Detection of exogenous floating marine debris: an overview of techniques associated with remote sensing

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Abstract

Exogenous floating marine debris (EFMD) is a worldwide concern and its ubiquitous characteristics and long-term threat have raised calls for new venues to enable easier and prompt detection at large. The main focus of this paper is to evidence search and detection methods for EFMD using remote sensing techniques. This paper contributes to update research information in the topic under scrutiny and to screen for possible gaps to mitigate EFMD impacts. Several needs for research were found, and, before any work to establish the ground truth could take place, a spectral library model for EFMD going through several stages of biofouling must be created using passive or active research methods. Search methods need to be automated using empirical models based on stratified set-ups previously tested. Several sensors show potential for an indirect search for EFMD, but direct detection of EFMD using multispectral and radar instruments still needs further research through integration with conceptual and empirical modeling techniques.
Keywords: floating debris, marine debris, marine litter, remote sensing, search techniques, detection techniques, indirect and direct methods.

1 Introduction

Because the use of the term exogenous floating marine debris (EFMD) is found in the literature to be synonymous with very distinct concepts such as, exogenous floating debris, floating marine debris, floating debris, and marine debris, a definition for these concepts should be a prime consideration. EFMD can be defined as solid materials of human or land origin that in some way reach the sea and, due to its long-term buoyancy characteristics, stay afloat for a period of time

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long enough to have an impact on human or faunal populations and their habitats. Contrary to EFMD, exogenous floating debris (EFD) can reach any water body. Floating marine debris (FMD) is EFMD associated with organic debris produced within the oceanic system, such as, algae or shells. Floating debris (FD) is these EFD associated with organic debris originated or not within the marine system itself. Marine debris (MD) comprehends all debris found in any non-freshwater body, independently of its origins, characteristics, and permanency in the medium under consideration.

A wide scope of the known negative impacts of EFMD is present in the literature, but the most pressing and maybe not yet completely understood are those which might lead to up-down, bottom-up and horizontal effects through populations and ecosystems. An example of a possible unforeseen case of food-chain disruption with negative lateral consequences is when plastic micro-particles are physically absorbed by at least one of its elements. For instance, zooplankton feeding capability [1] and algae photosynthetic production are impaired [2] if such occurs. This is only the tip of the iceberg for the connection between EFMD pollution and marine environmental health, since, according to Moore *et al.* [3], dramatic findings of 6:1 particulate plastic/neuston ratio was found for the North Pacific.

Anther physical negative expression of EFMD presence is related with specific habitats or its users, which, for instance, is differentiated positively to threatened habitats and populations. Examples of known effects on individuals and populations are as follows: the disruption of satiation, feeding and breeding mechanisms [4, 5], entanglement [6–11], and the spread of exotic and dangerous organisms [12, 13]. Moreover, the decrease of tourism and fishing activity [14, 15] and the increase of accidents at sea are also a concern [5].

The major accumulation and sinking areas for the EFMD are relatively well studied by, for example, Howell *et al.* [16], Martinez *et al.* [17], and Pruter [18]. They raised some light on the accumulation of EFMD in gyres ("garbage patches") and other hot spots as a result of the convergence of oceanic currents. For instance, taking into account meso- and large-scale spatial variability, Howell *et al.* [16] and Martinez *et al.* [17] studied the mechanisms associated with the EFMD concentration, transport and retention in some of those convergence zones for, respectively, the North Pacific and the South Pacific. Morishige *et al.* [19] found also a more seasonal effect related with a quantitative relationship between EFMD deposition on the French Frigate Shoals and the El Nino/El Nina phenomenon.

Because EFMD show a wide range of sizes [20–22] and is of distinct origins and compositions [20, 23–26], its aggregating and distribution patterns, influenced by systemic trendy variation in the ocean wind stress and heat patterns, vary through time and are also location dependent. Besides, fouling communities on floating debris change through the oceanic permanence time and contribute also towards its detection problem by changing its buoyancy, floating stability [27], and even reflectance characteristics. Of course, all of these aspects make the detection of EFMD challenging and so there is a need to look for new break-through scientific approaches.

