in Mediterranean MPAs. The project foresees a phase of harmonisation of methodologies, include the transfer of methodologies to the southern countries of the basin and local MPAs through the COMMON project (funded by the European Neighbourhood Instrument cross-border cooperation), and entails actions that address the whole management cycle of marine litter, from monitoring and assessment to prevention and mitigation, as well as actions to strengthen networking between and among pelagic and coastal MPAs.

Project deliverables included a document on the state of the art, compiling current methods to monitor marine litter and its impacts on biodiversity, and aimed at identifying the knowledge gaps that need to be overcome through harmonisation; and a 'Toolkit for monitoring ML and its impacts on biodiversity in Med MPAs', with the overarching aim of providing an operational toolkit for implementing the PlasticBusters MPAs harmonised marine litter monitoring approach.

PLASTREND and MIDaS

Both PLASTREND and MIDaS are projects carried out by the University of Cádiz. PLASTREND aimed to analyse the historical trends of plastic pollution, and predict future trends. MIDaS aimed to estimate the inputs, distribution and fluxes of plastic in the marine environment. A global-scale assessment included a large database on floating litter (Morales-Caselles et al., 2021). Results indicated that the ultimate destination of litter is the deep seafloor. Monitoring activities planned by the two projects involved visual observations and physical sampling of FMML in rivers and at sea. The University of Cádiz also participates in RESMALI and other ESA projects related to remote sensing of marine litter.

Portuguese Space Agency (PT Space)

In 2020 the Portuguese Space Agency launched the Moonshot Challenge([8]) to advance monitoring of plastic litter on a planetary scale, making use of AI and Satellite Data.

Riverine and marine floating macro litter monitoring and modelling of environmental loading (RIMMEL)

The JRC's RIMMEL project was the first-ever European-scale quantification of loads of floating litter to the European seas. It aimed to quantify floating macro litter loads through rivers to marine waters and to model litter loading based on the characteristics of the catchments. The approach was based on a monitoring app developed for tablets and set up for river observation. RIMMEL observations were carried out from bridges close to the river mouth to monitor the litter brought by the river to the sea. A network for observation across the EU (Black Sea, Baltic Sea, north-east Atlantic region and Mediterranean Sea) was built: the Riverine Litter Observation Network (RiLON). Results of the project showed that 82 % of items found in European rivers are plastic, almost half of which are fragments. A model estimated that annually 626 million floating macro litter items are transported by rivers into the sea (González-Fernández et al., 2021).

5.4. Non-governmental organisations

EU MS should report marine litter assessments at the national scale under MSFD obligations. However, in many cases, NGOs provide support to the MS national assessments with the results obtained from monitoring activities at sea. Although most NGOs' activities are oriented to beach litter monitoring, some organisations also address the monitoring of FMML, mainly through visual observations from small and medium-sized vessels (e.g. Legambiente, in Italy, taking part both in the MEDSEALITTER and PlasticBusters projects), or large vessels such as ferries (e.g. the EcoOcéan Institut, in France, taking part in the MEDSEALITTER project, and collecting FMML from ferries for the French Office for Biodiversity for the MSFD; and the Accademia del Leviatano, in Italy, undertaking high sea surveys along regular ferry lines since 2013).

([8]) Moonshot Challenge: https://www.moonshotchallenge.ai/past-editions

6. Conclusions, development needs and future steps

To efficiently address marine litter issues, scientifically sound and fit-for-purpose information from all marine environmental compartments is required. Information about marine litter sources, pathways, density and distribution, composition, and fate are fundamental for planning effective mitigation measures; and a coordinated and consistent monitoring effort is the basis for obtaining such data.

This report provides an overview of the recent developments of FMML monitoring, which are needed for a sound update of the existing monitoring guidance (Galgani et al., 2013), and is the underlying information for providing standardised protocols and improved guidance on FMML monitoring within the European seas and beyond.

Specific advice common to all monitoring approaches can be summarised as follows.

