Who's better at spotting? A comparison between aerial photography and observer-based methods to monitor floating marine litter and marine mega-fauna.

Odei Garcia-Garin[1,*], Alex Aguilar[1], Asunción Borrell[1], Patricia Gozalbes[2], Agustín Lobo[3], Jaime Penadés-Suay[2], Juan A. Raga[2], Ohiana Revuelta[2], Maria Serrano[1] and Morgana Vighi[1]

[1]Department of Evolutionary Biology, Ecology and Environmental Sciences, and Institute of Biodiversity Research (IRBio). Faculty of Biology. University of Barcelona. 08028 Barcelona. Spain. [*]odei.garcia@ub.edu

[2]Cavanilles Institute of Biodiversity and Evolutionary Biology, Science Park, University of Valencia, PO Box 22085, 46071 Valencia, Spain.

[3]Instituto de Ciencias de la Tierra "Jaume Almera" (CSIC), Lluis Solé Sabarís s/n, 08028 Barcelona, Spain.

Abstract

Pollution by marine litter is raising major concerns due to its potential impact on marine biodiversity and, above all, on endangered mega-fauna species, such as cetaceans and sea turtles. The density and distribution of marine litter and mega-fauna have been traditionally monitored through observer-based methods, yet the advent of new technologies has introduced aerial photography as an alternative monitoring method. However, to integrate results produced by different monitoring techniques and consider the photographic method a viable alternative, this 'new' methodology must be validated. This study aims to compare observations obtained from the concurrent application of observer-based and photographic methods during aerial surveys. To do so, a Partenavia P-68 aircraft equipped with an RGB sensor was used to monitor the waters off the Spanish Mediterranean coast along 12 transects (941 km). Over 10000 images were collected and checked manually by a photo-interpreter to detect potential targets, which were classified as floating marine macro-litter, mega-fauna and seabirds. The two methods allowed the detection of items from the three categories and proved equally effective for the detection of cetaceans, sea turtles and large fish on the sea surface. However, the photographic method was more effective for floating litter detection and the observer-based method was more effective for seabird detection. These results provide the first validation of the use of aerial photography to monitor floating litter and mega-fauna over the marine surface.

Keywords: remote sensing, aerial surveys, marine pollution, marine vertebrates, seabirds, Mediterranean Sea.

Highlights

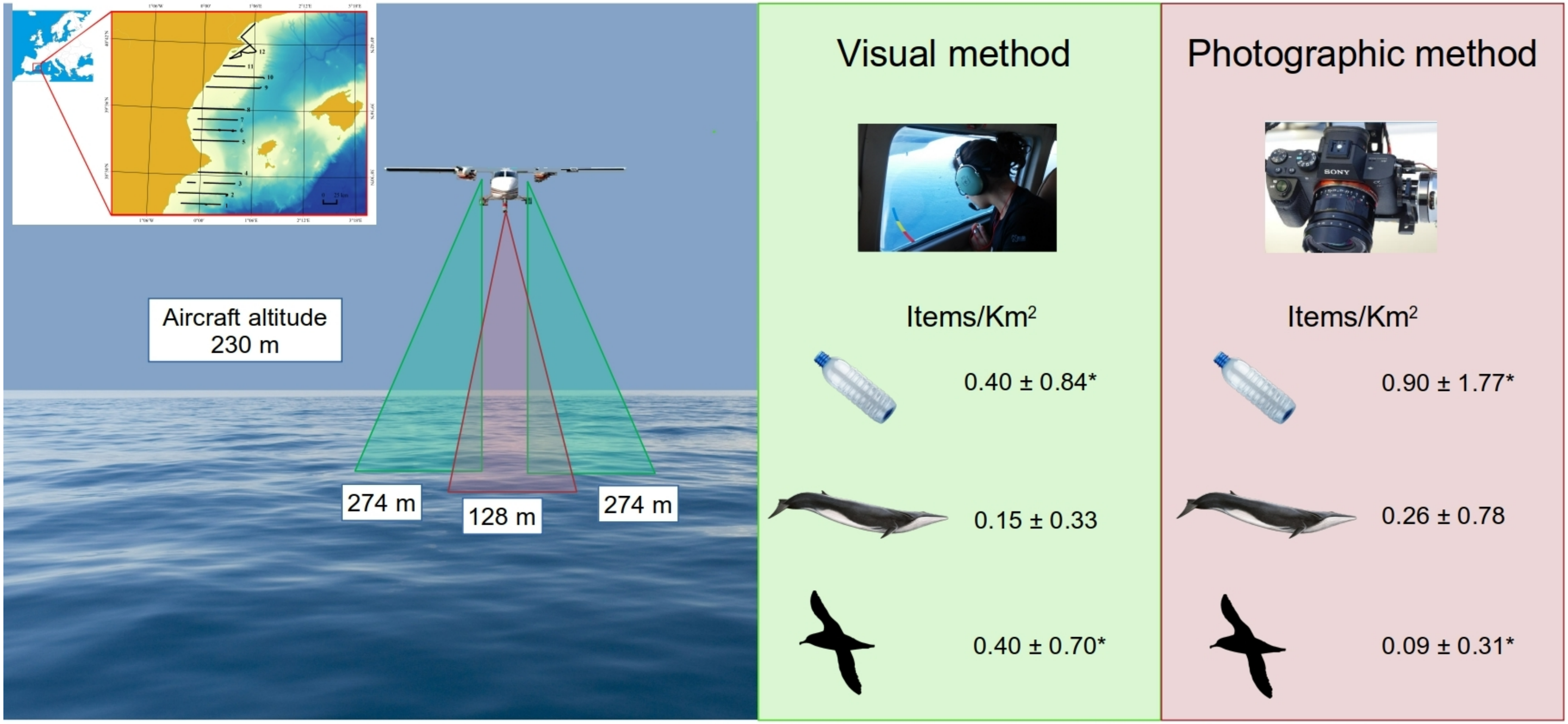
1. We compared results from concurrent visual and photographic aerial surveys.

