Modelling exposure to plastics for the marine biota: Risk maps for fin whales in the Pelagos Sanctuary (North-Western Mediterranean)

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Introduction

Plastic materials have undisputably revolutionized our daily life and their countless purposes are reflected by their ubiquitous presence as litter in the environment. As a consequence, the concern about effects and long-term consequences of plastic waste is increasing. Not only is plastic persistent, causing unsightly issues, but it interacts with marine biota, for which it is often a cause of harm due to entanglement or ingestion (Deudero and Alomar, 2015), or for its potential release of a variety of toxic compounds (Engler, 2012; Worm et al., 2017).
The problem of plastic pollution in the environment, and in particular in marine ecosystems, has been known for decades, with the first impacts being observed in the 50's (with first records of marine turtles ingesting plastic, as documented by Cornelius, 1975 or Balazs, 1985), less than ten years after the discovery of the most used polymers. Recently, awareness on the problem of plastic pollution has been raising and brought to the public attention thanks also to captivating definitions – like the *"garbage patches"* – and the heart-breaking, countless photos of seabirds, marine turtles and beached cetaceans entangled in or killed by plastic.
In parallel with scientific research discovering about how plastic fragmentates into smaller and smaller particles, more and more environmental compartments are found to be contaminated by plastic: lakes and streams, soils, sediments, marine biota and even the air. With the invention of plastics, polymer science has introduced a unique material in terms of both utility and low-cost. However, its durability and end-of-life mismanagement have also led to a global danger for ecosystems and all populations (including humans) relying on the many ecosystem services provided by nature.

The ultimate solution to plastic pollution is, in the first place, to prevent contamination (Koelmans et al., 2014). To mitigate the negative effects of plastic on the environment it is therefore necessary to identify its sources and sinks, and to understand the mechanisms contributing to its redistribution. Only in this way knowledge-based local actions can be effectively implemented.

1.1 Plastic litter in the Mediterranean Sea: a threat for the marine ecosystem

Over 17,0000 marine species inhabit the Mediterranean Sea, about 7% of the world's marine biodiversity. At the same time, the Mediterranean basin is among the most impacted ecoregions globally due to an increasing anthropogenic pressure (Halpern et al., 2008), with a coastal population of 507

millions in 2008, predicted to rise to between 520 and 570 millions by 2025 (UNEP Blue Plan Activity Centre, 2008), and maritime traffic which amounts to 19% of the world's maritime freight volume (SRM, 2013). These threats are worsened and amplified by the introduction of non-native, invasive species (Zenetos et al., 2012; Micheli et al., 2013) and by the impacts of climate change (Lejeusne et al., 2010).
The Mediterranean Sea is no stranger to the issue of marine litter: some samplings have revealed concentrations similar to the ones of the North Atlantic Gyre (Suaria et al., 2016). The seasonal variability of surface currents and the strong influence of wind prevent the formation of garbage patches, making plastic pollution in this sea more like *a plastic soup* (Suaria et al., 2016). Suaria et al. (2016) estimate between 873 and 2,576 tonnes of plastic floating in the so-called *mare nostrum*. Furthermore, at least 134 species have been found to be affected by floating and seafloor litter, including endangered and commercial species (Deudero and Alomar, 2015) (in 1.1, some examples of species affected by marine litter).

(a)

(b)

(c)

Figure 1.1: (a) A sea turtle entangled in abandoned fishing nets, (NOAA); (b) a dead albatross chick in Midway Atoll National Wildlife Refuge (Pacific Ocean), (U.S. Fish and Wildlife Service); (c) a hermit crab using plastic garbage as a substitute for shells (Shawn Miller).

Part of the Mediterranean biodiversity is due to the presence of marine mammals. The Mediterranean Sea hosts at least 21 cetacean species (IUCN, 2012), some of which have been classified as Vulnerable or Endangered. Some cetaceans play a key ecological role in marine ecosystems (Katona and Whitehead, 1988; Pace et al., 2015) and have been also reported as sentinels or indicators for the state of the ecosystem they live in (Coll et al., 2010; Azzellino et al., 2014). Not least, they are an iconic and charismatic taxon that captures public attention, factors that can in turn provide a significant drive towards effective ecosystem conservation and management. This has been quite the case for the

creation of an *International Sanctuary for the Protection of Mediterranean Marine Mammals*, also known as the *Pelagos Sanctuary* (`http://www.sanctuaire-pelagos.org/`). It is located in the North-Western Mediterranean Sea, between South-Eastern France, Monaco, North-Western Italy and Northern Sardinia, with a surface of more than 87,000 km^2.
One of the most abundant marine mammals in this area is the fin whale *Balaenoptera physalus* (Fig. 1.2), a mysticete whose local population size amounts to about 3,500 individuals. The fin whale is known to feed on krill in Pelagos during summer season, though it can be observed in this area all the year round (Forcada et al., 1996; Notarbartolo di Sciara et al., 2003). The fin whale has been regarded as one flagship species to highlight the impacts of microplastics on marine life (Germanov et al., 2018): plastic can cause a significant reduction in nutritional uptake for filter feeders like fin whales, with animals feeding on the same quantities of particulate matter but receiving a lowered nutritional benefit. Furthermore, Fossi et al. (2012) have detected leached plastic additives in Mediterranean fin whales, evidence of microplastic ingestion. For this reason, *Balaenoptera physalus* has been selected as a target species for this study, whose aim is an assessment of the presence of plastic waste in its feeding grounds within the area of Pelagos.

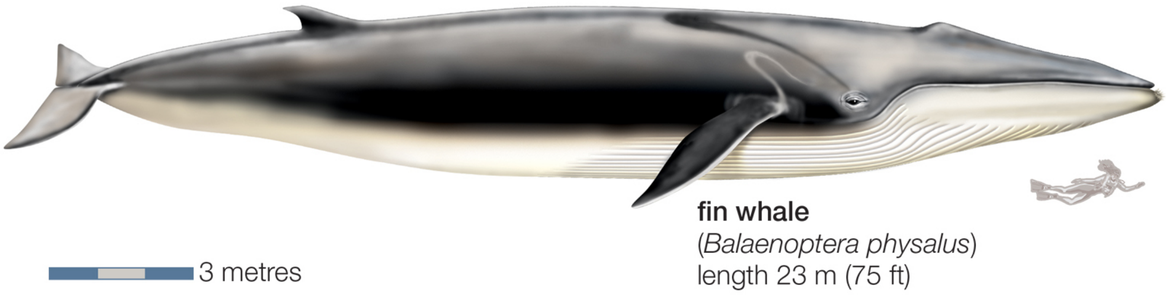


Figure 1.2: The fin whale Balaenoptera physalus. (Image from Encyclopaedia Britannica)

1.2 Goals of this work

This research has been structured in three main parts. The first part involves the numerical modelling of plastic particles and their advection by surface currents, using reanalysis data. The dynamicity of surface circulation makes this approach crucial to have a clear and accurate understanding of the movement of plastic fragments in the sea, so as to study their propagation, highlight the presence of temporal accumulation zones, and assess the exposure of coasts to beached waste.

The second part of this work consists in evaluating the potential suitable habitat of the fin whale, on the basis of satellite-informed time varying data. After Fossi et al. (2017), the evaluation of the location of potential feeding grounds of *Balaenoptera physalus* has been performed here by considering the predictors identified by Druon et al. (2012) for their environmental niche model. This model has been calibrated by Druon et al. (2012) on the decade 2000-2010, thus permitting us to assess the level of plastic exposure potentially faced by the fin whales whose sightings were part of the calibration dataset used by Druon et al. (2012).

The third and final part of this work overlaps maps of plastic concentration (the *hazard*) and potential suitable habitats of the fin whale (the *exposure*) so as to assess the risk for the fin whale (intended as

the mapping of the product between *hazard* and *exposure*) and, on a wider perspective, on the marine wildlife in Pelagos.
As preventing contamination is central to tackle plastic pollution in our seas in the first instance (Koelmans et al., 2014), an in-depth analysis of the sources of plastic contamination informed by real-life plastic waste production data can finally be used as a tool to address local actions on the most impacting sources.

2

Methods

2.1 Modelling the distribution of marine plastic litter in the study area

Numerical simulations are one of the key tools to improve the understanding of plastic pollution and its propagation in the marine environment. Lagrangian modelling is the preferred approach due to the similarities between the definition of Lagrangian particle and microplastic particle. Lagrangian particles are assumed to be point-like, and represent a certain mass of the tracer of interest. They do not interact with each other and are conservative. Their advection is simply modelled by recording the trajectory of particles being moved by velocity fields that represent the flow of the transport media, and registering their coordinates at suitable points in time, calculated by solving the simple differential equations of motion.

