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Setting the scene for Mediterranean litterscape management: The first basin-scale quantification and mapping of floating marine debris☆

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ABSTRACT

Plastic pollution has become one of the biggest environmental concerns of the Anthropocene as it represents a major threat to both wildlife and human health. Garbage patches in the world's oceans are well documented, but quantitative assessments of floating debris are still lacking in some major areas. The Mediterranean Sea is one such area, despite being one of the most plastic polluted environments. We used data from the first international basin-scale survey of the Mediterranean Sea to provide the first abundance estimate of floating mega-debris (>30 cm) and map their distribution over the entire Mediterranean Sea. We estimated the total number of floating mega-debris at 2.9 million items, taking into account imperfect detection. Items larger than 30 cm represent only one fourth of the complete load of anthropogenic debris (>2 cm) in the Mediterranean, which scales up the estimate to 11.5 million floating debris. The highest densities were observed in the central Mediterranean, and the lowest in the eastern basin. This acute marine pollution might threaten to disrupt entire ecosystems through its impact on marine fauna (entanglement, ingestion, contamination), eventually impacting the tourism industry and the well-being of Mediterranean populations.

1. Introduction

The accumulation of human-derived debris in the world's oceans is a major environmental concern of the Anthropocene, particularly the accumulation of plastic (Gregory, 2009; Thompson et al., 2009; Haward, 2018). New records of plastic production and spillage volumes into the ocean are set every year (350 million tons produced in 2017 alone; Plastics Europe, 2018). Once released into the ocean, debris threaten all marine life: from coral to whales (Kühn et al., 2015; Rochman et al., 2016). Meso-to mega-debris cause entanglement and smothering (resulting in starvation, drowning or mutilation), or intestinal occlusion (resulting in poor health or death through starvation or perforation; Vegter et al., 2014; Rochman et al., 2016). Micro-debris, in particular micro-plastics, are ubiquitous in the environment (Galgani et al., 2015; Law, 2017) and have deleterious consequences on the health of animals when ingested, through adverse effects of the material itself and of the complex mixture of chemicals adsorbed on it (Rochman, 2015). Those adverse effects include negative impacts on the feeding capacity, growth or survival of individuals, which ultimately reduces their fitness (Rochman, 2015). The accumulation of the harmful effects of plastics at the organism level over entire populations impairs average survival and reproductive success of population and alteration of ecological assemblages (Kühn et al., 2015; Rochman et al., 2016), with potentially hazardous consequences for ecosystem functioning at the macro-scale (Browne et al., 2015).

Oceanic gyres cause debris to concentrate in garbage patches throughout the world's ocean. The five sub-tropical gyres in the Pacific, Atlantic and Indian Oceans are the major sinks of plastic and non-plastic debris in the world, and as such have been extensively documented with numerical simulations and *in-situ* observations (Law et al., 2010; Lebreton et al., 2012; Cózar et al., 2014; Eriksen et al., 2014). However, *in-situ* quantitative assessments of floating anthropogenic debris at a basin-scale are lacking in some areas. The

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semi-enclosed Mediterranean Sea is one of such areas, despite being considered as the 6th major garbage patch and one of the most debris polluted seas in the world (Lebreton et al., 2012; Eriksen et al., 2014; Cózar et al., 2015; United Nations Environment Programme / Mediterranean Action Plan, 2015). The Mediterranean garbage patch is characterised by a very short distance between source and accumulation areas of marine debris, coupled with a fast accumulation rate (Alessi et al., 2018). This characteristic arises from the Mediterranean being a major tourist area, with over 200 million visitors per year (about 30% of worldwide tourism), and one of the busiest marine traffic areas in the world (30% of the worldwide maritime traffic; Alessi et al., 2018). It represents only 1% of the world's oceans, yet it hosts some 10% of the world's marine biodiversity, with an endemism level of 9% (Coll et al., 2010; United Nations Environment Programme / Mediterranean Action Plan, 2015). In this context, quantitative assessments and a clear understanding of the risks of anthropogenic debris in the Mediterranean Sea at the basin-scale is paramount for conservation of its biodiversity, but require intense transboundary collaboration in this politically sensitive region.

The implementation of adequate conservation strategies in the Mediterranean is currently hindered by the lack of sufficient knowledge to identify higher vulnerability areas for marine fauna. For now, recent intensive sampling of floating debris distribution on transects or stations scattered over the central and western basin and the Adriatic Sea have confirmed the status of garbage patch for the Mediterranean Sea (Cózar et al., 2015; Ruiz-Orejón et al., 2016; Fossi et al., 2017; Di-Méglio and Campana, 2017; Alessi et al., 2018; Arcangeli et al., 2018; Campana et al., 2018), as was suggested by simulations of surface debris drifting by way of ocean circulation (Mansui et al., 2015; Zambianchi et al., 2017). Yet, we still lacks a ground-truthed estimation of floating debris density interpolated over the entire Mediterranean Sea, and in particular we lack information on debris distribution within the eastern basin. The aim of this study was to fill this gap and to provide the first estimate of the abundance of floating mega-debris over the entire Mediterranean Sea and the first ground-truthed basin-scale map of mega-debris distribution, herein setting the scene for quantifying the threats caused by anthropogenic debris at the Mediterranean Sea scale.