2. The two methods are equally effective to detect cetaceans, sea turtles and large fish.

3. The photographic method proved more effective to detect floating marine macro-litter.

4. The visual method proved more effective to detect low densities of seabirds.

5. Results encourage using photographic methods to monitor marine litter and mega-fauna.



* Significant differences ($p < 0.05$, Wilcoxon's signed rank test)

1. Introduction

Floating marine macro-litter (FMML, *i.e.*, items larger than 2.5 cm in length, Galgani et al., 2013) can cause severe injuries to marine organisms; entanglement and/or accidental ingestion has been reported in various species of marine birds (*e.g.*, Van Franeker et al., 2011), cetaceans (*e.g.*, De Stephanis et al., 2013; Di-Méglio and Campana, 2017), turtles (*e.g.*, Camedda et al., 2014; Domènech et al., 2019) and fish (Boerger et al., 2010). Due to the ever-increasing pressure from marine litter, a number of regional, national, and international legislative regulations recommend an increase in monitoring efforts and the development of efficient and standardized methods to monitor FMML and its impacts on marine organisms. The systematic collection of data on the abundance, distribution and trends of FMML and mega-fauna would contribute to the identification of potential risk areas/seasons and to a better assessment of the magnitude of this threat.

FMML and marine fauna have been traditionally monitored through observer-based methods, either applied from marine platforms such as ferries and other kinds of vessels (*e.g.*, Arcangeli et al., 2017; Di-Méglio and Campana, 2017; Fortuna et al., 2007; Suaria and Aliani, 2014) or from manned aircraft. Observer-based aerial surveys have been extensively used in terrestrial environments and are widely used to monitor the abundance and distribution of FMML and mega-fauna in the sea (*e.g.*, Brooke et al., 2015; Gómez de Segura et al., 2007; Hodgson et al., 2013; Lecke-Mitchell and Mullin, 1997; Unger et al., 2014). However, the accuracy of the data obtained through observer-based methods may present some biases, mainly related to the experience and training of the observers (Colefax et al., 2017; McEvoy et al., 2016),

During the last decade, manned aircraft and unmanned aerial vehicles (UAVs) equipped with different types of cameras have been widely employed to monitor marine fauna worldwide, including seabirds (Büttger et al., 2015), sea turtles (Gordon et al., 2013), harbour seals (Hoeschle et al., 2015), harbour porpoises (Williamson et al., 2016), dugongs (Hodgson et al., 2010), and several other cetacean species (Gibbs et al., 2019). In addition, infrared cameras, RGB video cameras and LIDAR installed in manned aircraft have allowed the detection and monitoring of, among other things, derelict nets in the Gulf of Alaska (Pichel et al., 2012), FMML within the "Great Pacific Garbage Patch" (Garaba et al., 2018; Gibbs et al., 2019; Lebreton et al., 2018), macro-litter on beaches (Nakashima et al., 2011) and oil spills (*e.g.,* Bradford and Sanchez-Reyes, 2011; Leifer et al., 2012). In addition, satellite imagery will also represent a useful tool for monitoring the sea surface in the near future (Cubaynes et al., 2018; Topouzelis et al., 2019).

However, the areas covered by photographic surveys are generally smaller than those that could be covered by observer-based surveys performed using distance sampling methods (Buckland et al., 2001, Buckland et al., 2015), which have no limitations related to the storage space or battery charge duration of the recording systems. Moreover, despite the wide use of aerial photography for monitoring purposes and the great efforts to develop suitable algorithms for the analysis of the very large number of images obtained (Goddijn-Murphy et al., 2018; Kylili et al., 2019), the currently available algorithms for the automated detection and identification of FMML in aerial images are still far from perfect, and the analyses are still often performed manually.

However, despite the disadvantages presented above, the use of aerial photography provides major benefits over traditional observer-based surveys, including 1) an increase in accuracy, as the survey area can be precisely designated *a priori* or determined *a posteriori* from the images, and the exact size of the targets can be calculated when the image ground sampling distance (GSD) is known; 2) a reduction in human error, as the images provide a permanent record, which allows subsequent re-analysis by multiple photo-interpreters to check doubtful targets and to answer further scientific questions; and

3) a reduction in human safety risks and costs, because during photographic surveys, only the pilot and possibly a camera operator have to board the aircraft; the trained personnel time is reduced, and the processing time could be further reduced by applying automated algorithms (Thaxter and Burton, 2009).

For these reasons, aerial photography methods are likely to detect higher densities of FMML and mega-fauna and are increasingly used for monitoring programmes. However, as most of the available data and information included in the baseline studies have been collected through observer-based surveys; to allow the integration of data obtained through photographic methods into existing observer-based databases, it is essential to test whether the results obtained from these two methodologies are comparable.

The aim of this study was to compare the FMML and marine mega-fauna observations produced by concurrent observer-based and photographic aerial surveys to validate the use of aerial photography to monitor the marine surface. The results of such a validation would allow a step forward in the assessment of the long-term trends of the FMML distribution and its potential impacts on marine biodiversity.

2. Materials and methods

2.1. Flight planning

The concurrent observer-based and RGB photographic aerial surveys were performed from a high-wing aircraft (Partenavia P-68) equipped with bubble windows over the waters off the Mediterranean coast of Spain. The surveys took place in an area located between the Ebro River Delta and the province of Alicante, with depths ranging from 10 to 1300 m (Fig. 1). The flights were performed at a constant groundspeed of 90 knots (166 km h^{-1}) and a constant altitude of 230 m (750 ft), which is the minimum flight altitude based on local legislation and allows the detection of objects larger than 30 cm (Gómez de Segura et al., 2006; MEDSEALITTER consortium, 2019). A large number of seabird species (*e.g.*, the Balearic shearwater and the European storm petrel), when floating on the sea surface, are smaller than 30 cm, which is the smallest detectable size for the two methods in this study and could lead to an underestimation of relatively small birds. The surveys were conducted over 4 days in March 2018 along 12 transects. Three groups of transects (1:4, 5:8, and 9:11), established during three full working days, were equidistant and perpendicular to the coast, while transect 12 was partially parallel to the coast to guarantee suitable monitoring of the Ebro River Delta and its possible effects on FMML accumulation (Fig. 1, Table S2). The FMML, mega-fauna and seabirds were surveyed throughout all the transects, except for transect 12, on which seabirds were not considered.

2.2. Observer-based survey

The standard team for the observer-based survey included two experienced observers, one at each side of the aircraft, and a person in charge of recording the information collected by the observers. The FMML was monitored within two fixed strips of 274 m, one for each side of the aircraft. Only those objects within the strips were recorded, and the observations from the two strips were merged together for analysis (MEDSEALITTER consortium, 2019) (Table 1). The strip width was estimated using a hand-held inclinometer by considering the area between 90º and 40º (the observable area within 274 m from the transect line at an altitude of 230 m). Coloured tape marks were placed on the windows to delimit the area of observation. For the mega-fauna observations, the distance sampling method (Buckland et al., 2001) was used: the angle between the horizon and the observed individual was determined using a hand-held clinometer to estimate its perpendicular distance. However, only the mega-fauna sightings recorded within 90º and 40º on the two sides of the aircraft were included in the analyses to obtain comparable density results.