The significant costs associated with direct sampling techniques, i.e., associated with direct "field work" in a given study area, have made it prohibitive to implement them worldwide in a systematic approach. Moreover, with the advent of an increasing number of remote sensing and modeling applications being made available at increasingly low costs, changes in the methodological techniques of search and detection of EFMD must be observed. These alterations should create a synergist point break, necessary to rise a more demanding rational to have readily available outputs to, e.g., easily monitor illegal dumping, monitor outputs resulting from environmental disasters, improve rescues at sea in case of ship or plane accidents, and implement efficient collection methods for EFMD.

Even knowing that both the surveying methods associated with the water column, sea-bottom, and beaches, and species indicators and habitats are indirect proxies to study EFMD dynamics, these methods, unless a remote sensing technique is used, are not referred to in this paper because they include a vast range of dispersive methodologies that cannot be aggregated lightly under the remote sensing umbrella.

Taking into account that the research question defined for this paper is, *Can remote sensing help mitigate negative impacts of EFMD on oceanic systems?,* the present paper aims, one the one hand, to make a brief overview of some search and detection strategies present in the literature and associated with remote sensing technologies. On the other, a complementary section of recommended research aspects designed to understand EFMD dynamic behavior is presented. The paper is divided as follows: after the definition of objectives in the introductory part, a brief overview of search and detection techniques (definitions and historical overview) is introduced, and the work ends with a discussion section and the conclusions.

2 Search and detection techniques for EFMD: definitions

Before starting to describe some of the search methodologies found in the literature, it is important to define some of the terminology used, such as: direct *versus* indirect methods, object oriented *versus* proxy oriented detection, and active *versus* passive methodologies.

While direct methods use visual or aided visual inspection to locate debris, which, once found, can be readily removed or not from the affected area, indirect methods, which are usually used to aid clean-up crews, are very diverse in nature and can use a wide array of approaches relying on a given proxy for EFMD search or detection. Some examples of the latter are, forecasting and eddy detection methods, the prospection of biological or specific habitats to use as indicators of the EFMD quantity and quality, and methods of integration concerning previous knowledge about the system (Table 1). Any of the direct and indirect methods can be used within the context of other methods such as, object or proxy detection, and active or passive methodologies. Direct detection techniques for beach and sea bottom MD are, within the EFMD context, considered as indirect techniques. While examples of direct techniques for beach sediments using aerial photographs [28–30] or uniform color space aerial photographs to detect plastic [31] are present in the literature, direct search and detection for sea bottom MD usually focus on coral reef health studies (e.g., Dameron *et al.* [32]). However, the greatest problem related with beach, water column and sea-bottom indirect techniques to understand EFMD behavior relies on the lack of diffusion models with well-defined rates and processes between the diverse components of the systems at hand, i.e., beach, sea-bottom, water column, and open sea surface water.

Object oriented methods of search and detection, as foreseen by their nomenclature, are those targeted to detect directly or indirectly the EFMD through the use of a given detectable MD object. Proxy oriented methods use surrogates to understand EFMD dynamics (*e.g.*, use of an indicator for plastics, such as, Northern fulmars [33]), and, as with object oriented methods, can be understood within an active or passive context. Active and passive methodologies are associated, respectively, with those requiring or not an *in loco* experimental approach to be addressed.

Spatial sampling can be systematic or stratified. The systematic method is usually used for systems where little previous knowledge exists and an efficient sampling of the study area is primordial [34]. It is within this methodology, that the tessellated hexagons technique was developed by White *et al.* [35] to preserve an equal area grid approach [34]. Stratified sampling usually uses indirect methods of search and detection to focalize the effort within a search area [34].

3 Search and detection techniques for EFMD: historical overview

Due to the comparative dimension of the EFMD and the ocean, not only the detection techniques to be used in any study need to be evaluated punctually, but the search approach, which cannot be forgotten as an important effort constraint for each area under surveillance, must be carefully chosen. Several search and detection approaches have been found in the literature associated with remote sensing techniques (Table 1). Among the indirect methods we have the following with interest for a remote sensing discussion: ocean modeling using Lagrangian drifters, and eddies behavior and algae accumulation using altimeter information, Light Detection and Ranging (Lidar), and Synthetic Aperture Radar (SAR) data. Several oceanic circulation models have been established to overview back- and forward-casting of EFMD distribution paths, accumulation sinks, and environmental forcing constraints [36, 37]. The techniques provided global or regional settings for circulation by relying on several sources of information such as water temperature and surface winds satellite data to model possible dispersion paths, and buoys, Lidar or SAR imagery for eddy detection.