To achieve this goal, the ACCOBAMS Survey Initiative (ASI) simultaneously monitored marine megafauna, anthropogenic activities and floating mega-debris during the summer of 2018. The ASI was an unprecedented international survey conducted under the framework of the Agreement on the Conservation of Cetaceans of the Black Sea, Mediterranean Sea and Contiguous Atlantic Area (ACCOBAMS), a treaty aimed at cetacean conservation in the Mediterranean and Black Seas - a daughter instrument of the Convention on the Conservation of Migratory Species of Wild Animals (Bonn Convention). Thanks to intense international collaboration, the survey covered nearly the entire Mediterranean Sea (77.3%, ≈1.92 million km^2; Fig. 1). Building from these outstanding

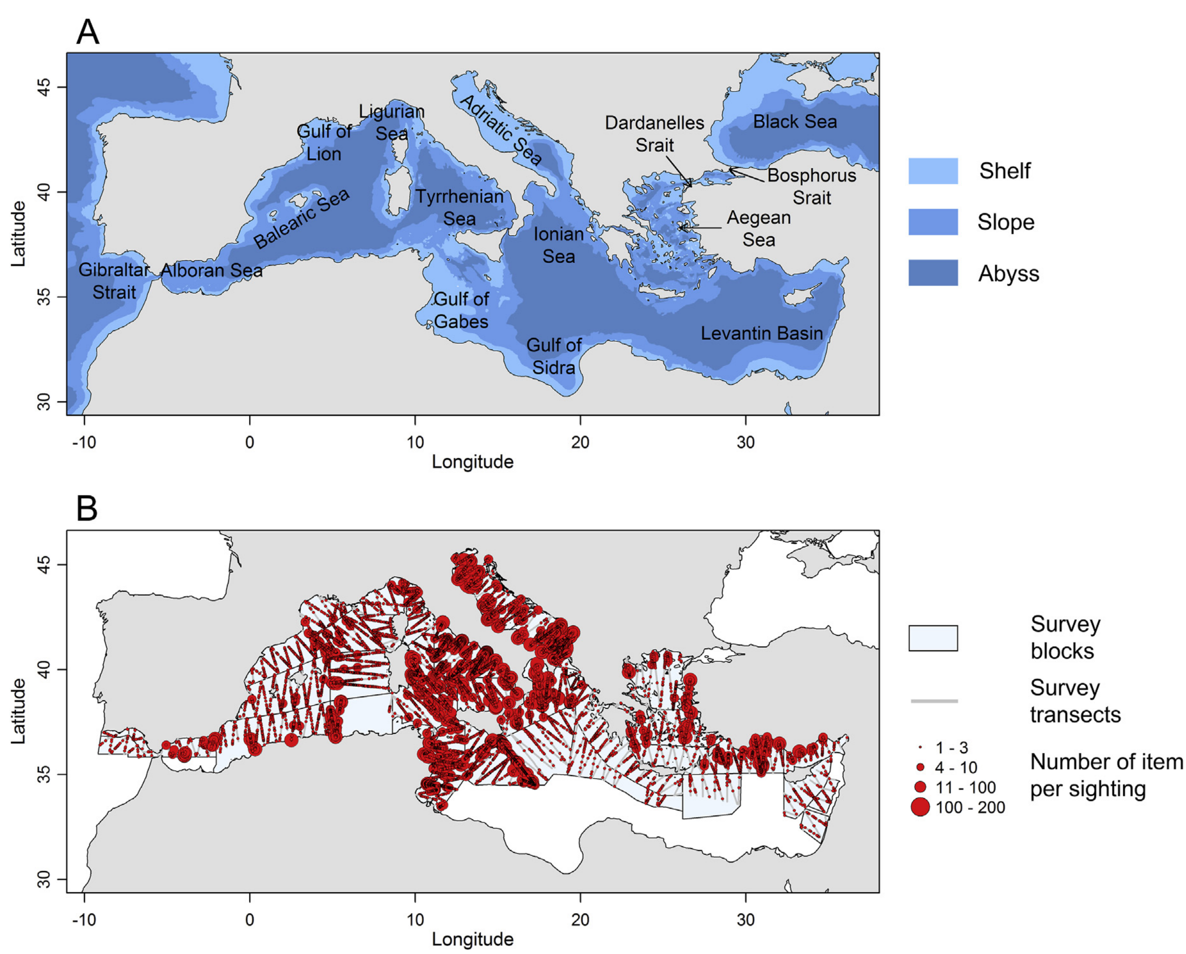

Fig. 1. A - Bathymetric chart of the study area with geographical names. B - ACCOBAMS Survey Initiative (ASI) blocks, sampled transects and distribution of sighted floating mega-debris. Transects were sampled once by 14 different teams operating 8 planes simultaneously in different areas. There was no aerial survey effort off the coasts of Morocco, Libya, Egypt and east of Cyprus where the ASI survey was conducted by boat.

data, we used Bayesian hierarchical Species Distribution Model to spatially estimate the presence probability of mega-debris at the basin-scale and estimate the mega-debris density over the Mediterranean by coupling the presence probability map with a bootstrap procedure on number of sighted items. The Bayesian hierarchical Species Distribution Model allowed us to correct for the imperfect detection (linked to observation conditions and observers) inherent to aerial survey detections and to provide an unbiased estimation of mega-debris distribution and density.