When the observers reported a sighting, the data recorder took note of the time, the position (obtained with a GPS), and either the category and number of FMML items or, in the case of marine mega-fauna sightings, the species, number of individuals and the angle of observation. The environmental conditions, including the Beaufort sea state, amount of sun glare (categorized as 0 (0-25 %), 1 (25-50 %), 2 (50-75 %) and 3 (75-100 %)), and cloud cover were also updated at the beginning of each transect and whenever any change occurred.

2.3. Photographic survey

The camera used for the photographic survey was a Canon EOS REBEL SL1, placed under the aircraft in the nadir position. The camera, connected to the GPS signal of the aircraft, was set to take a picture every two seconds, with fixed settings: 5.6 focal length, 800 ISO and 1/2000 seconds shutter speed. The image footprint (1A and 1B) and GSD (2) were calculated as follows:

$$(1A)\ Across - track\ footprint = \frac{Flying\ height(mm)}{Focal\ lenght(mm)} * (\text{Sensor width (pixels)} * \text{Pixel size (mm)})$$

$$(1B)\ Along - track\ footprint = \frac{Flying\ height(mm)}{Focal\ lenght(mm)} * (\text{Sensor height (pixels)} * \text{Pixel size (mm)})$$

$$(2)\ GSD = \frac{\text{Sensor width (mm)} * \text{Flying height (m)} * 100}{\text{Focal lenght (mm)} * \text{Sensor width (pixels)}}$$

Onboard the aircraft, a person was in charge of operating the camera from a tablet through the Waldo Flight Control System software. As images were taken every two seconds at a speed of 90 knots and an altitude of 230 m, there was a gap of 7.6 m between consecutive images. Consequently, the area covered by the photographic transects was smaller than that covered by the visual transects, which was accounted for in the density calculations (Table 1).

To reduce error, it is recommended that at least three researchers inspect images separately, and if the three detection estimates differ by less than 10 %, the final estimate is calculated as the arithmetic mean of the three values. However, given the high number of images obtained in the present study, only one experienced photo-interpreter manually reviewed the images to detect and identify the targets. Doubtful target identifications were checked by a second researcher to confirm potential detections. The average time dedicated to the visual analysis of each image was 20 seconds, leading to an overall effort of approximately 56 hours for the inspection of all the images.

2.4. Classification of the detected targets

The targets detected through both methods were classified into three main categories: FMML, mega-fauna (*i.e*., cetaceans, marine turtles and sunfish) and seabirds. The seabirds were not identified to species and were analysed separately due to their different behaviour relative to other mega-fauna. Floating liquids (*e.g.*, oil and foams), organic matter and unidentified items were not included in the analysis of the FMML.

The FMML was classified by category and composition according to the master list for floating objects proposed by the Technical Subgroup on Marine Litter within the Marine Strategy Framework Directive (Galgani et al., 2013), which was modified according to the guidelines provided by the Interreg MED MEDSEALITTER project (MEDSEALITTER consortium, 2019; see Table S1).

2.5. Statistical analysis

The sampling units were created by grouping 9.3 linear km along each transect, a length encompassing 100 images. However, if the total length of the transect was not an exact multiple of 9.3 km, the excess area was grouped together with the adjacent sampling unit, and a larger sampling unit was created. Each image/observation was associated with a given sampling unit on the basis of its respective GPS coordinates. The densities of the targets detected within each sampling unit were calculated as items/km^2 (Table 1).

The normality and heteroscedasticity of the distribution of the densities detected through the two methods were tested across sampling units for each category (FMML, mega-fauna and seabirds) using Shapiro-Wilk and Levene tests, respectively. The densities of the three categories did not follow a normal distribution ($p < 0.0001$, Shapiro-Wilk test). The density variances were homogeneous for the FMML ($p = 0.1$, Levene test) and mega-fauna ($p = 0.5$, Levene test) but not for the seabirds ($p = 0.0001$, Levene test). Thus, the densities of the FMML, mega-fauna and seabirds observed by the two methods were compared across the sampling units using a paired-sample Wilcoxon signed-rank test. The densities of the different categories of FMML detected using the two methods were also compared through a non-parametric paired-sample Wilcoxon's signed-rank test. Finally, Spearman's correlation test was used to assess the correlation between FMML density and the distance from the coast and to test whether the two methods could detect such correlations similarly. A $p < 0.05$ significance level was used for all the statistical analyses. The calculations were carried out within the R programming environment (R Core Team, 2014).

3. Results

The environmental parameters and densities of the FMML, mega-fauna and seabirds were variable across the transects, as summarized in Table 2. According to the MEDSEALITTER protocol for FMML aerial monitoring, surveys should be performed with a Beaufort state less than or equal to 3 (MEDSEALITTER consortium, 2019). This condition was satisfied in most transects except for transects 10 and 11, and the sun glare intensity was generally low except for transects 10, 11 and 12. Although the transects established with a Beaufort force > 3 and strong sun glare should not be used to determine the FMML distribution and abundance, we included these results in the comparison between the two methods, assuming that they would be affected in a similar way.

3.1. Observer-based survey

A total of 458 targets were detected in the 515 km^2 survey area (Fig. 2 A). The targets mainly consisted of plastic litter items (45.41 %, including unidentified items, buoys, boxes, aggregated plastics, bags, buckets and fish boxes), followed by seabirds (38.65 %), and mega-fauna (15.94 %, represented by sunfish (*Mola mola*), sea turtles (*Caretta caretta*), striped and bottlenose dolphins (*Stenella coeruleoalba* and *Tursiops truncatus*, respectively), Risso's dolphins (*Grampus griseus)*, and Cuvier's beaked whales (*Ziphius cavirostris*)).

3.2. Photographic survey

The images spanned 5184 x 3456 pixels each, and their footprint and GSD were 128.2 m x 86.46 m and 2.5 cm/pixels, respectively. A total of 135 targets were detected in the 10119 images acquired (Fig. 2 B), 71.9 % of which were plastic litter items (most of which were unidentified items and aggregated patches and buoys followed by bags and boxes), 20.7 % of which were mega-fauna (including sunfish, sea turtles, Risso's dolphins and Cuvier's beaked whale), and 7.4 % of which were seabirds. Examples of the vertical images of FMML, mega-fauna and seabirds are shown in Fig. S1.