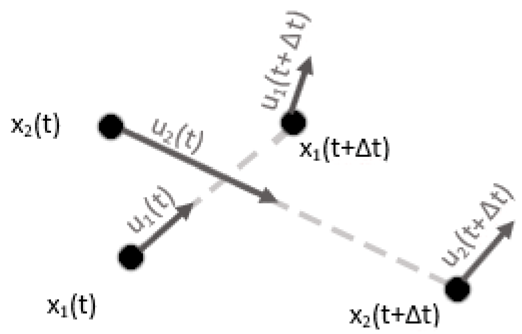


Figure 2.1: Example of Lagrangian simulation. Particles 1 and 2 are transported from their positions $x_1(t)$ and $x_2(t)$ by the local velocity vectors $u_1(t)$ and $u_2(t)$. At the end of the time step Δt, the updated particle locations, $x_1(t + \Delta t)$ and $x_2(t + \Delta t)$ will be their initial positions during the next iteration.

The flowing of the ocean currents is described using velocity fields obtained from ocean general circulation models, such as HYCOM and NEMO (as in Lebreton et al., 2018; Liubartseva et al., 2018, and several others). In this case, reanalysis techniques are used to ensure that model outputs provide an accurate representation of actual circulation patterns, since they account for (and partially incorporate) measured data. The advection of plastic particles in this study is forced by ocean current velocities provided by reanalyses available thanks to Copernicus, the Marine environment monitoring service of the European Union (`http://marine.copernicus.eu/`), specifically, the Mediterranean Sea Physics Reanalysis product (available at `https://doi.org/10.25423/medsea_reanalysis_phys_006_004`).

To assess the distribution of particles in the study area, complementary to sources of plastic waste, removal mechanisms from the sea compartment have been taken into account. Once in the marine environment, in fact, buoyant plastic fragments can leave the surface layer due to fragmentation in smaller and smaller pieces (mainly due to exposure to UV radiation, Kalogerakis et al., 2017), sinking or beaching on coastlines. Thus, to include removal of plastic fragments in the model, we characterized Lagrangian particles by a certain "life-time", intended as the duration of their transport, regardless of the release modality. Implying that sinking is a Poissonian process, particle residence times in the marine environment could be extracted by approximating an exponential distribution with average decay rate $\lambda = \frac{1}{50}\mathrm{d}^{-1}$ into three classes with relative frequency of 1/3 each. The mean value of advection duration for each class can be easily calculated as 10, 36 and 105 days of advection before sinking. The calculated advection times are consistent with the existing literature (Liubartseva et al., 2016; Poulain et al., 2012; Holmström, 1975; Chubarenko et al., 2016).

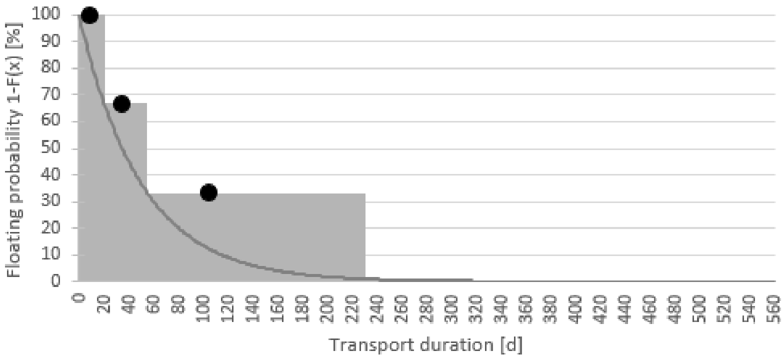


Figure 2.2: Particle advection times, modelled here with an exponential distribution with decay $\lambda = \frac{1}{50}d^{-1}$ (solid gray line). The approximated distribution is discretized into three classes (gray histogram). Particle advection times used in simulation correspond to the means of the selected classes (black dots).

All these details being implemented, the simulations have been run to have daily particle distributions over the summer season, which has been assumed to last from 20$^{\text{th}}$ June and 23$^{\text{rd}}$ September, to account for the yearly variability of the solstice and equinox dates. In other words, each year of simulation includes 96 days of particle location data. Considering all source types and the three iterations (one per advection time), a total of 1,739,100 particles is released altogether every day, accounting for about 3 billion particles simulated and being monitored along an eleven years window (2000-2010).

2.1.1 A simulation domain for the Pelagos Sanctuary

Even though the main focus of the study is to provide ecologically relevant indicators for the area of the Pelagos Sanctuary, the simulation domain covers a wider geographical area, spanning from 3.5°E to 12.5°W latitude and from 38.5°N to 45°N (see Fig. 2.3): this choice has been made for a better and more realistic simulation of particle transport on a larger scale, as litter may enter the Mediterranean Sea also from sources that are far away from the Marine Protected Area and then reach it during advection.

In our simulations, particles have been released from three types of sources: coastlines, mouths of the major rivers and main maritime routes (Fig. 2.3). To increase variability and somehow mimic occasional release, an additional random displacement in a 100 m radius has been applied to each particle before initializing simulations.

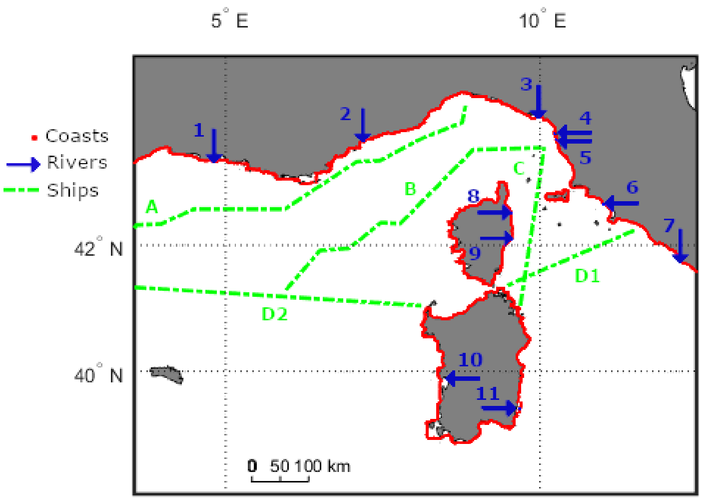
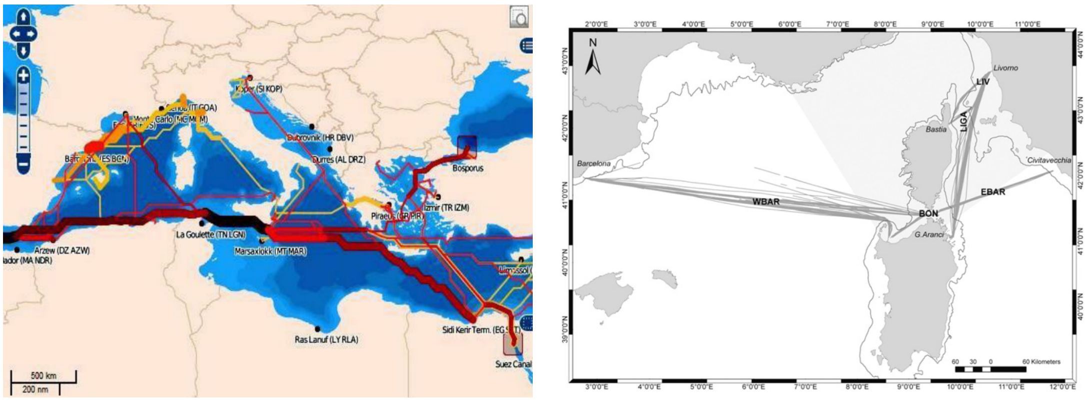


*Figure 2.3: Sources of particles used in the simulations. Major rivers flowing directly into the simulation domain (blue arrows indicate their mouths) have been numbered from West to East: **1.** Rhone, **2.** Var, **3.** Magra, **4.** Serchio, **5.** Arno, **6.** Ombrone, **7.** Tevere, **8.** Tavignano, **9.** Golo, **10.** Tirso, **11.** Flumendosa. Shipping lanes (green dash-dotted lines): **A** Genova-Barcelona, **B** Livorno-Barcelona, **C** Livorno-Olbia, Civitavecchia-Barcelona eastern **D1** and western section **D2**.*

Coastlines included in the simulation domain encompass the Italian regions of Liguria, Tuscany, Sardinia and part of Lazio, and the French Cote d'Azur, part of the Languedoc-Roussillon coast and Corsica. Overall, 3,843 particle release sites have been selected. From each release point on the coastline, marked as red dots in Fig. 2.3, 300 particles were released every day.
Eleven rivers have been included in the simulation domain for their high average annual discharge, which makes them likely to introduce a large amount of debris in the Mediterranean Sea. The selected rivers are Magra (Liguria), Serchio, Arno and Ombrone (Tuscany), Tevere (Lazio), Tirso and Flumendosa (Sardinia) in the Italian part of the domain; and Rhone (Camargue, in the Languedoc-Roussillon region), Var (Cote d'Azur), Golo and Tavignano (Corsica) in France (numbered in Fig. 2.3). The number of particles released daily from rivers amounts to 30,000, to ensure an adequate spreading of the riverine-released particles over the geographic domain, considering that rivers are assimilated to point-like sources.