2. Material and methods

Estimating abundance of objects necessitates taking into account the accuracy in detection process. The accurate detection of mega-debris in aerial surveys largely depends on observation conditions (*e.g.* sea state; Buckland et al., 2015), therefore imperfect detection was accounted for in the analysis in order to ensure that estimates were not biased due to observers missing some debris in sub-optimal conditions. We estimated the effect of observation conditions on the probability of detecting floating mega-debris using occupancy models in a Bayesian framework (Royle and Dorazio, 2008), incorporating as prior information data from a previous aerial survey of the Mediterranean Sea (the French SAMM survey, conducted in 2012 following the same protocol; Fig. 2). Occupancy modelling corrects for imperfect detection by separating the detection process (detection probability) from the presence process underlying sighting data, providing a spatial estimation of presence probability in the study area (Royle and Dorazio, 2008). We finally estimated the mega-debris density over the entire Mediterranean Sea by coupling the presence probability map with a bootstrap procedure on number of sighted items based on the ASI data.

2.1. Survey data

The summer SAMM survey (*Survol Aérien de la Mégafaune Marine*; aerial survey of marine megafauna) was conducted from May to August 2012 over the French Exclusive Economic Zone in the Mediterranean Sea (Supplementary Materials, Fig. S1A; Pettex et al. (2014)). The ACCOBAMS Survey Initiative (ASI) was conducted from June to August 2018 over most of the Mediterranean Sea and the western edge of the Gibraltar Strait (Fig. 1 and Supplementary Materials Fig. S1B). The main unsurveyed fraction was the south-eastern Mediterranean Sea, where aerial surveys were not authorized but ship-based surveys performed. In both SAMM and ASI surveys, data collection followed a strip-transect protocol, and coverage of the study area was optimized using a zig-zag layout for transects.

High-wing double-engine aircraft (Britten-Norman-II) were used in the SAMM survey, while three types of aircraft were used during the ASI survey: Britten-Norman-II, Partenavia, and Cessna 337 G Skymaster. All aircraft were equipped with bubble windows so that observers could scan the sea surface and sub-surface right below the aircraft on the transect line. Observers were trained to search for all mega-debris larger than 30 cm in size present in a 200 m strip on either side of the aircraft, following strip-transect methodology (Buckland et al., 2015). While the protocol used during the SAMM surveys required only categorizing between fishing trash and other mega-debris (Pettex et al., 2014), the ASI protocol required distinguishing between fishery, plastic and processed wood debris when possible. Partenavia and Cessna aircraft carried teams of three observers each, and Britten-Norman-IIs carried four observers. Two observers were actively surveying at all times during transects, one on either side of the aircraft, and one person was responsible of data recording. Positions were regularly rotated between data recording, right and left observation. The additional observer on Britten-Norman-IIs allowed rest time to be included in the observers' duty cycle during long flights. The aircraft flew at a constant speed of ≈167 km/h (90 knots) at a height of ≈183 m (600 feet) above see level.

Observation conditions (*e.g.* sea state, turbidity, cloud cover, glare severity, glare orientation) and a subjective estimation of small cetacean detectability (hereafter "subjective conditions") were systematically recorded during active survey effort. Observation conditions were recorded at the start of a transect and whenever conditions changed within a transect. Flight data and sightings were recorded using VOR v8.6 software during SAMM survey and SAMMOA v1.1.2 software during ASI survey (http://www.observatoire-pelagis.cnrs.fr/publications/les-outils/article/logiciel-sammoa).

A total distance of 14 137 km was flown during the SAMM survey and 55 738 km during the ASI (Table 1). Legs of homogeneous detection conditions were subdivided into 10 km segments for subsequent analyses (*i.e.* spatial modelling), standardizing the sampling units with respect to effort, and the total number of mega-debris encountered was tallied for each segment.

Table 1
Survey-specific effort (sampled distance, km) and sighting metrics (number of detections, mean number of items per detection and the mean encounter rate per segment). Distances were calculated using the Lambert 93 Conformal Conic projection for SAMM and with the Sphere Equidistant Conic Mediterranean projection for ASI.

	SAMM	ASI
Total effort	14 100 km	55 800 km
Total effort in good conditions (Beaufort sea state ¡ 4 and subjective conditions medium to excellent)	13 000 km (92%)	40 500 km (73%)
Total number of detections	6500	17 700
Total number of sighted items	16 500	40 900
Mean number of item per detection [min; max]	2.5 [1; 250]	2.3 [1; 200]
Mean (± sd) encounter rate per segment (item per km)	1.13 (± 3.3)	0.80 (± 3.2)

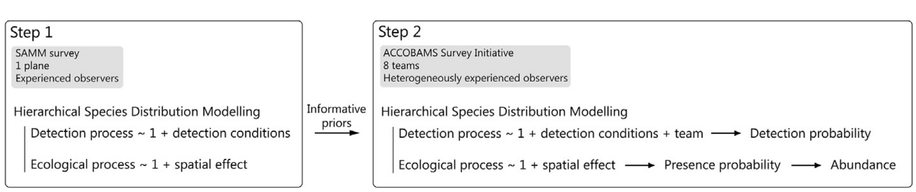

Fig. 2. Methodological chart summarising the analytical procedure used for this study. We first estimated detection and presence probabilities of mega-debris in the north-western Mediterranean Sea with a Hierarchical Species Distribution Model using data from the SAMM survey, conducted in 2012. Second, we estimated detection and presence probabilities of mega-debris over the entire Mediterranean Sea from the ASI data, using parameters estimated from the SAMM survey as informative priors for the detection probability and weakly informative priors for the presence probability. Abundance estimate was eventually derived from the presence probability.