3.3. Method comparison

The FMML, mega-fauna and seabird densities were compared via a paired-sample Wilcoxon's signed-rank test. The median of the differences between the photographic and observer-based methods across the sampling units was not significantly different from zero for the mega-fauna (p = 0.75; Fig. 3 C & D). However, a statistically significant difference was observed for the FMML, which had a higher density when using the photographic method (p = 0.01; Fig. 3 A & B), and seabirds, which were better detected by the observer-based method (p = 0.0001; Fig. 3 E & F) (Table 2).

The densities of unidentified plastics, aggregated patches and bags detected through the photographic method were significantly higher than those detected through the observer-based method (p = 0.01, p = 0.02, and p = 0.04, respectively, paired-sample Wilcoxon's signed-rank test) (Table 3). However, the densities of buoys, boxes, buckets and fishing boxes detected through the two methods did not statistically differ (p = 0.36, p = 0.13, p = 0.06, and p = 0.37, respectively, paired-sample Wilcoxon's signed-rank test) (Table 3).

The FMML density detected through the observer-based method was inversely correlated with the distance from the coast ($\rho = -0.36$, p = 0.0003, Spearman's correlation test), but the same correlation was not statistically significant for the FMML density obtained through the photographic method ($\rho = -0.19$, p = 0.056, Spearman's correlation test).

4. Discussion

The comparison between the observations obtained through the photographic and the observer-based surveys produced three main results: 1) the photographic method is more effective than the observer-based method for detecting FMML on the sea surface; 2) both methods are equally effective for detecting cetaceans, marine turtles and sunfish; and 3) the observer-based method is more effective than the photographic method for detecting seabirds.

4.1. Floating litter

Aerial monitoring of FMML can be significantly affected by factors such as time of day, sun glare, cloud covering, sea state and wind speed, which may have significant effects on the possibility of detecting floating targets (Colefax et al., 2017). Automatic detection of FMML is also made difficult by its irregular shape and the effect of changing weather conditions on the images (Maire et al., 2013), even though some researchers have recently presented new algorithms that may solve these issues (*e.g.*, Goddijn-Murphy et al. 2018, Kylili et al., 2019).

The majority of our surveys happened with a positive sea state and sun glare conditions, allowing the detection and identification of several categories of FMML through both methods. However, the litter densities detected through aerial photography across the sampling units were on average 2.25 times higher than those detected visually, highlighting a better efficiency of the photographic method.

The observer-based method allowed the identification of more FMML categories than the photographic method, but overall, the densities of unidentified and aggregated items detected by the photographic method were higher. This result may be interpreted as a consequence of the fact that, depending on the conditions in which the photos are taken, floating targets may be better identified by the human eye in real-time than from photographic images. However, as the photographic method allows checking the images several times by multiple photo-interpreters, a higher number of items was detected overall compared to that of the observer-based method, including patches and aggregated items and items that could not be identified at the category level. Instead, the densities of buoys and boxes, which have a positive buoyancy and are more easily detected and identified, were the same for the two methods.

The results obtained from the observer-based survey indicated relatively high FMML densities in sampling sites closer to the coast, consistently with studies highlighting higher FMML densities near the coast than those in the oceanic waters (Ryan et al. 2014). Indeed, with the exception of the areas located within or near the five ocean gyres (*e.g.,* Lebreton et al., 2018), the highest concentrations of litter are often found in proximity to densely populated urban centres, touristic areas and shipping routes (Suaria et al., 2014). However, this correlation was weaker with the results obtained from the photographic method, probably as a consequence of the smaller area surveyed.

Overall, our results further support the importance of airborne sensors for monitoring the sea surface and detecting floating litter, as already stressed by various authors (Mace, 2012; Pichel et al., 2012; Veenstra and Churnside, 2012). Even if aerial photography is already being used for this purpose at a large scale, including for the monitoring of the "Great Pacific Garbage Patch" (Garaba et al., 2018; Gibbs et al., 2019), the abundances and densities of FMML obtained with photographic methods cannot be included in the databases obtained from observer-based surveys without a previous validation of the methods. Thus, the results of the present study are highly relevant to the comparison of the results obtained from photographic surveys with those obtained from conventional observer-based monitoring of floating litter.

In addition, airborne platforms may be a promising source of evidence-based information for the calibration and validation of future satellite missions aimed at detecting, tracking, identifying, and quantifying ocean plastics (Mace, 2012): photographic surveys for monitoring FMML can be considered a technological intermediary between the satellite- and observer-based methods (Garaba et al., 2018).

4.2. Mega-fauna

Our results show that the observer-based and photographic methods are equally effective for detecting cetaceans, marine turtles and sunfish, providing further validation of photographic surveys as a viable alternative to traditional observer-based surveys for monitoring marine mega-fauna on the sea surface. This result is consistent with similar studies, showing that relevant marine mammal species can be detected and classified to the species level in photographic images (Gibbs et al., 2019; Thaxter & Burton, 2009). Taylor et al. (2014) also found that the mean densities of blue shark, loggerhead turtle and ocean sunfish estimated from photographic methods were significantly higher than those estimated from observer-based methods. Such a difference was not highlighted in our study, probably due to the low number of marine mega-fauna observations. As the overall surface of the area that was monitored visually was larger than the area monitored photographically, two dolphin species could be detected only through the observer-based method. It is likely that a larger sample size would reveal significant differences between the ability of two methods to detect the densities of cetaceans, sea turtles and large fish.

Although our results show that the two methods produce comparable results, the advantages of the photographic method also include logistic and economic factors. Observer-based aerial surveys generally require the participation of a number of volunteers or dedicated and trained observers and can sometimes be performed under unsafe conditions (Buckland et al., 2012), and the observations produced cannot be validated afterwards to assess the reliability of the counts and the species identity. An increasing number of national and international regulations (*e.g.*, the Marine Strategy Framework Directive, MSFD 2008/56/EC) require concurrent monitoring of marine mega-fauna and its stressors, including marine litter. These monitoring actions would involve a large number of observers and a massive amount of working hours if performed through observer-based surveys. Photographic surveys, instead, guarantee concurrent monitoring for the presence of marine fauna and marine litter within the same flights and involve only the pilot and a camera operator. In addition, the analysis of images performed *a posteriori* by trained photo-interpreters allows a better determination of the number of targets and the identification of species and/or items with better precision.

The automatic detection and recognition of targets in the imagery obtained through remote sensing is a key issue of this monitoring technique and may provide further support in locating and identifying marine mega-fauna in the images (Buckland et al., 2012; Bryson & Williams, 2015). Although there are large difficulties in building effective algorithms, some researchers have reached relevant results, developing methods to automatically detect marine animals, birds, rocks and the sea surface (Maussang et al., 2015). Therefore, automated vertical images from aerial platforms open a new horizon of monitoring, and improving technology ensures ever-increasing reliability and quality assurance.