- Spatial and temporal stratification, replication and representativeness must always be considered in the sampling design.
- The minimum sampling area and number of replicates are dependent on the scope of the monitoring and must be defined in the sampling design based on available data on FMML densities in the monitored area.
- The monitoring platform and technique must be selected according to the scale of monitoring (i.e. small vessels and drones are recommended for monitoring coastal areas, while large vessels and aircraft are recommended for open sea areas and basin-scale monitoring), and the available resources (e.g. observers, camera recording systems).
- Only experienced observers must be employed for visual monitoring; standard training for observers should include indications on data collection and identification of items according to the TG ML Joint List of Litter Categories.
- All monitoring approaches are affected by weather conditions. To allow comparison of data, it is recommended that surveys be performed with sea state conditions ≤ 3 on the Beaufort scale and that weather conditions (e.g. wind and waves) always be reported.
- FMML must be classified according to an agreed set of litter categories; to guarantee data consistency, the Joint List of Litter Categories has been prepared by the TG ML. Litter size must be estimated according to common classes, as the minimum size detectable from different platforms may vary.
- The use of mobile applications for data collection is recommended; if that is not possible, simplified data sheets can be used, provided the system of classification of litter is the same as in the TG ML joint list.
- Monitoring efforts must consider the high mobility of FMML in their strategic planning and the monitoring scope definition. The dependency on currents, weather and other environmental conditions might require adaptive monitoring, which might be more easily achieved with automated technologies.
- As a general rule, the need to adopt and implement the same monitoring approach and compatible reporting systems must be further stressed at different organisational levels, to guarantee a comprehensive assessment of FMML and the identification of FMML hotspots (areas of accumulation).
- The implementation of large-scale and long-term monitoring programmes is recommended, and requires a combined effort by MS to produce comparable litter data, which are necessary to assess long-term trends and the effectiveness of mitigation measures.
- On a broader scale, global comparability of monitoring results would enable large-scale prioritisation linked to international priorities such as those defined within the G7 and the G20, and UN Sustainable Development Goal 14.
- New methodologies using automated spectroscopic and imaging techniques need to be further developed and their application should be encouraged, as they could, in the longer term, substantially reduce the costs of monitoring while increasing the spatial scale and limiting the biases related to visual observations.

- In the development of new monitoring methods, the gap between the experimental set-up for a new methodology and its integration into monitoring programmes must be taken into account. This step requires scrutiny and a competitive selection process.

Overall, the development comparable of quantitative and large-scale baselines of FMML's presence, distribution and density is a key element for the holistic assessment of the status of our oceans and seas.

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List of abbreviations and definitions

ACCOBAMS	Agreement on the Conservation of Cetaceans of the Black Sea, Mediterranean Sea and Contiguous Atlantic Area
AI	Artificial Intelligence
AMAP	Arctic Monitoring and Assessment Programme
AMARE	Actions for Marine Protected Areas
ASI	ACCOBAMS Survey Initiative
BSC	Black Sea Commission
CNN	Convolutional neural network
CNR ISMAR	Institute of Marine Sciences of the Italian National Research Council
COMMON	Coastal management and monitoring network for tackling marine litter in Mediterranean Sea
D10	Descriptor 10 of the marine strategy framework directive
DeFishGear	Derelict fishing gear management system in the Adriatic region
EEZ	Exclusive economic zone
EMBLAS	Environmental Monitoring in the Black Sea
EMODnet	European Marine Observation and Data Network
ESA	European Space Agency
EUROqCHARM	European Quality Controlled Harmonisation Assuring Reproducible Monitoring and Assessment of Plastic Pollution
FMML	Floating marine macro litter
GES	Good Environmental Status
GESAMP	Group of Experts on the Scientific Aspects of Marine Environmental Protection
GPS	Global positioning system
HELCOM	Helsinki Convention on the Protection of the Marine Environment of the Baltic Sea Area
IFREMER	Institut Français de Recherche pour l'exploitation de la Mer
IMO	International Maritime Organization
Interreg MED	Transnational European cooperation programme for the Mediterranean area
IOCCG	International Ocean Colour Coordinating Group
IPA	Instrument for Pre-Accession Assistance
ISPRA	Italian Institute for Environmental Protection and Research
JRC	Joint Research Centre
MAP	Mediterranean Action Plan
MARLISCO	Marine litter in European seas: Social awareness and co-responsibility
MPA	Marine protected area
MARPRO	Conservation of Marine Protected Species in Mainland Portugal
MS	Member State
MSFD	Marine Strategy Framework Directive
NASA	National Aeronautics and Space Administration
NGO	Non-governmental organisation

NOAA	National Oceanic and Atmospheric Administration
OSIP	Open Space Innovation Platform
OSPAR	Convention for the Protection of the Marine Environment of the North-East Atlantic
PAME	Protection of the Arctic Marine Environment Working Group
PERSEUS	Policy-oriented marine environmental research in the southern European seas
PET	Polyethylene terephthalate
POP	Persistent organic pollutant
UAV	Unmanned Aerial Vehicle
RAP	Regional Action Plan
RESMALI	Remote sensing for marine litter
RiLON	Riverine Litter Observation Network
RIMMEL	Riverine and marine floating macro litter monitoring and modelling of environmental loading
RNDVI	Reversed Normalised Differenced Vegetation Index
ROMS	Regional Ocean Modelling System
RSC	Regional Sea Convention
R/V	Research Vessel
SVR	Support Vector Regression
SWIR	Short-wave infrared
TG ML	MSFD Technical Group on Marine Litter
UNEP	United Nations Environment Programme

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Annexes

Annex I. General operational characteristics of visual observations reported in scientific studies

Table S1. Operational characteristics of visual observations reported in scientific studies