2.2. Statistical analysis

2.2.1. Detection and presence probability estimation

We used hierarchical modelling in a Bayesian framework to estimate the detection probability and presence probability of mega-debris simultaneously (Royle and Dorazio, 2008; Lele et al., 2012) using the hSDM.ZIB.iCAR function from the hSDM package in R 3.5.1 (Vieilledent et al., 2014; R Core Team, 2018). Hierarchical modelling allowed us to conceptualize a sighting as being the result of a measurement process (detectability) and a process of interest (presence). Extensions to complex structures, such as spatial dependence, are straightforward in this framework. During survey s, the i^{th} sighting y_{ijks} is the result of a Bernoulli process whereby observer team j can detect a debris item - given that it is present in cell k ($z_{ks} = 1$) - with a probability δ_{ijs} of:

$$\begin{cases} y_{ijks} \Big| z_{ks}, \delta_{ijs} & \sim \mathscr{B}\text{ernoulli}(z_{ks} \times \delta_{ijs}) \\ \delta_{ijs} | W_{ijs}, \gamma & = \text{logit}^{-1}(W_{ijs}\gamma) \end{cases} \tag{1}$$

W is a design matrix of input values. Mega-debris presence was modelled using a Bernoulli process and an intrinsic Conditional AutoRegressive process (iCAR; Banerjee et al., 2004) to account for spatial dependence between observations:

$$\begin{cases} z_{ks} | \theta_{ks} & \sim \mathscr{B}\text{ernoulli}(\theta_{ks}) \\ \theta_{ks} | \beta_0, \rho_{ks} & = \text{logit}^{-1}(\beta_0 + \rho_{ks}) \\ \rho_{.s} | \tau_s, N, M & \sim \mathscr{MVN}\left(0, [\tau_s(M-N)]^{-1}\right) \end{cases} \tag{2}$$

where $\rho_{.s}$ is a vector of spatial random effect for survey s, M is a diagonal matrix with the number of neighbours of cell k, and N is a sparse matrix with $N_{kl}1$ if cells k and l are neighbours and 0 otherwise. The iCAR process allows for spatial autocorrelation with the probability of mega-debris presence at one site depending on that of its neighbouring sites. A site was operationalized as a 0.3° by 0.3° cell on a regular grid mapped onto the Mediterranean Sea. No covariates were included in the model for macro-debris presence as we aimed at describing debris distribution, not the drivers of their accumulation.

We used a Bayesian framework to incorporate prior information of the effect of observation conditions on mega-debris detection probability. We first analysed data from the SAMM survey to estimate the vector of observation conditions' effects γ. These estimations were then used as priors in the analysis of the ASI data. A team of observers was common to both the ASI and SAMM surveys, justifying the use of the SAMM survey to inform the ASI. In summary, the effect of observation conditions on mega-debris detection probability was estimated using (i) SAMM data, using weakly informative priors; and (ii) ASI data, using the estimates from SAMM as informative priors (Fig. 2).

The two sides of the aircraft were considered separately when estimating the effect of observation conditions. The inputs for this analysis were: segment length, Beaufort sea state, subjective conditions, cloud cover, glare severity, glare extent (the percentage of the survey area covered by glare, computed from glare orientation) and turbidity. A model selection procedure was conducted in which all models with combinations of 2–7 inputs were fitted to the SAMM data. Segment length was always included to account for an expected increase in detection probability with increased effort. Inputs were mean-centred and scaled to a standard deviation of 1. We used weakly-informative priors:

$$\begin{cases} \beta_0 & \sim \mathscr{N}(0.0, 1.5) \\ \tau & \sim \Gamma(2.0, 1.0) \\ \gamma_0 & \sim \mathscr{N}(0.0, 1.5) \\ \gamma_{l \in [1:7]} & \sim \mathscr{N}\left(0.0, \frac{\log 2}{2}\right) \end{cases} \tag{3}$$

Three Markov chains were initialized and run for 100 000 iterations. The first 50 000 iterations were discarded as burn-in and the remaining 50 000 were thinned by a factor of 40 to reduce autocorrelation. Parameter convergence was assessed using the Gelman-Brooks-Rubin $\widehat{\text{R}}$ statistic, assuming that convergence was successful if $\widehat{\text{R}} < 1.1$. Model selection was done using the Widely-Applicable Information Criterion (WAIC (Vehtari et al., 2017)) estimated with the `loo` package (Vehtari et al., 2018). Posterior distributions of parameters were summarized by their means, standard deviations and 80% credibility intervals.