4.3. Seabirds

According to our results, the observer-based method is more effective than the photographic method for detecting seabirds. The apparent contradiction between this result and those obtained for the FMML and mega-fauna may be explained by three main factors. 1) While cetaceans, fish and sea turtles can be observed only on the sea surface and in the few centimetres below it, seabirds can be observed not only floating at sea but also flying in the three-dimensional aerial space between the aircraft and the sea surface. Being equal the ground surface, the observer-based monitoring methods cover larger volumes of space than the photographic methods. 2) The photographic surveys did not generate sufficient seabird observations to perform a proper density comparison between the methods. 3) Flying birds remain within the field of view of the camera for short periods of time, whereas observers are able to follow moving targets for longer periods of time.

Hence, a possible solution to overcome at least one of these biases may be to cover larger areas to obtain comparable observations. Other studies comparing the two methods indicated that seabird surveys conducted using aerial photography can be more accurate than those conducted with observers (Chabot and Francis, 2016). For instance, Žydelis et al. (2019) recorded more bird sightings, identified more species and detected higher densities of nearly all species through digital video surveys than with concurrent observer-based surveys. In addition, the results from Kulemeyer et al. (2011) suggested that the frequencies of three sea duck species were underestimated by an observer-based method, being lower than those determined through an aerial photographic method. According to these authors, aerial photography may prove to be the tool of choice to identify seabird species and to precisely count individuals in large groups, whereas the human eye may allow only a rough estimate (Žydelis et al., 2019). However, in the present study, birds were not identified at the species level with either of the two methods, and no large groups of seabirds were encountered. Thus, our results suggest that in areas of scarce bird density, three-dimensional visual observations may record more individuals than bi-dimensional aerial photography.

To overcome the limitations of aerial photography described above, UAVs are frequently used for seabird monitoring (*e.g.*, Brisson-Curadeau et al., 2017; Weimerskirch et al., 2018). Drones may provide an effective alternative to aircraft for the following reasons: 1) they can fly at lower altitudes, leading to an increase in image resolution; 2) they can be programmed to take several pictures per second, which allows a continuous overlap between photographs; 3) image processing programs (*e.g.*, Agisoft PhotoScan) can produce georeferenced orthomosaics from the overlapped photographs, providing a single high resolution image of the surveyed areas; 4) the weight, cost and environmental footprint of drones are reduced compared to those of aircraft; and 5) the risks for the pilot and researchers are null (Bryson & Williams, 2015). On the other hand, the average endurance of UAVs is generally limited compared to that of manned aerial vehicles, which are able to cover larger areas.

4.4 Time effort

To properly compare the observer-based and photographic methods, it is necessary to calculate the overall time effort needed for data collection and processing within the two methods. The observer-based method needs a standard team of two to three observers (if one is dedicated exclusively to marine litter) and a person in charge of recording data and organizing the database afterwards, leading, for an 8-hour survey, to an overall time requirement ranging between 26 and 34 hours (8 hours per person per survey plus 2 hours for data management).

On the other hand, the photographic method needs a camera operator and one or two photo-interpreters, leading, for an 8-hour survey in which approximately 2500 images are taken, to an overall effort of approximately 24 hours (8 hours for the camera operator plus 14 hours for photo interpretation and 2 hours for the inspection of doubtful targets).

Although the time required for the two methods is of the same order of magnitude, the effort is slightly reduced for photographic surveys, which is another reason to consider the photographic method a viable alternative to observer-based methods. Moreover, the development of new, efficient algorithms to automatically detect targets will further reduce the effort dedicated to manually inspecting the images (Bryson & Williams, 2015).

5. Conclusions

The results of this paper provide a first validation of the photographic method for FMML monitoring, enabling the comparison of data obtained through this method with those obtained from observer-based methods and thus the determination of temporal trends in marine mega-fauna and FMML density and distribution. The increasing application of photographic methods for monitoring the marine surface is supported by a number of factors, including the constant improvement of technology, ensuring the reliability and quality of data, and the development of automated algorithms that will allow the analysis of thousands of images per hour.

Our results indicate that for FMML and mega-fauna (with the exception of seabird) monitoring, the photographic method is equally as efficient as or more efficient than the observer-based method. The use of manned aerial vehicles is recommended for the purpose of monitoring large spatial scales, while the use of UAVs is recommended for relatively small-scale monitoring and/or when more accurate data are needed. However, further research is needed to select the best devices for identifying floating litter, to cope with the issue of sun glare reflection, and to improve the currently available algorithms.