As for maritime routes, 854 points have been placed every 2 km along the naval tracks obtained from the SafeMED GIS (`http://safemedgis.rempec.org/`) and from the ones observed by Campana et al. (2018). Namely, the selected routes are: Genova-Barcelona, Livorno-Olbia, Livorno-Barcelona and Civitavecchia-Barcelona (dash-dotted lines marked with letters in previous Fig. 2.3).



(a) *(b)*

Figure 2.4: Major shipping routes in the Mediterranean Sea. (a) Data after the Regional Marine Pollution Emergency Response Center for the Mediterranean Sea (REMPEC) (2009). (b) Routes monitored by Campana et al. (2018).

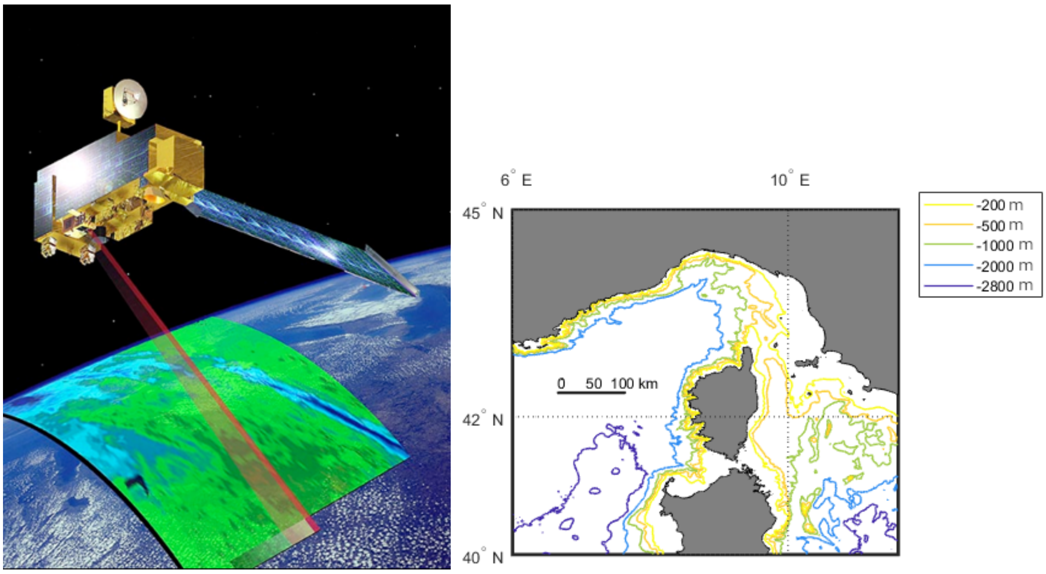
2.2 Potential habitat of *Balaenoptera physalus*

To identify maps of exposure to plastic for fin whales, we used a simplified version of the model calibrated by Druon et al. (2012): we applied it by selecting as potential habitat criteria the range of chlorophyll-a concentration and water depth. We therefore used MODIS-Aqua data (Moderate Resolution Imaging Spectroradiometer aboard the NASA-Aqua satellite, available at `https://oceandata.sci.gsfc.nasa.gov/MODIS-Aqua/`) and bathymetry data from GEBCO (see Fig.2.5). Fin whale potential (or suitable) habitat has been identified by the simultaneous presence of the optimal chlorophyll-a concentration range 0.11 to $0.39\,\mathrm{mg/m^3}$ for MODIS-Aqua and water depths ranging from -200 to -2800 m, as most ($> 80\%$) of the recurrent potential habitat located by Druon et al. (2012) appears to have those depths.

2.3 From particle-based simulations to ecological risk maps

The simulation outputs consist in 1,056 daily particle displacement matrices covering the geographic domain of interest for each type of particle source (coasts, rivers or ships), giving a total of 3,168 data structures to be analysed. Further spatiotemporal processing of the outcomes is then fundamental to study particle distribution patterns and to make those results readable in terms of hazard for whales. The goal is in fact to couple the hazard map with the suitable habitat for *Balaenoptera physalus*, so as to assess the exposure of whales to plastic in the North-Western Mediterranean Sea.

Processing of the simulation outcomes included averaging, calculation of the coefficient of variation over the simulated years and assessment of the contribution of each single source to plastic pollution in Pelagos.
Daily results have been averaged over the summer season of each year, keeping distinct at first the three types of sources (coastal, riverine or maritime), and subsequently aggregating them to reveal a more comprehensive and realistic picture of plastic distribution in the study area. The obtained yearly averages were then normalized by dividing them by their maximum values, so as to obtain a



(a) *(b)*

Figure 2.5: (a) Concept of MODIS scan (on Aqua satellite) (from `https://podaac.jpl.nasa.gov/`*); (b) Water dephts in the study area, as provided by GEBCO*

data-driven, weightable set of hazard maps. Source aggregation has then been operated by applying different weights, namely a coast-to-rivers-to-shipping lanes ratio of 50%:30%:20% after Liubartseva et al. (2018).
Then, inter-annual averaging has been applied on the whole study period (2000-2010), once again considering at first the three different sources of plastic contamination independently, and then aggregating them as explained above.

Visually comparing plots of average particle concentrations throughout the years can already give a qualitative idea of the interannual variability of plastic distribution. However, a quantitative indication has been obtained by calculating a measure of temporal dispersion of plastic concentration over time in each cell of the domain, the coefficient of variation (CV). This quantity, is calculated by dividing the standard deviation by the mean, thus measuring the extent of variability. Again, the coefficient of variation has been calculated over the decade by first distinguishing the sources and then by aggregating them via the 50:30:20 weights proposed for the Mediterranean region by Liubartseva et al. (2018).

Another analysis that has been applied to the simulation output is the assessment of source apportionment for the particles entering the Pelagos Sanctuary. The contribution of the different sources on plastic pollution in Pelagos has been evaluated, on a yearly basis, by computing for each source point the ratio between the average number of particles that entered the Sanctuary and the overall amount of simulated particles within the Marine Protected Area, independently of their origin. The inter-annual mean values of the relative source contributions can then be easily evaluated through averaging. In a second instance, the three types of release sites have been weighted with the 50:30:20 scheme proposed by Liubartseva et al. (2018) and then averaged. To this end, sites whose inter-annual mean contribution exceeded the 95$^{\text{th}}$ percentile of the obtained distribution have been highlighted to map the most impacting sources in the considered period.

2.3.1 Mapping the potential risk for *Balaenoptera physalus* and for other filter-feeding megafauna

Risk of exposure to plastic has finally been calculated following an approach similar to the one used by Wilcox et al. (2012, 2015), namely as the product between two gridded fields of plastic density data (as resulting from our Lagrangian simulations) and fin whale potential suitable habitat (calculated as described in Section 2.2), i.e.:

$$\text{Fin whale exposure} = \text{hazard of plastic presence} \times \text{exposure of relevant species} \qquad (2.1)$$

To do so, monthly averaged simulation outputs, comprehending all release sites, have been used to assess the risk for *Balaenoptera physalus* in the decade 2000-2010, ad hoc recalibrating the niche model by Druon et al. (2012) using satellite data (as described in Section 2.2), by converting it into a gridded mask whose cells have value 1 for suitable sites and zero for others. According to our method, areas that are not likely to be crossed by feeding fin whales would be mapped as no risk (= 0) areas.

The risk maps obtained as explained above have been compared with the ones designed for filter-feeding species in another approach by Sherman and Van Sebille (2016), where exposure is based on Net Primary Production (NPP), an indicator of phytoplancton growth, which is at the basis of the food chain. NPP has been obtained by the monthly-averaged Mediterranean Sea Biogeochemistry Reanalyses provided by Copernicus (available at `https://doi.org/10.25423/MEDSEA_REANALYSIS_BIO_006_008`).