Within this context, Leberton *et al.* [36] created, based on realistic scenarios, a global ocean circulation model coupled to a Lagrangian particle-tracking set-up to simulate several years of input, transport and accumulation of floating debris. A random walk with separated lateral and longitudinal coefficients was used in

Table 1: Examples of remote sensing studies classified for EFMD, using distinct approaches of search and detection.

Detection methods	Search methods	MD/species/ habitat types	Study area	Study objective	Remote sensing imagery used	Reference
Indirect, passive	Object oriented	Macroplastic debris, beaches	Tobishima island, Japan	Detection of plastic pixels of any color	Webcam	Kataoka *et al.* [31]
	Proxy oriented	Depth, habitat classification – proxies for coral reefs area	Nothwestern Hawaiian islands, USA	Estimate MD accumulati on	IKONOS	Dameron *et al.* [32]
	Proxy oriented	Chlorophyll-a, surface temperature - eddies detection	Senegal, West Africa	Eddies detection	Aqua/ MODIS AVHRR/ ASAR	Alpers *et al.* [38]
Direct, passive	Object oriented	tsunami EFMD	Okirai bay, Japan	EFMD detection by size and estimate velocity	ALOS PALSAR	Arii *et al.* [39]
		tsunami EFMD	Tohoku, Japan	EFMD detection	Terra/ MODIS	Aoyama [40]
		metallic objects	Atlantic Ocean, off Brazilian coast	crashed aircraft detection	X-band COSMO-SkyMed	Paes *et al.* [41]

this study to simulate turbulence. Maximenko *et al.* [42] used a global set of trajectories of satellite-tracked Lagrangian drifters to study worldwide EFMD dynamics. They took into account the geography and specificities of accumulation zones under study. This approach illustrated the combined effect of the floating object geometry, the wind and upper-oceanic currents. Using a global ocean model (HYCOM/NCODA) to simulate the transport and accumulation of 2011 Japanese tsunami floating debris, Leberton and Borrero [43] found its provable accumulation in the North Pacific subtropical gyre. Reahard *et al.* [44], on other hand, created fore- and backtracking simulations using satellite based sea surface height and height anomaly to assess sources and transport of EFMD at sea.

Pichel *et al.* [45], within the GhostNet project, used, besides a circulation model, wind and current models associated with tagged buoys to determine convergence areas for EFMD. Pichel *et al.* [46] developed a likelihood estimate of encountering concentrations of MD in a specific area – debris estimated likelihood index (DELI) – using a combination of sea surface temperature, chlorophyll-a and chlorophyll-a gradient. However, and according to Morishige and McElwee [47], ground-truthing is a gap inherent of this model.

Under the remote sensing array, and within an object oriented search and detection classification for EFMD, one of the most important aspects for consideration is the imagery type. The passive sensors use the energy reflected or emitted by the objects, and can vary from: RGB (red, green, blue) video, digital cameras, multispectral and hyperspectral sensors, thermal imagers [48], and Moderate Resolution Imaging Spectroradiometer (MODIS) [40]. An aspect to ponder when selecting a sensor is, taking into account the characteristics of the EFMD to detect, the existence of a trade off between spatial coverage and spatial resolution. RGB video has an important weakness by presenting a false detection rate related to the intrinsic variability in light and surface characteristics [48]. Mutispectral sensors, by presenting seven bands, might, according to Veenstra and Churnside [48], turn out to be useful in detecting EFMD. Hyperspectral cameras with thirty bands, and spectral resolution of 10 nanometers or less, show also some promising attributes to detect EFMD in shallow waters [48]. The thermal imagers detect heat radiated at 3–5 or 7–14 micrometer wavelengths bands, but did not perform very well with, at least, derelict fishing gear [48].