Platform	Monitoring methodology	Strip width	Observation height	Speed	References
Large to small-sized vessels	Fixed-width strip	7–50 m	1.5–24 m	10–16 knots	Gónzalez-Fernández et al., 2022
Aircraft	Distance sampling	—	183 m	100 knots	ACCOBAMS, 2021a
Aircraft	Distance sampling	—	183 m	100 knots	ACCOBAMS, 2021b
Small-sized vessel	Fixed-width strip	6 m	1.5 m	10–50 m s^{-1}	Curmi and Axiak, 2021
Medium-sized vessel	Fixed-width strip	15 m	4 m	—	Pogojeva et al., 2021
Medium-sized vessel	Fixed-width strip	10 m	—	5 knots	García-Garin et al., 2020
Aircraft	Fixed-width strip	200 m	180 m	90 knots	Lambert et al., 2020
Vessel	Fixed-width strip	—	—	—	Pogojeva et al., 2020b
Large-sized vessel	Fixed-width strip	50 m	8–9 m / 20–22 m	10–14 knots	Suaria et al., 2020
Large-sized vessel	Fixed-width strip	—	9 m	7.28 knots	Campanale et al., 2019
Medium-sized vessel	Fixed-width strip	7 m	2.2 m	2–3 knots	Palatinus et al., 2019
Large-sized vessel	Fixed-width strip	50 m	11 m	8–20 knots	Rothäusler et al., 2019
Large-sized vessel	Fixed-width strip	25–100 m	17–25 m	19–25 knots	Arcangeli et al., 2018
Small-sized vessel	Fixed-width strip	—	—	—	Campana et al., 2018
—	Fixed-width strip	50 m	—	—	Constantino et al., 2018
Aircraft	Fixed-width strip + sensors	—	400 m	140 knots	Lebreton et al., 2018
Large-sized vessel	Fixed-width strip	50 m + 50 m	—	6 knots	Ourmieres et al., 2018
Medium-sized vessel	Fixed-width strip	10 m	< 3.2 m	< 4 knots	Zeri et al., 2018
—	Fixed-width strip	10 m	—	—	Campanale et al., 2017
—	Fixed-width strip	10 m	—	—	Carlson et al., 2017
Small-sized vessel	Distance sampling	—	1.6–1.9 m	15 knots	Currie et al., 2017
Aircraft	Fixed-width strip	200 m	183 m	90 knots	Darmon et al., 2017
Medium-sized vessel	—	—	3 m	6 knots	Di-Méglio and Campana, 2017

Platform	Monitoring methodology	Strip width	Observation height	Speed	References
—	Fixed-width strip	20 m	—	3–5 knots	Fossi et al., 2017
Large-sized vessel	Distance sampling	—	18 m	4.7–12.7 knots	Bergmann et al., 2016
Helicopters	—	—	53–249 m	109–182 km h^{-1}	Bergmann et al., 2016
Medium-sized vessel	Distance sampling	—	6 m	10 knots	Sá et al., 2016
Large-sized vessel	Fixed-width strip	—	12 m	20 km h^{-1}	Miranda-Urbina et al., 2015
Medium-sized vessel	Fixed-width strip	—	4 m	7 knots	Suaria et al., 2015
—	Fixed-width strip	20 m	—	—	Eriksen et al., 2014
Large-sized vessel	Fixed-width strip	50 m	12–15 m	—	Ryan, 2014
Medium-sized vessel	Distance sampling	—	5 m	10 knots	Suaria and Aliani, 2014
Large-sized vessel	Distance sampling	—	10 m	—	Goldstein et al., 2013
—	Fixed-width strip	100 m	—	—	Luperini et al., 2013
Large-sized vessel	Fixed-width strip / distance sampling	50 m	10–13 m	—	Ryan, 2013
—	Fixed-width strip	10 m	—	—	Thiel et al., 2013
Aircraft	Fixed-width strip	—	300 m	100 m s^{-1}	Pichel et al., 2012
Large-sized vessel	Fixed-width strip	20–70 m	11 m / 20 m	5–12 knots	Thiel et al., 2011
Large-sized vessel	Distance sampling	—	10 m	17.6 km h^{-1}	Titmus and Hyrenbach, 2011
—	Fixed-width strip	60 m	—	—	Topcu et al., 2010
Medium-sized vessel	Fixed-width strip	20 m	4 m	10 knots	Hinojosa and Thiel, 2009
Medium-sized vessel	Fixed-width strip	50–100 m	3.8 m	7 knots	Pyle et al., 2008
Aircraft	Sensors	—	305 m	—	Pichel et al., 2007
—	Fixed-width strip	50 m	—	—	Aliani et al., 2003
	Fixed stations	200-m radius			
Small-sized vessel	Fixed-width strip	10 m	1 m	4–10 knots	Thiel et al., 2003

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