Monthly maps of risk, obtained with both the methods based on Druon et al. (2012) and Sherman and Van Sebille (2016), have been averaged on the summer seasons of each studied year to obtain, on a yearly basis, a mean risk map of Pelagos Sanctuary. Decade-averaged risk maps have also been produced for both approaches.

3

Results

3.1 Plastic distribution in the Pelagos area and source apportionment

3.1.1 Particle distribution in single-source scenarios

Particle displacement, as resulting from Lagrangian simulations, shows a consistent inter-annual variability, appreciable by a visual comparison of the yearly mean plots. In general, particle behaviour is different depending on the type of source: linear sources, like coastlines and maritime routes, tend to spread tracers on a wider area than point-like sources (river mouths). Diffusion of particles from point-like sources does strongly depend indeed on the local features of water circulation observed in a specific year (see Appendix A). An analysis of long-term plastic circulation patterns can be made from the inter-annual average particle distributions on the simulated decade (Figure 3.1). It can be observed that the spatial distributions of plastics is far from being spatially heterogeneous. Quite interesting high density locations are the gyre-like structure in the Tyrrhenian Sea or the high concentration area in the Ligurian Sea (marked by black boxes in Figure 3.1c). Not only such structures emerge on the decennial averaged maps of Figure 3.1, but they are recurrent during the years (see Appendix A).

The study of the variation coefficient helps in understanding the inter-annual variability of the observed concentration patterns, as caused by Mediterranean currents. As outlined in Figure 3.2, the average density patterns are interested by relatively small inter-annual variability in some areas, while they are more heavily influenced by the effect of isolated occurrence of concentration peaks in others. In summary, while shores are more constantly influenced by particles released from shorelines themselves, their exposure to other sources may vary from year to year, depending on the actual circulation regime. Furthermore, particles discharged from rivers show a highly varying distribution in the Ligurian Sea during the years (see Appendix A.2), right in the middle of Pelagos.

As for the apportionment of the contribution of each release point to the overall amount of particles entering Pelagos, shown in Figure 3.3, sources located within the boundaries of Pelagos appear to be contributing the most for all the three release scenarios studied, which can be somehow expected. This is particularly evident for coastal and riverine particle inputs (Figures 3.3a and 3.3b), which make evident a remarkable difference between the sources located within the Sanctuary and the others. Some maritime sources outside Pelagos appear instead to have a minor impact through the years (see

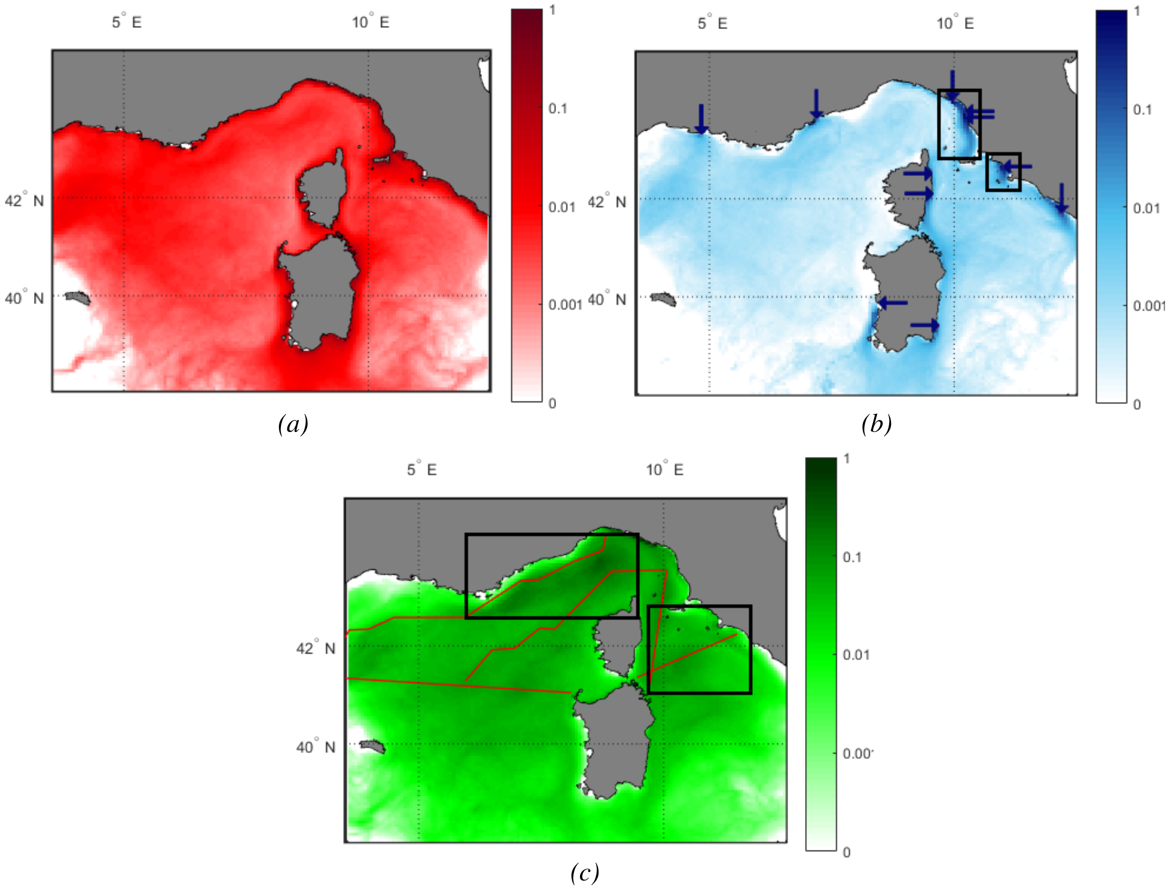


Figure 3.1: Interannual average of particle distribution for the period 2000-2010 from each source of release: (a) coasts, (b) rivers and (c) ships. The features (blue arrows and red lines) in panels b and c correspond to the release sites from rivers and maritime routes. Particle density in each cell has been normalized by the inter-annual maximum of the relevant spatial distribution and plotted in logarithmic scale. Boxes in (b) and (c) highlight the locations mentioned in the text for the relevant source type.

also figures in Appendix B.3).

Interestingly, the only source points located outside the boundaries of the Marine Protected Area that provide a constant contribution throughout the years are some short sections of the maritime routes. While the highest impact comes again from the parts of the routes that cross the Sanctuary, a non-negligible contribution to plastic concentration within Pelagos seems to be provided, in all simulated years, by some portions off the western border of the Sanctuary.

3.1.2 Overall plastic distribution

Despite the importance of understanding the contributions of various sources to the hazard caused by plastic pollution, a more operative and practical understanding of long-term particle accumulation sites in the simulation domain can be provided by observing the overall average and variation coefficient on 2000-2010, considering all three sources together. As explained in Section 2.3 at page 8, we weighted particle distribution resulting from release by coastlines, river mouths and ships by using the