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Figures and Tables

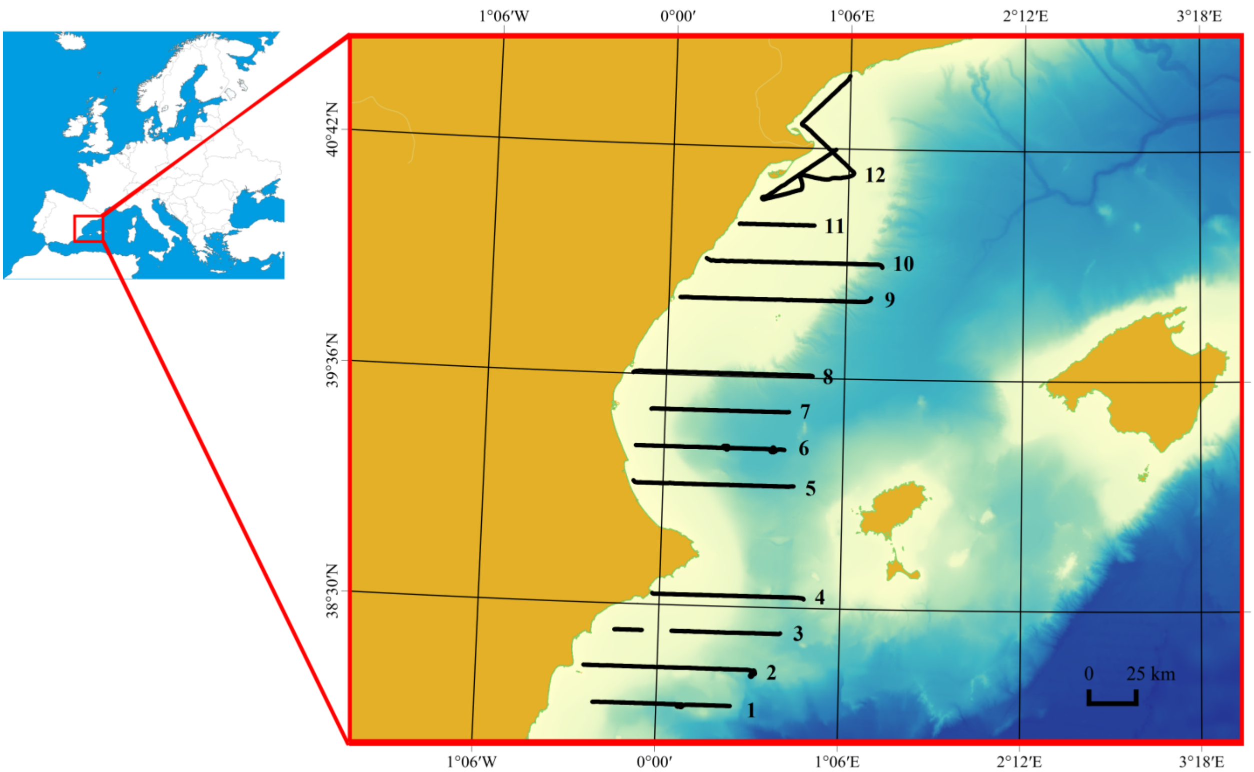

Figure 1 Study area and GPS tracks of the surveyed transects.

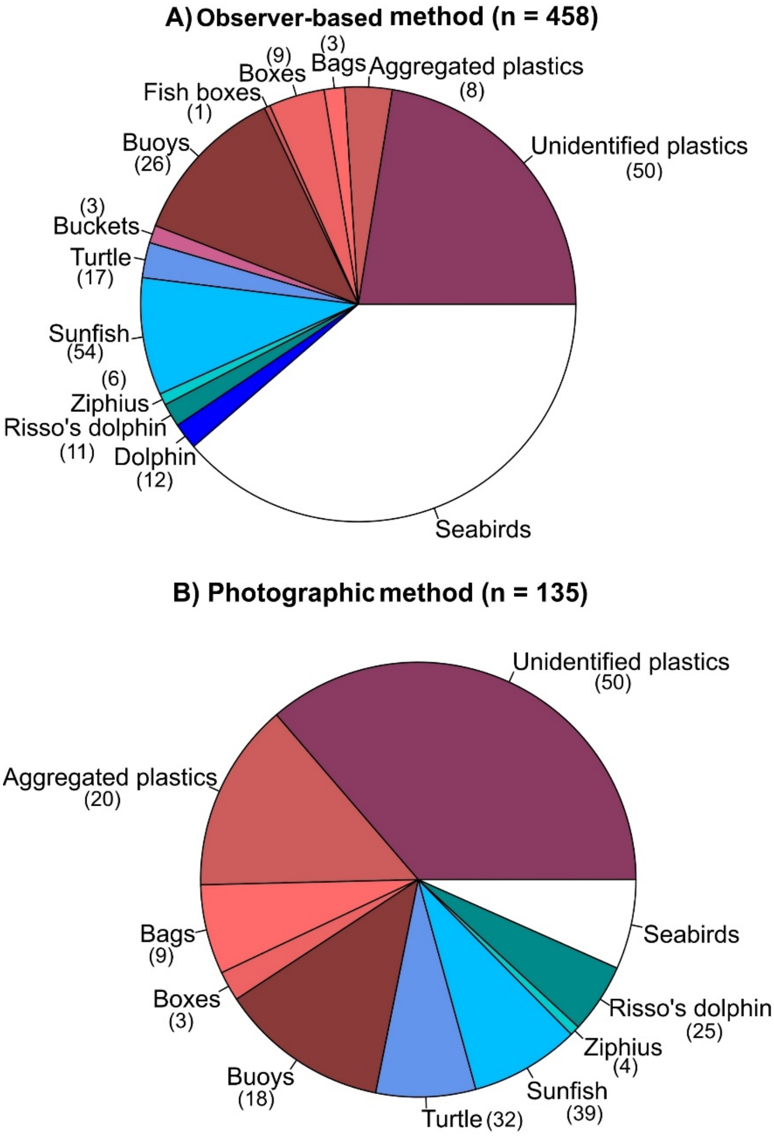

Fig. 2 Marine targets detected by the observer-based method (A) and the photographic method (B) (n = Total targets detected). Purple shades represent FMML categories, blue shades represent mega-fauna species; seabirds are represented in white. The percentage of each category of item/species within its respective category is represented in brackets.