After the 2011 earthquake off the Japanese Pacific coast, earth observation satellites were used to monitor the damage caused by the disaster and to monitor the tsunami EMFD [40]. Aoyama [40] used pseudo-color images R:G:B – band1: band2: band1 – from Terra/MODIS with a spatial resolution of 250 m to detect them. He proposed, in this way, a method to identify EFMD using two-dimensional scatter diagrams for the chosen spectral bands. The drawback for the MODIS usage is related with its sensitivity to weather and daytime conditions, and by presenting a lower spatial resolution than SAR. Harris *et al.* [49], using multispectral imagery from WorldView-2, complemented this information by creating a spectral library for some EFMD usually found at sea.

A few examples of active sensors used to detect EFMD are, Lidar and radar. Green laser Lidar showed auspicious results to detect differential algae clumping patterns [45], while fluorescence Lidar is promising to detect phytoplankton [48]. SAR, phased array L-band SAR – PALSAR – mounted on the Advanced Land Observing Satellite – ALOS – was used by Arii *et al.* [39] to sense tsunami EFMD, since its imagery is characterized by, regardless of the weather and time of day, a higher resolution than MODIS with flexible operability. According to those authors [39], the swath width of no more than 200 km should be taken into account when monitoring EFMD and the resolution should be 50 m or less. However, when detecting small isolated debris a fine resolution of less than 10 m should be considered.

4 Discussion

It is particularly important to conjointly use distinct types of remote sensing sensors for search and detection of EFMD since, in this way, the differential positive characteristics of each method are potentiated [34, 48]. However, according to Mace [34], a crucial step is associated with the development of a strata approach of search and detection for a successful EFMD clean up strategy. Direct methods for EFMD, using multispectral and radar instruments, reached a stall with storm-related items, but a new urge of research was found based on indirect search and detection methods for EFMD based on the differential algae clumping patterns on eddies. This trend is reassured by a clear concentration of research on the behavior of eddies around the world for the last years (e.g., Crawford *et al.* [50], Karimovaa *et al.* [51], Liu *et al.* [52], and Rogachev [53]) and this residual knowledge might mark a later trend for EFMD detection and search techniques. However, still further investigation is needed to follow the promising role of indirect measurements for EFMD search and detection. Indirect methods of EFMD search relying on Lagrange settings are useful to understand the underlying aspects of its distribution and concentration, but unless the techniques are implemented in a regional setting, such as is done in the works of Pichel *et al.* [45], Reahard *et al.* [44] and Yoon *et al.* [54], its interest for implementing clean up strategies and understanding EFMD patchiness behavior in the water column is limited within a remote sensing framework.

Studies of biofouling on EFMD are now going under a rising bloom of research and have been taking two main venues to understand the following: (1) succession time frames associated with it [55–59] and (2) its impact on the EFMD intrinsic capabilities to withstand on the surface water [27, 56, 57, 60]. All those aspects are important to predict EFMD behavior and to better target the methods used for search and detection. However, unless spectral signatures are obtained for all the phases of EFMD residence at sea, its use, within a remote sensing setting, might be limited. Spectral signatures for plastics are under scrutiny for a near infrared aperture [61, 62], but, for an effective remote sensing setting, a need for the full spectrum of all EFMD is crucial to further deepen the research in this area.

5 Conclusions

It is important that efforts be directed to collect all instances of EFMD before it particulates and further damage in the oceanic system occurs. The focus, on the light of EFMD, must be concentrated on the behavior, distribution and techniques used for its search and detection. Many more studies need to be undertaken in looking for cost-effective and easy-to-implement techniques for the search and detection of EFMD, so a call for research in this area is still in place. Thus, various aspects related with EFMD still remain in the work, and, among those, two are very promising for future research: (1) to study the intrinsic and extrinsic spectral behavior of EFMD taking into account all the aspects that may demise its prompt location at sea using a remote sensing setting, and (2) conceptual and empirical modeling for all the aspects concerning EFMD search and detection. Besides, the successful method for EFMD detection must resolve the issues related with the daunting task of distinguishing between them and the surrounding environment, by dealing with the fouling dynamics, and, according to McElwee *et al.* [63], partially submersed objects, sea state (e.g., white caps), solar reflectance and other non-target items.

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