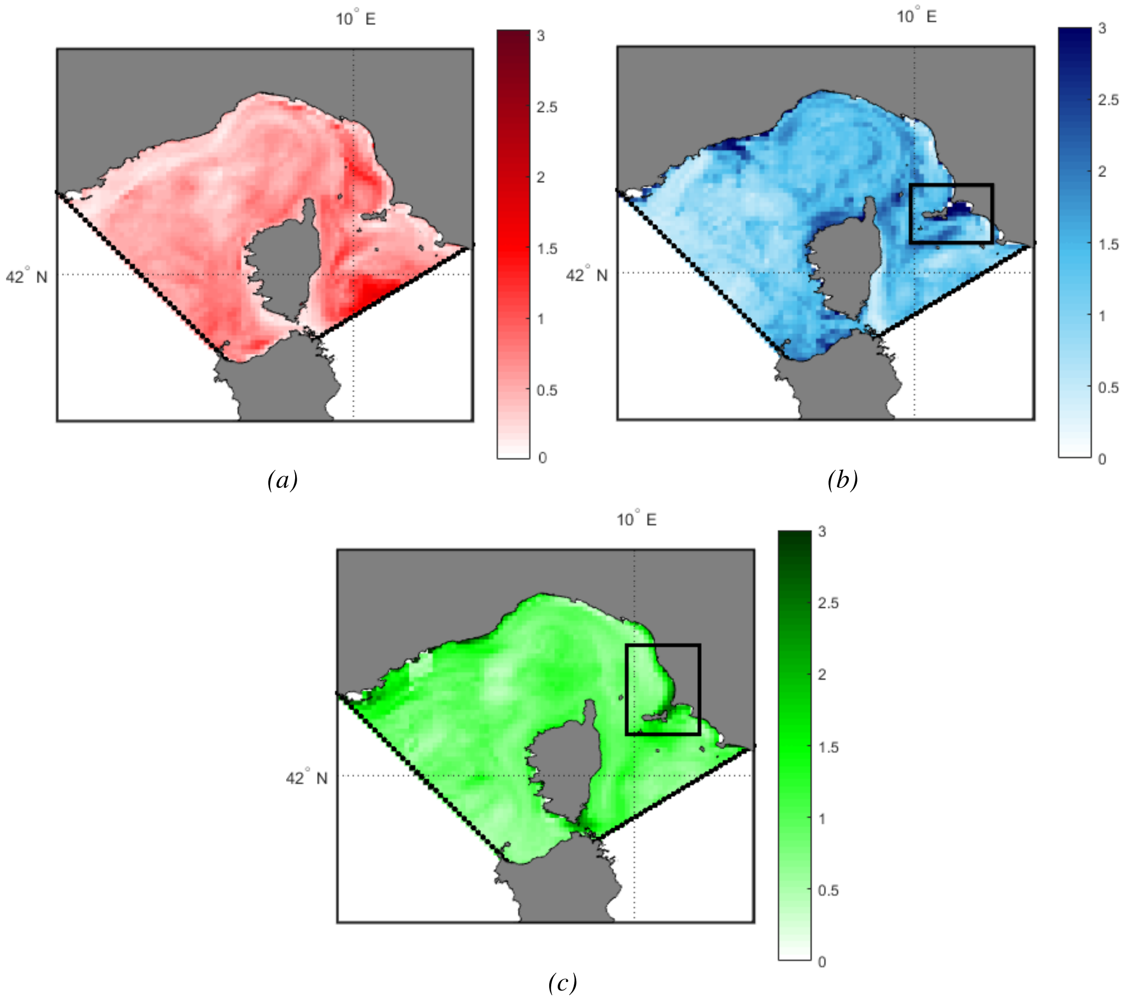


Figure 3.2: Coefficient of variation for 2000-2010 in the Pelagos Sanctuary area, delimited with black lines. Black boxes in (b) and (c) point out the Follonica gulf and the coast of Tuscany north of Elba Island, mentioned in the text.

coasts-to-rivers-to-maritime routes ratio of 50:30:20, as proposed by Liubartseva et al. (2018) for the Mediterranean Sea.

In summary, particle distribution varies in the simulated decade depending on the source type and the strength and direction of the marine currents of that particular year. Some hotspots appear to be more time-persistent than others, like the high particle concentrations that build up along the shorelines, or north-west of Elba Island. On the other hand, other features that form farther from coasts, like the high concentration areas in the Ligurian and Tyrrhenian Seas, vary conspicuously in extent, shape and peak values, although they are present in all the summers of the years considered.

We identified the sources which impact the most on Pelagos Sanctuary, among all the modelledones, as the top 5%. This has been performed both for each simulated year (figures in Appendix B.3) and for the inter-annual average value evaluated for the whole decade (Figure 3.5). Quite unexpectedly, no coastal sources figure among the top 5% contributors in most years, despite their role in certain particle accumulation areas (see Section 3.1.1 above), and the weight assigned by Liubartseva et al.

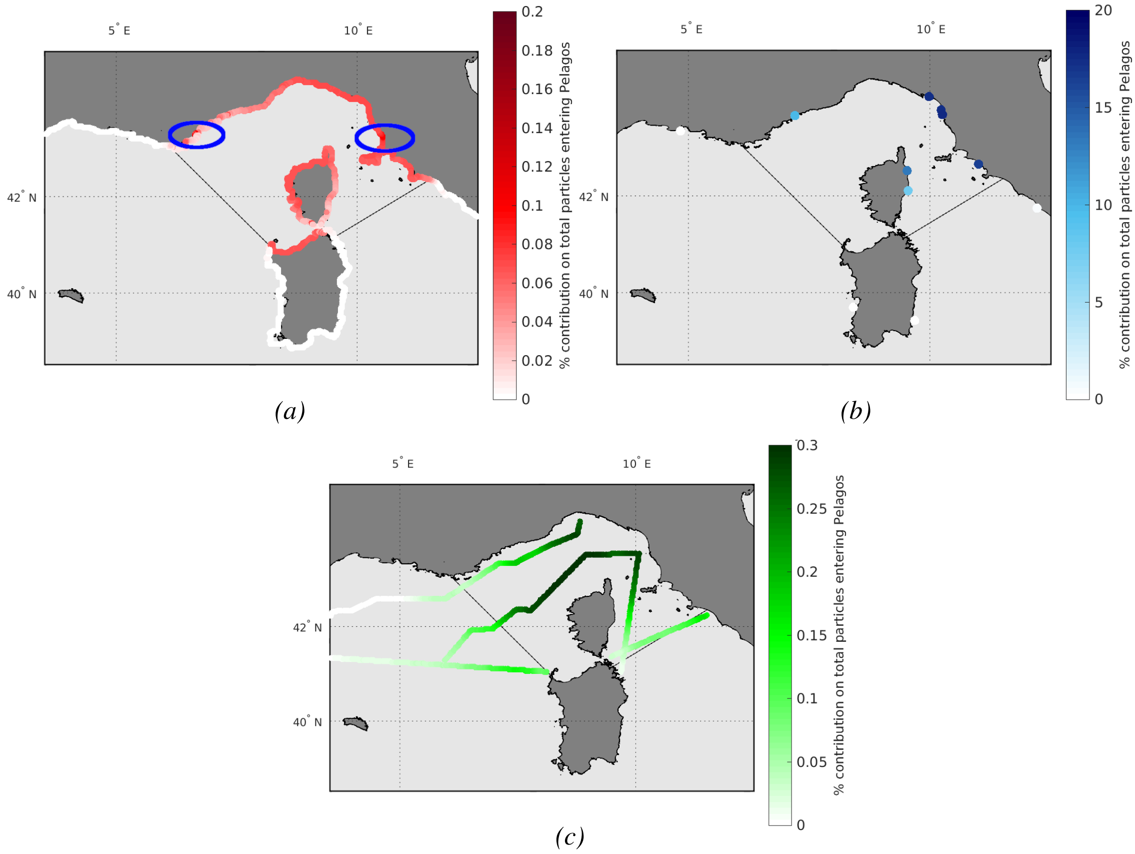


Figure 3.3: Percentage of average contribution in 2000-2010 by each of the three sources. The boundaries of Pelagos Sanctuary are shown in black.

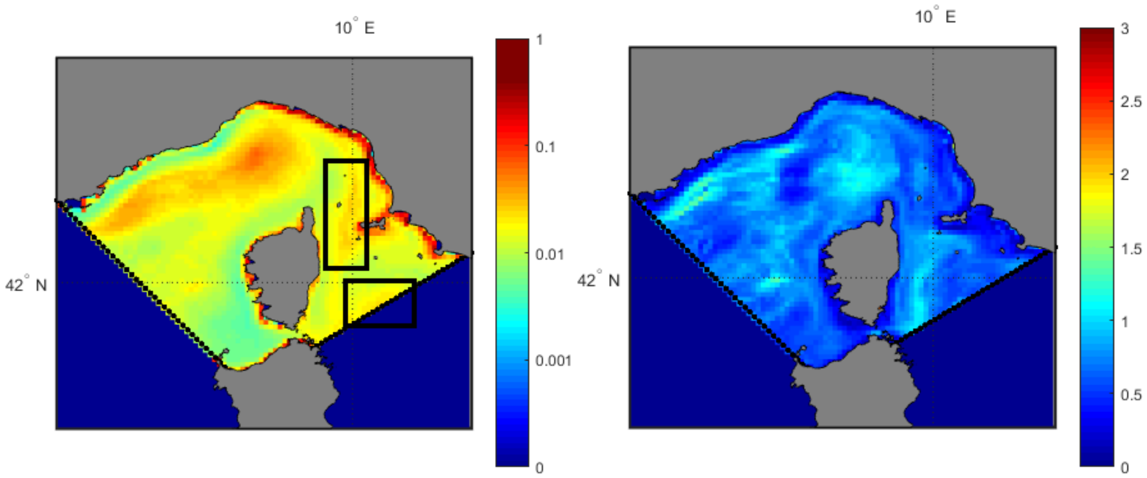
(50%, against the 30% of rivers and 20% of ships). However, all release points located on the shores contribute to more than 40% of the particles in Pelagos on average altogether. This happens because, even if their single contribution is low, their overall impact on the studied area is important.

Among the most impacting sources, highlighted in Figure 3.5, there are some transects of the maritime routes that cross the Sanctuary. This is all the more remarkable, as ships are assigned the lower weight in the scheme used here as proposed by Liubartseva et al. (2016).