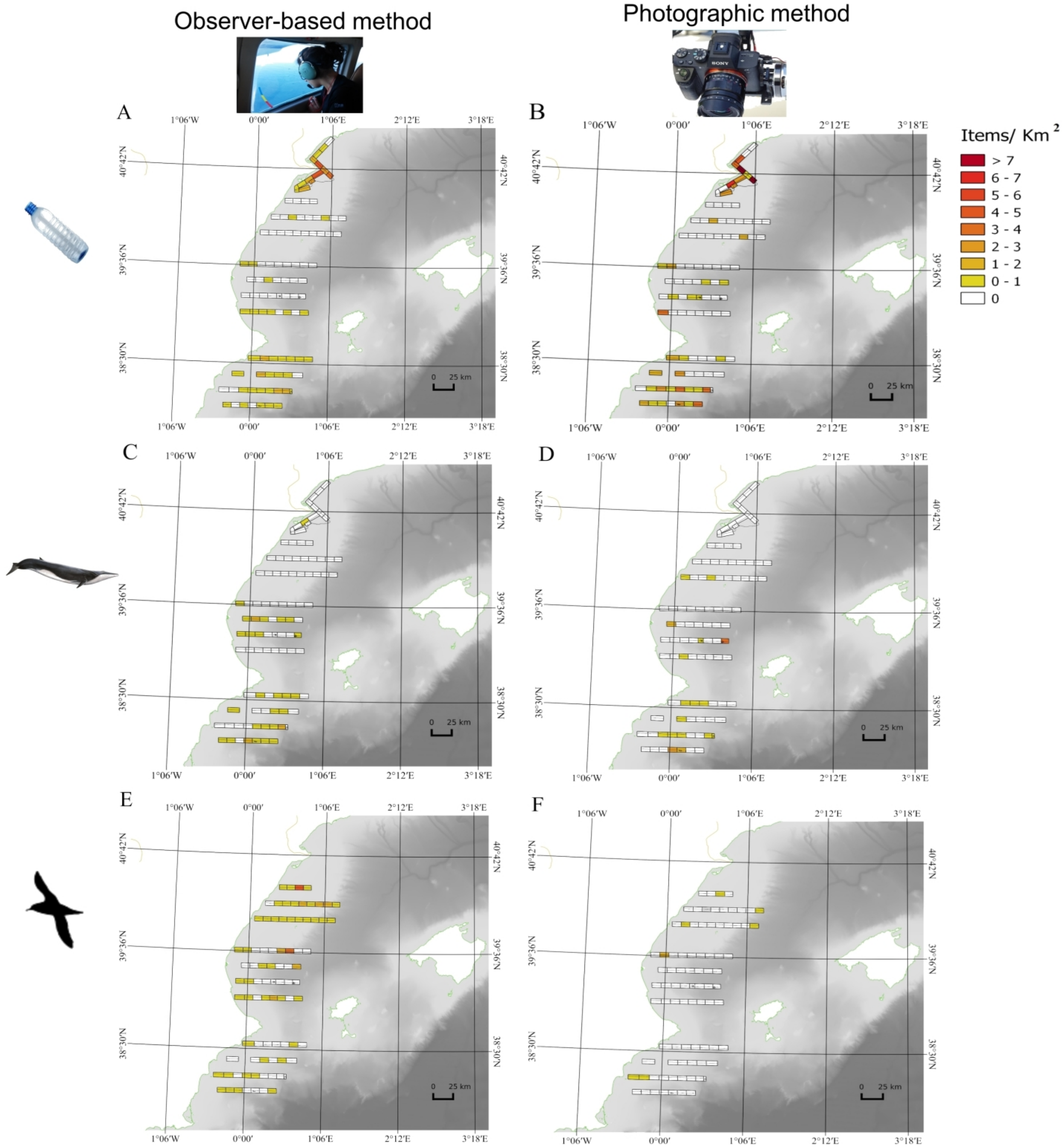

Figure 3. Density of floating litter (A, B), mega-fauna (C, D) and seabirds (E, F) detected through the observer-based (A, C, E) and photographic (B, D, F) surveys. Sampling units are depicted in each transect.

Table 1 Details of the photographic and observer-based aerial surveys.

	Photographic survey	Observer-based survey
Altitude (m)	230	230
Speed (knots)	90	90

Sampling unit length (equivalent to 100 images, km)	8.6	9.3
Distance between images (m)	7.6	-
Length of the surveyed area (km)	865.2	941.1
Transect width (m)	128.2	548
Survey area (km^2)	110.9	515.7

Table 2. Number of sampling units (n), environmental conditions and densities of marine targets (mean ± SD) split by category and observation method for each transect.

					FMML* (items/km^2) (mean ± SD)		Mega-fauna (individuals/km^2) (mean ± SD)		Seabirds* (individuals/km^2) (mean ± SD)	
Transect	n	Beaufort force	Sun glare	Clouds (%)	Photographic	Observer-based	Photographic	Observer-based	Photographic	Observer-based
1	7	1 - 2	1	75	1.56 ± 1.63	0.20 ± 0.18	0.68 ± 1.06	0.37 ± 0.45	0.00 ± 0.00	0.25 ± 0.31
2	9	1 - 2.5	1	75	1.52 ± 1.44	0.43 ± 0.46	0.51 ± 0.48	0.33 ± 0.49	0.20 ± 0.40	0.15 ± 0.19
3	6	1 - 2.5	1	80	0.69 ± 1.15	0.40 ± 0.58	0.15 ± 0.37	0.16 ± 0.23	0.00 ± 0.00	0.13 ± 0.24
4	7	1 - 2.5	0 - 1	80	0.45 ± 0.58	0.62 ± 0.47	0.39 ± 0.49	0.25 ± 0.27	0.00 ± 0.00	0.17 ± 0.31
5	8	1 - 2.5	1	10	0.43 ± 1.21	0.07 ± 0.14	0.11 ± 0.32	0.02 ± 0.07	0.00 ± 0.00	0.76 ± 1.17
6	8	1 - 2.5	1	10	0.30 ± 0.46	0.02 ± 0.07	0.81 ± 2.11	0.39 ± 0.51	0.00 ± 0.00	0.28 ± 0.58
7	7	1 - 2.5	1	10	0.26 ± 0.45	0.00 ± 0.00	0.26 ± 0.69	0.32 ± 0.53	0.00 ± 0.00	0.09 ± 0.17
8	9	1 - 3	1	10 - 50	0.30 ± 0.65	0.19 ± 0.15	0.00 ± 0.00	0.00 ± 0.00	0.20 ± 0.61	0.47 ± 0.41
9	10	2 - 3	1	50	0.18 ± 0.58	0.00 ± 0.00	0.18 ± 0.39	0.00 ± 0.00	0.18 ± 0.39	1.57 ± 2.12
10	9	2.5 - 4	1 - 3	70	0.20 ± 0.61	0.04 ± 0.09	0.00 ± 0.00	0.00 ± 0.00	0.20 ± 0.40	0.65 ± 0.60
11	4	2 - 5	3	70	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.23 ± 0.46	0.47 ± 0.30
12	13	1 - 2	1 - 3	10 - 80	3.22 ± 3.41	1.01 ± 1.52	0.00 ± 0.00	0.02 ± 0.05	-	-
Total					0.90 ± 1.77	0.40 ± 0.84	0.26 ± 0.78	0.15 ± 0.33	0.09 ± 0.31	0.40 ± 0.70

* Significant difference between the two methods ($p < 0.05$, paired-sample Wilcoxon's signed rank test).

Table 3. Categories of plastic items (total number and density, expressed as items/km^2 ± SD) detected during the photographic and observer-based surveys. In brackets, the number of sampling units considered.

Plastic item category		Photographic survey	Observer-based survey
Unidentified plastics	Total	49	103
	Density (Unidentified plastics/km^2 ± SD; n = 97)	0.45 ± 0.97*	0.20 ± 0.43*
Aggregated patches	Total	19	16
	Density (Aggregated patches/km^2 ± SD; n = 97)	0.18 ± 0.71*	0.029 ± 0.13*
Buoys	Total	17	55
	Density (Buoys/km^2 ± SD; n = 97)	0.15 ± 0.75	0.11 ± 0.54
Bags	Total	9	7
	Density (Bags/km^2 ± SD; n = 97)	0.08 ± 0.30*	0.01 ± 0.54*

Boxes	Total	3	19
	Density (Boxes/km^2 ± SD; n = 97)	0.03 ± 0.18	0.04 ± 0.10
Buckets	Total	0	6
	Density (Buckets/km^2 ± SD; n = 97)	0.00 ± 0.00	0.01 ± 0.54
Fishing boxes	Total	0	2
	Density (Fishing boxes/km^2 ± SD; n = 97)	0.00 ± 0.00	0.01 ± 0.05
Total floating plastic items detected		97	208

* Significant difference between the two methods ($p < 0.05$, paired-sample Wilcoxon's signed rank test).