To account for the imperfect detection of mega-debris in the ASI data, two models of detection probability were tested: a model with all the inputs selected by WAIC with the SAMM data (see above), and an elaboration of that model which took into account observer teams as an additional input. Eight observer teams participated in the ASI, while a single team of four equally experienced observers from the same institute (Observatoire Pelagis) collected the SAMM data. This team was common to both the ASI and SAMM surveys, so we used this team as the reference team (intercept in the ASI model) to estimate the effect of other teams. Informative priors were used for intercept and observation variables, using the posterior distributions from the best model selected based on the SAMM data. Weakly-informative priors were used for all parameters, including those related to team effects:

$$\begin{cases} \beta_0 & \sim \mathscr{N}(0.0, 1.5) \\ \tau & \sim \Gamma(2.0, 1.0) \\ \gamma_0 & \sim \mathscr{N}(0.0, 1.5) \\ \gamma_{\text{Team} \in [2:8]} & \sim \mathscr{N}\left(0.0, \frac{\log 2}{2}\right) \end{cases} \tag{4}$$

Three chains were initialized and run for 100 000 iterations, the first 50 000 of which were again discarded as burn-in and the remaining 50 000 ones were thinned by a factor of 40 to reduce autocorrelation. Parameter convergence was assessed with the Gelman-Brooks-Rubin $\widehat{\text{R}}$ statistic assuming that convergence was reached if $\widehat{\text{R}} < 1.1$. Posterior distributions were thus approximated by a sample of 3750 values ($3 \times \frac{50\,000}{40}$). Model selection was done using the Widely-Applicable Information Criterion (WAIC; Vehtari et al., 2017) estimated with the loo package (Vehtari et al., 2018). Posterior distributions of parameters were summarized by their means, standard deviations and 80% credibility intervals.

The mean presence probability and its coefficient of variation were computed from posterior distributions of spatial parameters $\rho_{.s}$ in the best model selected for each survey.

2.2.2. Mega-debris density estimation

We estimated the density and abundance of mega-debris over the entire Mediterranean Sea based on the ASI data and estimated presence probability. Estimating the density of mega-debris requires an assumption on the link between occupancy and abundance since our hierarchical model (above) dealt with estimating the presence of mega-debris. Assuming a Poisson distribution for the number of sightings of mega-debris (corrected for imperfect detection) gives a simple relationship between presence probability θ from an occupancy model and the rate parameter λ (equation (1) page 354 in Royle et al., 2005):

$$\begin{cases} \theta &= 1 - e^{-\lambda} \\ \lambda &= -\log(1-\theta) \end{cases} \tag{5}$$

Equation (5) suggests the following model-based estimation scheme for mega-debris abundance in the Mediterranean Sea (dropping the subscripts for survey and observer team for convenience). In each ASI survey block $\mathbb{B}$, for each cell k in that block (with area A_k in square kilometres), the density of mega-debris sightings $\widehat{D}_k^*$ was estimated with

$$\widehat{D}_k^* = \frac{-\log(1-\theta_k)}{A_k} \tag{6}$$

if cell k was not surveyed, or, if surveyed, no mega-debris were detected; and with

$$\widehat{D}_k^* = \frac{\sum_{ik} n_{ik}}{0.2\sum_{ik} \text{Length}_{ik} \times \widehat{\delta}_{ik}} \tag{7}$$

if cell k was surveyed and mega-debris were detected. n_{ik} denotes the total number of sightings of mega-debris on segments i in cell k.

In each ASI survey block $\mathbb{B}$, the average number of mega-debris sighted (in number of items) was estimated using a bootstrap procedure. For each transect within a block, tallies of floating mega-debris were summed and divided by total number of sightings on the transect. Transects were then sampled with replacement, and for each bootstrap sample, the average number of items per sighting, $\overline{m}_{\mathbb{B}}$, was computed. This procedure was repeated 3750 times to match the length of the McMC samples from the hierarchical model (see above).

The density of mega-debris per square kilometres in ASI survey block $\mathbb{B}$ was then estimated as:

$$\widehat{D}_{\mathbb{B}} = \mathbb{E}\left[\widehat{D}_{k\in\mathbb{B}}^*\right] \times \overline{m}_{\mathbb{B}} \tag{8}$$

where $\mathbb{E}[.]$ denotes the expectation operator. The hierarchical model allowed us to predict $\widehat{D}_k^*$ in unsurveyed cells. To estimate the average number of mega-debris items per sighting for unsurveyed blocks, we used the average over all surveyed blocks. Finally, these estimated densities were post-multiplied by block surfaces to yield an estimate of total abundance of mega-debris. Uncertainties were accounted for at each step of this procedure to obtain a posterior distribution for total abundance, from which the 80% credibility interval around the estimated abundance was derived. See Table S4 for detailed estimated parameters per block.

3. Results

3.1. Mega-debris data

Some 16 500 debris were recorded during the SAMM survey, 8% of which were fishery debris, with an average encounter rate of 1.13 debris per km (Table 1, Supplementary Materials Fig. S1A). Some 41 000 floating mega-debris were recorded in total during the ASI (Fig. 1B, Table 1), with an average encounter rate of 0.8 mega-debris per km (standard deviation 3.2), ranging between 0 and 111 debris per km (Fig. 1B). More than two thirds of the mega-debris recorded were identified as plastics (68.5%; *e.g.* plastic bags, bottles, tarpaulins, palettes, inflatable beach toys, etc.), while 1.7% were fishery debris and 1.9% were anthropogenic wood-trash. The remaining quarter (27.9%) was anthropogenic mega-debris of an undetermined nature. Plastic debris were largely dominant in all blocks (Supplementary Materials Fig. S3).