All rivers flowing directly into the Sanctuary's waters are among the top 5% contributors during all the years considered. River Tevere (number 7), which seems to play only a minor role on average (see Figure 3.3b), is instead one of the most influential release points in some of the years (2005 and 2009, Figures B.2f and B.2j in Appendix B).

3.2 Potential suitable habitat of the fin whale in 2000-2010

As explained in Section 2.3.1 at p.10, two approaches have been applied to assess the exposure of the fin whale to plastic pollution in the examined area. One exploits a simplification of the model applied by Druon et al. (2012), tailored on *Balaenoptera physalus*, and the other is based on the NPP (after



(a) *(b)*

Figure 3.4: Average normalized particle distribution (log scale) (a) and coefficient of variation (b) in 2000-2010, within the Pelagos Sanctuary (delimited by black lines). All three sources have been weighted and grouped (see text). Boxes in (a) highlight two concentration hotspots described in this Section.

Sherman and Van Sebille, 2016), addressing in a wider sense the whole ecosystem. Estimation of the potential habitat is a crucial step to evaluate the risk of exposure to plastic. Habitat suitability has been computed monthly for both the methods exposed above (individual plots are visible in Appendix), and then summarized into seasonal and inter-annual average values, shown in Figure 3.6 (a) and (b).

The average suitable habitat, as computed with the simplified Druon model for the period 2002-2010 (see Section 2.3, p.8), appears to encompass the majority of the Pelagos Sanctuary (Figure 3.6a), except for the shallower waters of the Tuscan Archipelago and of the coasts of Corsica and Sardinia, and depths greater than 2800 m, off the west Sardinian coast. For what concerns the NPP, the highest values within Pelagos (Figure 3.6b) are located close to the northern coast of Tuscany (in the proximity of the mouths of rivers 4 and 5), in the Tyrrhenian Sea and in the Liguro-Provençal basin, extending westwards, which is notoriously an area characterized by high productivity (Stocchino and Testoni, 1977). Both methods used to estimate potential feeding grounds for the fin whale yield relatively similar results: shape and extension of suitable habitats are comparable with the ones with higher NPP.

3.3 Exposure of *Balaenoptera physalus* and other filter- feeding cetaceans to plastic particles

After obtaining the hazard of contamination by plastic in terms of average particle distributions in the Pelagos domain and describing species-specific criteria to identify the fin whale's suitable habitat, the risk due to potential exposure of this flagship cetacean species to plastic particles has been calculated as explained in Section 2.3.1.
Again, in addition to monthly and summer averaged exposure plots, exposure has been studied by averaging the summer season results of years 2000-2010 and evaluating the corresponding coefficients of variation for both approaches. The two methodologies provide coherent results because, in general,

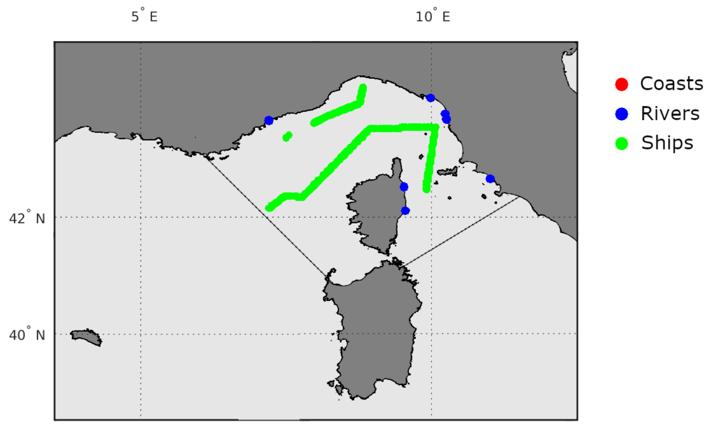


Figure 3.5: Map of the most impacting sources, defined as those that exceeded the 95° percentile of the overall distribution of source contribution on the Pelagos Sanctuary, averaged over the whole study period.

risk hotspots are located in the same or nearby areas for both assessment methods.
Maximum risk values are located along the coasts. For instance, both methods agree on the level of threat associated with the Ligurian and western Corsica coasts. In some areas, the two methods produce somewhat contrasting results, as for the eastern littoral of Corsica and the coastal marine area of Tuscany, where the suitability-based method provides a lower estimate of plastic exposure risk than the NPP-based method does. In fact, this area presents too shallow seafloor depth for the criteria applied after Druon but, at the same time, primary productivity here presents high average values (see again Figure 3.6b).
The widest hotspot of potential plastic exposure is, in both cases, located in the Ligurian Sea, the average severity of which declines moving along the French littorals. The two methods also predict a similar grade of interannual variation in risk of exposure for this region (see Figure 2.5a and 3.6f). Other two areas appear to be at considerable risk, the Tyrrhenian Sea and the area between the Tuscany Archipelago, but to a lesser extent compared with the Ligurian Sea.

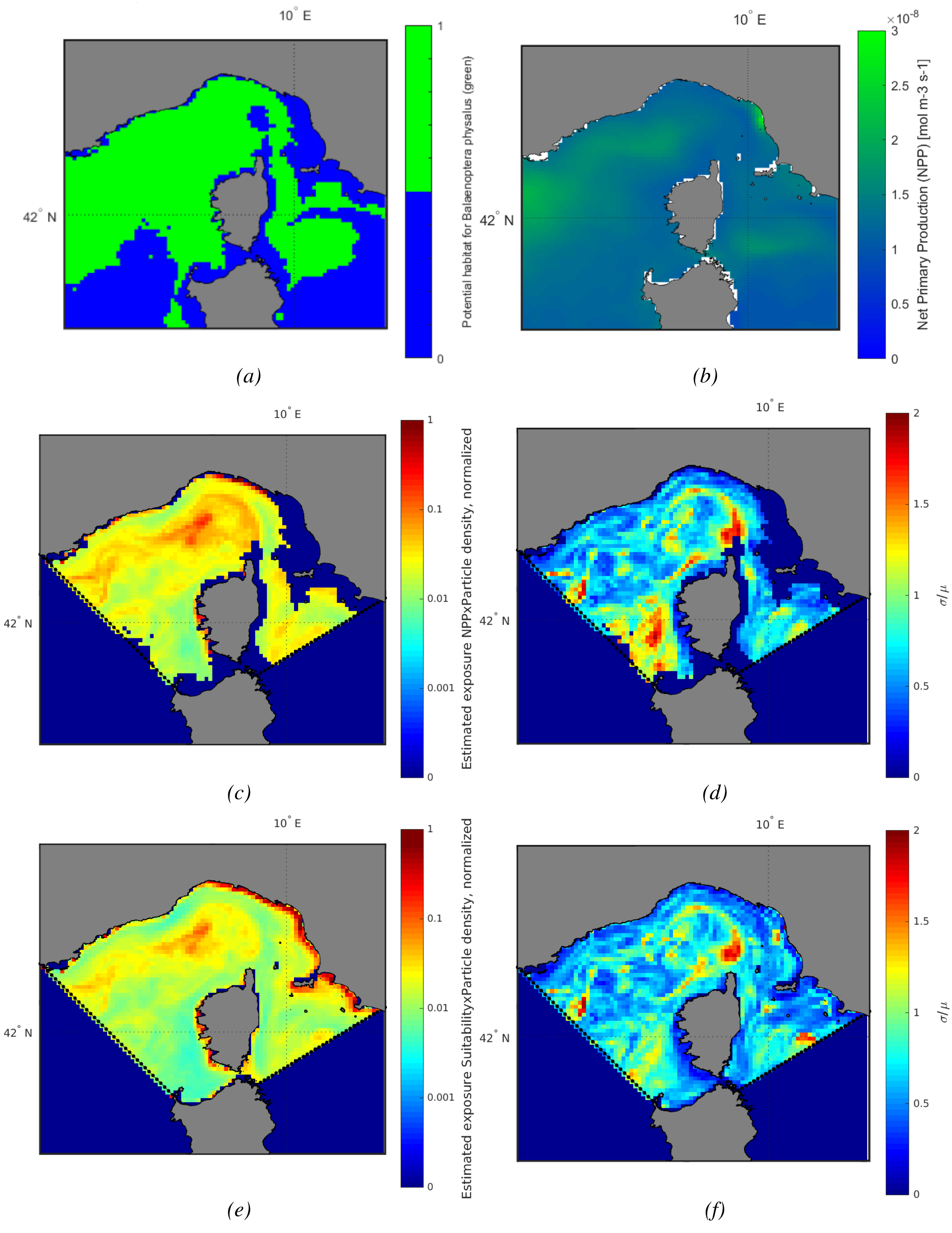


Figure 3.6: Panels (a) and (b): average suitable habitat calibrated using a simplification of the model by Druon et al. (2012) on 2002-2010 (a) and using the average NPP on 2000-2010, according to Sherman and Van Sebille (2016) (b). Averaged risk of exposure to plastics and coefficient of variation (CV) for both fin whales (panels c and d) and other filter-feeders (panels e, f).