Annex

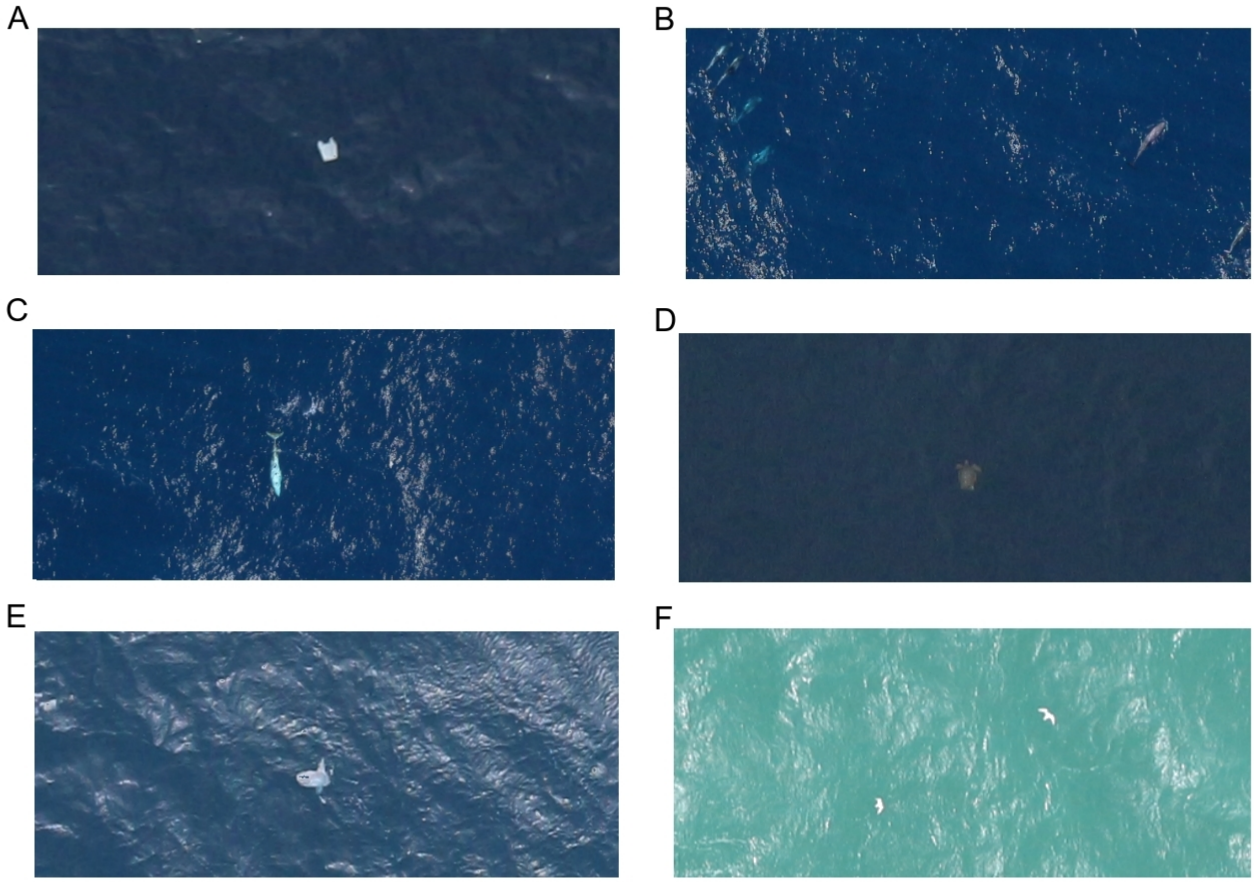

Figure S1 Aerial photographs of a A) FMML (a plastic bag), B) *Grampus griseus*, C) *Ziphius cavirostris*, D) *Caretta caretta*, E) *Mola mola* and F) seabirds. Images were cropped to improve the visibility of sightings.

Table S1 Modified MSFD master list (adapted for aerial surveys from MEDSEALITTER consortium, 2019) with the list of objects and Mediterranean mega-fauna that can be observed from aerial surveys.

Material/category	Description
Plastic, polystyrene, polyurethane	Bags, boxes, fish box, buoys, buckets, fishing nets
Processed wood	Pallets
Vegetable	Seaweed/marine plant, logs/plants parts
Liquids	Oil slick, isolated foam
Glass	Bottles
Textile	Clothing
Rubber	Balloons, tyres
Undefined material	Ropes, pieces
Animal	Animal carcasses
Mega-fauna (Mediterranean Sea)	*Stenella coeruleoalba, Tursiops truncatus, Delphinus delphis, Globicephala melas, Physeter macrocephalus, Grampus griseus, Balaenoptera physalus, Ziphius cavirostris*, *Caretta caretta, Mola mola*, seabirds...

Table S2 Date, position, direction and length of the transects conducted during the aerial surveys

Transect	Date	Start position (Lat, Lon)	End position (Lat, Lon)	Direction	Length of the photographic survey (km)	Length of the observer-based survey (km)
1	25/03/18	38.024, 0.447	38.023, −0.384	West	66.8	72.6
2	25/03/18	38.200, −0.446	38.180, 0.593	East	77.6	84.4
3	25/03/18	38.378, 0.740	38.373, −0.267	West	55.6	60.5
4	25/03/18	38.553, −0.044	38.542, 0.878	East	63.2	68.7
5	22/03/18	39.082, 0.801	39.089, −0.181	West	69.1	75.1
6	22/03/18	39.258, −0.175	39.254, 0.739	East	87.0	94.6
7	22/03/18	39.437, 0.762	39.433, −0.087	West	60.0	65.3
8	22/03/18	39.605, −0.206	39.610, 0.902	East	75.8	82.5
9	21/03/18	39.989, 1.254	39.971, 0.070	West	83.8	91.1
10	21/03/18	40.162, 0.225	40.136, 1.320	Est	76.5	83.2
11	21/03/18	40.331, 0.891	40.330, 0.424	West	34.1	37.1
12	14/03/18	41.049, 1.096	40.696, 1.017	SW, SE, SW, NE	115.7	125.8