3.2. Detection probability estimation

For the SAMM data, the best model incorporated all the inputs (Supplementary Materials Table S1). The best model for ASI data incorporated the same inputs, plus the team effect (Supplementary Materials Table S2). Standardized coefficients were similar for all parameters of the detection process except for the effort variable, whose effect was lower in SAMM than ASI (Fig. 3). The intercept parameter (*i.e.* the basal detection probability) was lower in the ASI, but confidence intervals of the estimate extensively overlapped between the two models. As expected based on sample size considerations and the use of informative priors, the uncertainty associated with estimates was lower in ASI compared to SAMM for all parameters.

Effort and subjective conditions had a positive effect on detection probability during the SAMM survey (Figs. 3 and S4), whereas the Beaufort sea state, turbidity and glare extent had a negative effect. Cloud cover and glare severity had negligible effects (Figs. 3 and S4). The same pattern was observed for the ASI model (Figs. 3 and S5), but the overall intercept was slightly lower. The effort had a strong positive effect on the detection probability. The negative effect of the Beaufort sea state was similar to that in the SAMM data, as was the positive effect of subjective conditions, but the negative effects of turbidity and glare extent were lower in the ASI data than in the SAMM data (Figs. 3 and S4). The detection probability differed among the eight teams in the ASI model (Figs. 3 and S5): there was no difference in detection probability between teams 1, 3, 4, 6 and 8, but teams 2 and 7 had a lower detection probabilities, while team 5 had a higher detection probability.

Overall, the estimated probability of detecting floating mega-debris during the ASI ranged from 0.1 in the worst conditions to 0.9 in optimal observation conditions: *i.e.* about 90% of debris actually present are not detected when seas are rough, while near perfect detection is probable when seas are calm (which was the case in 73% of the total survey effort).

3.3. Presence probability estimation

Estimated presence probabilities of mega-debris over the SAMM study area were similar between the two surveys (Fig. S6). During the ASI, only 20% of the Mediterranean was free of floating mega-

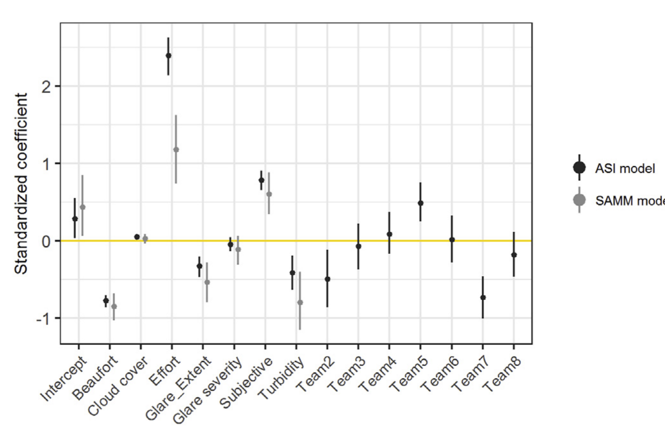

Fig. 3. Means and 80% credibility intervals of standardized coefficients for the detection process in the best models of ASI (black) and SAMM (in light grey) data.

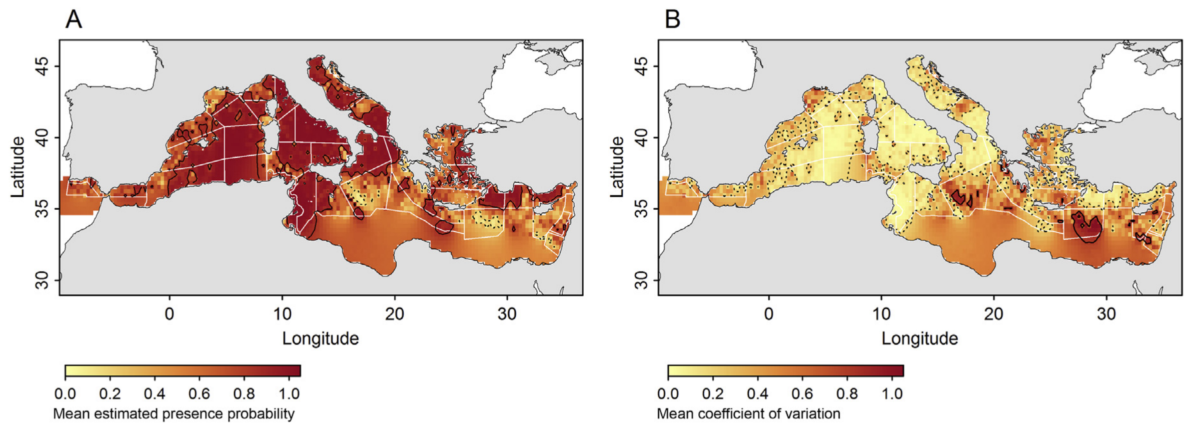

Fig. 4. A - Estimated presence probability (posterior mean) of floating mega-debris. B - Uncertainty in estimated presence probability (coefficient of variation). Isolines corresponding to contours of probabilities of 0.2 are shown in dotted black lines and 0.8 contours in solid black lines. ASI survey blocks are shown in solid white lines.

debris. The estimated presence probability was highest in the central and western Mediterranean, in the Tyrrhenian, northern Ionian, and Adriatic Seas and in the Gulf of Gabes ($\geq$ 80%; Fig. 4). The lowest presence probabilities occurred in the Levantine basin, in the southern Ionian Sea and in the Gulf of Lion ($\leq$ 50%).