4

Discussion and Conclusions

In the present work, an extensive number of Lagrangian simulations has been run to obtain the surface advection patterns of plastic litter on a wide geographical domain (3.5° - 12.5° E, 38° - 45° N) embracing the *Pelagos International Sanctuary for the Protection of Mediterranean Marine Mammals*. Aim of this modelling exercise was to assess the presence of plastic waste within the feeding grounds of *Balaenoptera physalus*, an endangered cetacean with a genetically separated population inhabiting the Mediterranean Sea. About 3 billion particles have been released from coastlines, major rivers and most congested shipping lanes during the study period 2000-2010, and particle transport has been forced by the surface ocean currents provided by Copernicus Mediterranean Sea Physics Reanalysis product (Lazzari et al., 2010). Fin whale suitable habitat has been calibrated on satellite-derived data and bathymetry derived data, using a selected subset of the criteria identified by Druon et al. (2012), based on whale sightings occurred during the decade 2000-2010. The same inter-annual scale has then been chosen for the simulations of plastic propagation, so as to assess the risk of plastic exposure potentially faced by the species. The potential feeding grounds detected in the present work have been compared with satellite-derived average Net Primary Production in the same areas, which has been used here as a proxy of ecosystem size. The suitable areas detected with both the simplified Druon model and the NPP maps have been used to finally compute the risk of exposure of the fin whale and of marine ecosystems in general to plastic pollution. Over the ecologically relevant summer months of the decade 2000-2010, the highest particle densities have been found in the Ligurian Sea, between the Tuscan Archipelago and Corsica and in the Tyrrhenian Sea, as well as along the eastern coastlines of the simulation domain used, in all the numerical experiments performed in this work (see Figure 3.4a at page 15).

Our modelling results are in a rather good agreement with the observational data of plastic pollution based on sampling procedures by Suaria et al. (2016), Fossi et al. (2017) (see Figure 4.1, p. 19) and Arcangeli et al. (2017) (except for the Bonifacio Strait, a high-density area not reproduced by the present elaborations), as well as the simulation results by Cózar et al. (2015), Fossi et al. (2017) and, to a lesser extent, Mansui et al. (2014) and Liubartseva et al. (2018). What stands out in every examined plot is that no area within the Pelagos Sanctuary appears to be “safe” from the potential pollution sources that have been selected in this work.

Our analyses confirm a known feature of the summer oceanography of the Pelagos area: the *Capraia gyre* (Schroeder et al., 2011; Suaria et al., 2016; Fossi et al., 2017). Named after the Capraia island, located north of Elba in the Tuscan Archipelago, the Capraia gyre characterized by high debris and

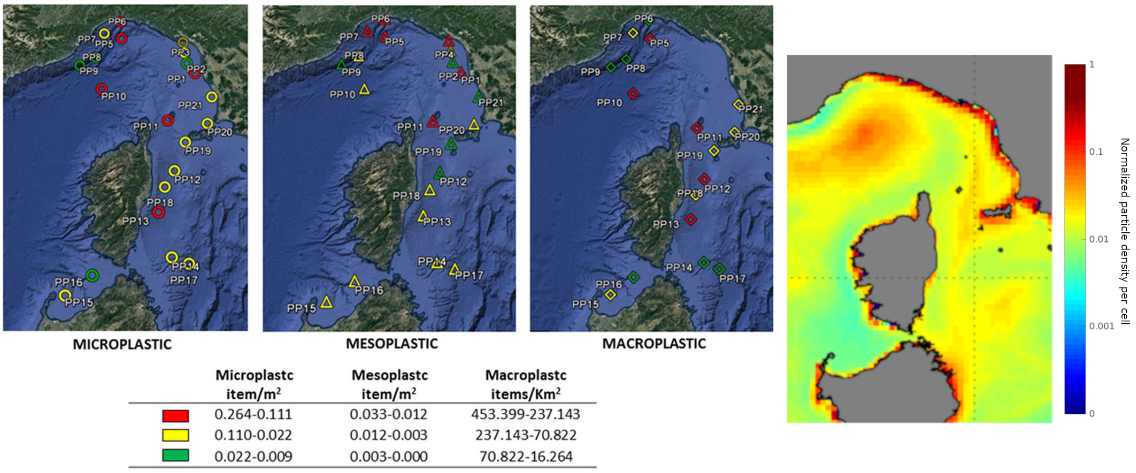


Figure 4.1: Comparison between the field sampling by Fossi et al. (2017) (Figure 4, at page 7) and our mapping of plastic distribution (Figure 3.4a at p.15)

microplastic concentration (Suaria et al., 2016; Fossi et al., 2017). This concentration hotspot emerged very clearly in our results. Simulations show that this region is also endowed with a low coefficient of variation, underlying its recurrent and persistent appearance in the summer seasons of the years considered.

Risk from floating microplastic debris to the endangered *Balaenoptera physalus* has been obtained by properly interesecting the elaboration of the particle density patterns (hazard) and indicators of potential habitat suitability for this species (exposure). The resulting risk not surprisingly appears to be higher in correspondence of the Ligurian sea “plume” of high particle density, coherently with the plastic-potential habitat overlay more qualitatively discussed by Fossi et al. (2017). The Liguro-Provençal basin is notoriously crucial for the fin whale *Balaenoptera physalus*, where this species has been sighted frequently (Panigada et al., 2005; Druon et al., 2012, see Section 1.2). Discrepancies between the two methods emerge in areas that present too shallow seafloor depths for the criteria applied after Druon and collaborators, where high average values of NPP are found instead. When focusing on fin whales, the Druon-derived method might be preferable because whale sightings rarely occur in the eastern part of Pelagos, where high productivity and particle densities are simultaneously found, but instead in the open sea between the north-western Corsica and the French coast in front of it (Panigada et al., 2005; Druon et al., 2012, see Section 1.2). The concordance we found here between the Druon et al. (2012) and the NPP approaches means that (i) the criteria here selected (ranges of chlorophyll-a concentration and water depth) may sufficient to obtain a good approximation of the potential habitat as identified by Druon and collaborators and (ii) NPP too can potentially be used as a relatively rough (yet quite unbiased) proxy of fin whale presence. Moreover, the potential whale habitat we modelled here (see Figure 3.6a, p. 17) is similar to both the one obtained by Druon et al. (2012) and the fin whale presence probability observed by Azzellino et al. (2012), as shown in Figure 4.2.

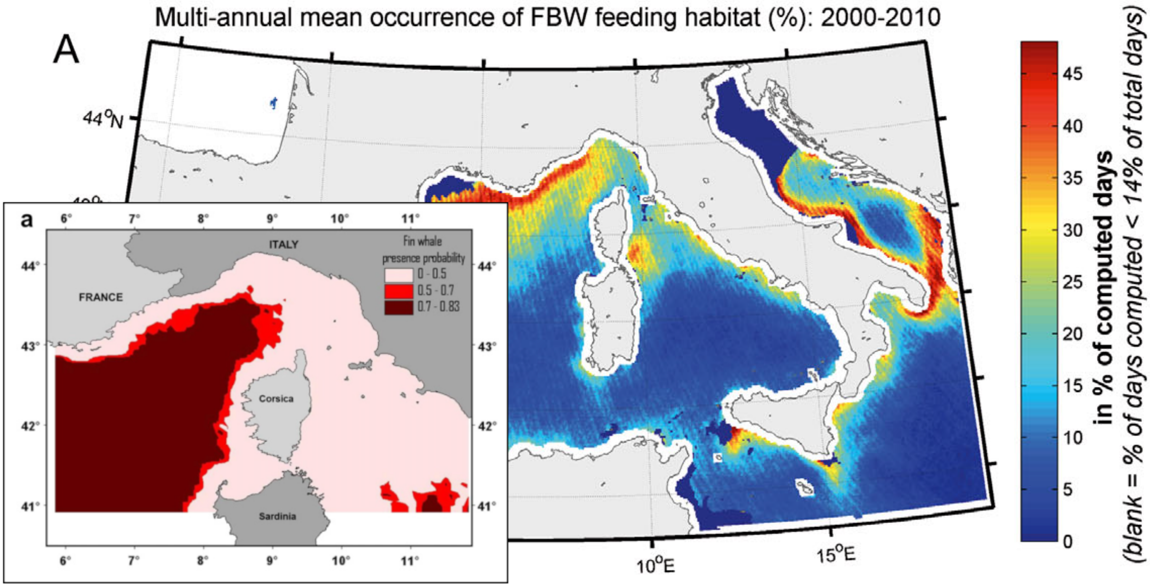


Figure 4.2: Figure 5A in Druon et al. (2012) (background) is compared with the fin whale presence (foreground), Figure 2a in Azzellino et al. (2014). The colour scale in Druon et al. (2012) Figure 5a represents how frequently a location has been found to be suitable on the total of computed days (e.g. days for which satellite data was available). In Figure 2a from Azzellino et al. (2012), color scale is set on fin whale presence probability on their sighting period (1990-2007).