3.4. Mega-debris density estimation

We estimated the quantity of floating mega-debris in the entire Mediterranean Sea in the summer of 2018 to a total of 2.9 million mega-debris (80% confidence interval: 2.7 – 3.1 million; average density of 1.5±0.1 items per km^2). High densities of debris were observed in the central Mediterranean (Tyrrhenian Sea, Adriatic Sea, northern Ionian Sea, off north-eastern Algeria and the Gulf of Gabes; Fig. 5 and Supplementary Materials Table S3). Cells with the highest densities occurred along the Tyrrhenian coast of Italy and in the Adriatic Sea, with up to 20 items per km^2. The lowest densities were observed in the eastern Mediterranean Sea.

Debris larger than 30 cm in size, however, represent only a fraction of all floating debris: in the central Mediterranean, only one fourth of all anthropogenic debris between 2 and $\geq$ 100 cm were larger than 30 cm (Suaria and Aliani, 2014). Assuming that the proportion of floating mega-debris larger than 30 in size cm is the same throughout the entire Mediterranean (*i.e.* $\approx$ 25.3% of all debris $\geq$ 2 cm), the total number of floating debris larger than 2 cm would scale up to $\approx$11.5 million of items.

4. Discussion

The spatially-explicit modelling of mega-debris presence from the first Mediterranean basin-wide aerial visual survey revealed a very heterogeneous distribution of floating mega-debris during summer. This is the first ground-truthing of the numerical simulations based on surface debris drifting by way of ocean circulation performed at the basin scale (Mansui et al., 2015). As such, this work will set a reference situation allowing the efficiency of future plastic pollution remediation strategies to be assessed.

Using hierarchical Bayesian models to account for imperfect detection provided very encouraging results and demonstrated the strong impairment of debris detection with an increase of sea state, glare extent and turbidity. Our results confirms that the perfect detection assumption made under strip-transect protocol does not hold when observation conditions derive from perfect detection. Sightings made under good observation conditions, *i.e.* a sea state lower than 4 in general, are commonly used to derive abundance or density estimate of debris over a study area, considering the detection probability to be homogeneous and at its maximum under those conditions. Yet, we showed that deriving from a sea

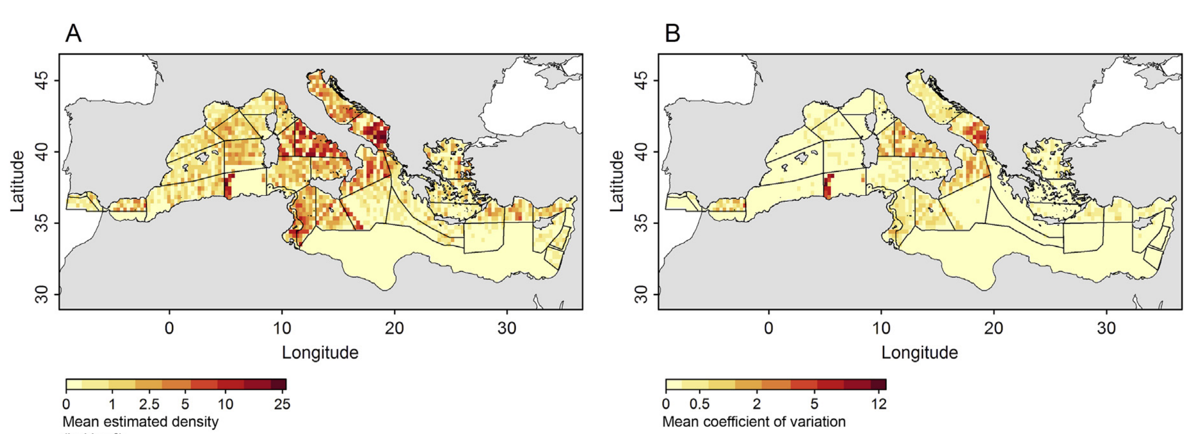

Fig. 5. A - Mean estimated densities of floating mega-debris (>30 cm) in number of item per km^2. B - Mean coefficients of variation of estimated densities per cell. ASI survey blocks are shown in solid black lines.

state of 0 to a sea-state of 3 imply a drop of ≈31% in detection probability of mega-debris. Therefore, our work calls for accounting systematically for imperfect detection into any abundance estimation procedure built from visual surveys following strip-transect protocol, irrespective of the target being debris or fauna (seabirds, turtles, fish …).

The line-transect protocol is the dedicated protocol to be used in case of varying detectability of objects with distance from the transect line and with observations conditions (Buckland et al., 2015), but such a protocol would be really difficult, if not impossible, to operationalise in a multi-target survey context for objects sighted in as large quantities as debris. The use of strip-transect protocol has proven to be operationally effective for collecting debris along with marine fauna and anthropogenic activities, but we show here that it as to be systematically associated to analytical process analogous to the hierarchical modelling used here to compensate for the non conservation of the perfect detection assumption.

We estimated that 2.9 million debris larger than 30 cm in size were floating in the Mediterranean Sea during the summer of 2018. The corresponding average density estimate (1.5 ± 0.1 items per km^2) was congruent with densities of floating debris ≥ 20 cm obtained from ship-based surveys in the central Mediterranean (2 − 5 items/km^2, not corrected for detection probability; Arcangeli et al., 2018). The same way, when extrapolating our estimate to debris larger than 2 cm in size, we obtained an estimate (11.5 million debris) of the same order of magnitude as a previous estimate of 62 million. Suaria and Aliani (2014) obtained this estimate by extrapolating densities from the central Mediterranean only, which explains it was larger than the estimation provided here. Due to the high level of heterogeneity in debris density revealed in this study - the first comprehensive estimate based on a survey of nearly the entire Mediterranean basin - we assert that great caution should be taken in making spatial extrapolation and drawing broader conclusions based on results of small-scale surveys within the Mediterranean Sea, as shown by the difference between our basin-scale estimate and the extrapolated estimate from the central Mediterranean Sea (Suaria and Aliani, 2014).

The floating mega-debris distribution was highly heterogeneous, but the observed pattern was associated with limited uncertainty. The longitudinal gradient in both presence probability and density of debris confirmed the largest prevalence of debris in the western and central basin compared to the relatively spared eastern basin. This distribution pattern of mega-debris mimics that of the Mediterranean biodiversity, which is greatest in the western basin (Coll et al., 2010). Coupled with the confirmation of the large prevalence of plastics in the marine debris of the Mediterranean Sea (more than two third; Suaria and Aliani, 2014; United Nations Environment Programme / Mediterranean Action Plan, 2015; Fossi et al., 2017; Arcangeli et al., 2018), this overlap suggests that the threat to Mediterranean fauna is at a maximum in the western basin. The close proximity to such a large amount of gathered debris poses a critical threat to Mediterranean marine biodiversity. Many endangered or vulnerable species −some endemic to the area- are at risk of entanglement or of ingesting debris, from deep-sea fishes to marine mammals, turtles and seabirds (Codina-García et al., 2013; Deudero and Alomar, 2015).

In addition to these direct threats, the widespread pollution and contamination caused by the fragmentation of floating debris into micro-particles exacerbate the vulnerability of many marine species that are already under pressure from ongoing environmental changes (Rochman et al., 2016; Alessi et al., 2018) and cause health hazards to higher trophic levels through trophic transfers of micro-particles covered with adsorbed organic pollutants (Thompson et al., 2009).

Beyond its impact on biodiversity, marine pollution might eventually disrupt entire ecosystems and associated services (Coll et al., 2010) and we may soon begin to see the impacts of the Mediterranean litterscape in the tourism industry and the well-being of its ever-growing coastal populations (through impact on landscape values, disappearance of fishing stocks, etc.). Currently, international instruments for addressing pollution take an incremental or piecemeal approach, resulting in a fragmented and largely toothless legal landscape (Kirk and Popattanachai, 2018). Rising to the challenges caused by pollution in the Mediterranean will require strong, binding international agreements and synergistic regulations that can only succeed with the serious involvement and commitment of governments, businesses and the civil societies of this biodiversity-rich region that is under high environmental and geopolitical stress.

5. Conclusion

Plastic pollution represents one of the biggest immediate challenges in the Mediterranean. An accurate description of the plastic litterscape at the basin-scale was therefore crucial to contribute understanding the origin and fate of these anthropogenic debris and identify areas of higher risk to marine life. Building from the first international basin-scale visual survey of the Mediterranean Sea, this study estimated the summer abundance of floating debris over the entire Mediterranean to 11.5 million debris, with highest densities in the central and western basins. This first basin-scale map of mega-debris distribution confirms the large prevalence of debris in the Mediterranean and highlights that their distribution closely mimics that of biodiversity. These results will set the scene for identifying high vulnerability areas to plastic debris for marine fauna, and permitting the implementation of adequate strategies to thwart plastic pollution in the Mediterranean Sea and its impact of marine ecosystems.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

C. Lambert: Conceptualization, Methodology, Formal analysis, Validation, Data curation, Visualization, Writing - original draft, Writing - review & editing. **M. Authier:** Conceptualization, Methodology, Formal analysis, Validation, Writing - original draft. **G. Dorémus:** Methodology, Investigation. **S. Laran:** Methodology, Conceptualization, Investigation, Data curation, Writing - original draft. **S. Panigada:** Funding acquisition, Investigation, Project administration, Writing - original draft, Writing - review & editing. **J. Spitz:** Conceptualization, Supervision, Writing - original draft. **O. Van Canneyt:** Methodology, Investigation. **V. Ridoux:** Conceptualization, Funding acquisition, Project administration, Supervision, Visualization, Writing - original draft, Writing - review & editing.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envpol.2020.114430.

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