The Mediterranean Sea is, at the same time, a densely populated, semi-enclosed sea and one of the most trafficked maritime areas in the world (SRM, 2013). Under such anthropogenic pressure, it is no surprise that the quality of its waters and biodiversity are threatened. Human disturbance connected to shipping lanes is known and includes collisions between ships and wildlife, underwater noise and pollution (EU Habitats Directive, EC 1992). To date, plastic pollution coming from shipping lanes has been investigated less than the one coming from other inputs (coastlines, rivers) because it is supposed to be of secondary relevance. However, evidence of the impact of maritime routes on plastic pollution impact is increasing (Campana et al., 2018; Arcangeli et al., 2017; Liubartseva et al., 2018). As found both by Liubartseva and collaborators (2018) and in the present research, inputs coming from maritime lanes apparently outweight the contributions coming from other sources, as litter is discharged directly into the sea even far from coasts, travels long distances before the action of removal mechanisms (~300 km, Liubartseva et al., 2018) and shows a low tendency to beaching (this work). In plain words, as one would say, plastic and litter in general produced by maritime activities "enter the sea from inside the sea and there it remains". Control of waste discharged in the sea has been a policy targeted for more than 40 years, namely since the International Convention for the Prevention of Pollution from Ships (MARPOL) 73/78. However, illegal discharge is still a widespread phenomenon.

Marine litter has been recognized as one of the main causes of marine pollution by the EU Marine Strategy Framework Directive (MSFD, 2008/56/EC, Descriptor 10), launched in 2008 with the main goal of achieving Good Environmental Status (GES) of European marine waters by 2020. As preventing contamination is the primary action to tackle plastic pollution in our seas (Koelmans et al., 2014), modelling can be an effective tool to address informed waste management policies at a local scale, as it can identify the most impacting sources. According to the results of the present work, to reduce plastic pollution in the Pelagos International Sanctuary for the Protection of Mediterranean Marine Mammals, *it seems to be especially important to act on the sources within its boundaries*. Effective waste management policies, raising public awareness on correct waste disposal and volunteering actions (as clean-ups) can reduce inputs coming from both coastlines and rivers. Nonetheless, acting on sea-based activities could be easier, as ships are tracked by GPS and follow known routes, so they might potentially be targeted on an individual basis: this requires improvements to the current practice of harbour waste management, as proposed by the European Commission in January 2018 (Proposal for a Directive of the European Parliament and or the Council on port reception facilities for the delivery of waste from ships, repealing Directive 2000/59/EC and amending Directive 2009/16/EC and Directive 2010/65/EU).

Plastic pollution is a global threat to the world's ecosystems and it appears to be more and more complex as scientific research keeps discovering new contaminated environmental compartments and new processes at play. To study this phenomenon, a high level of small-scale detail as well as the monitoring of oceanic-scale distribution patterns and oceanographic features are simultaneously required. For such a scale-wise differentiated problem, the tools provided by modelling and remote sensing technologies are crucial to get better insight into its physical-chemical nature (plastic transport by currents, degradation and fragmentation…) and also on its potential impacts on the ecosystems, using proxies of ecosystem size and productivity integrated with species-specific sightings data.
Tackling plastic pollution requires targeted actions and the primary solution appears to be prevention of contamination in the first place (Koelmans et al., 2014). An improvement of the current life-cycle management of plastic items can be effectively informed by the instruments of information and communication technology, hopefully progressing towards a more circular and sustainable economy.

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A.4 Overall distribution (coasts+rivers+ships*)

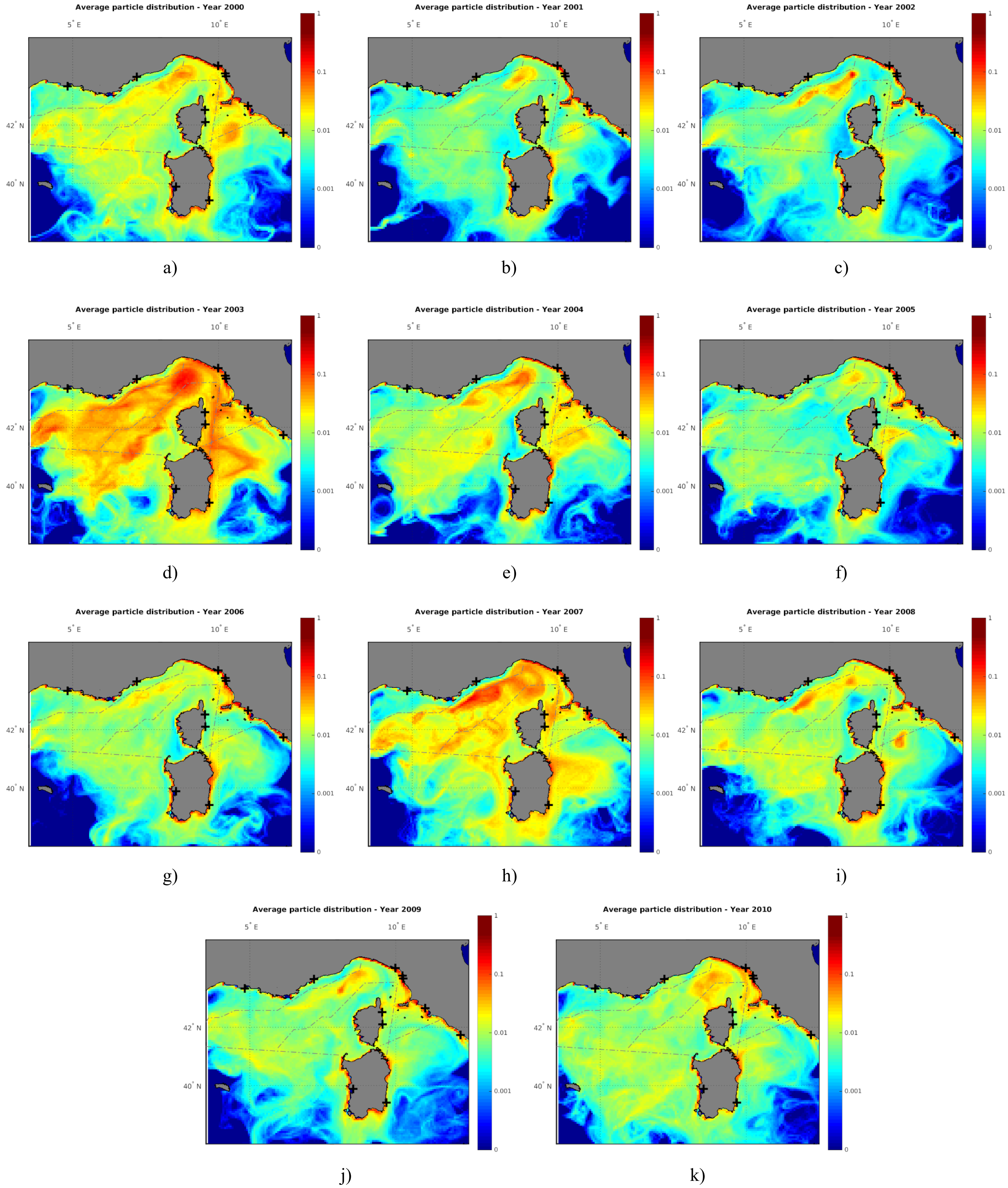

Figure A.4: Annual average particle distribution in the years 2000-2010 resulting from all considered sources (50:30:20 coasts-to-rivers-to-ship weight ratio applied after Liubartseva et al., 2018). Black '+' signs indicate river mouths release locations, while dot-dashed grey lines are the maritime routes. Particle density in each cell is normalized by the yearly maximum of the relevant spatial distribution and plotted in logarithmic scale.

* *Full version of the appendices is available at* https://tinyurl.com/appendices-plastic

B.4 Most contributing sources - yearly average

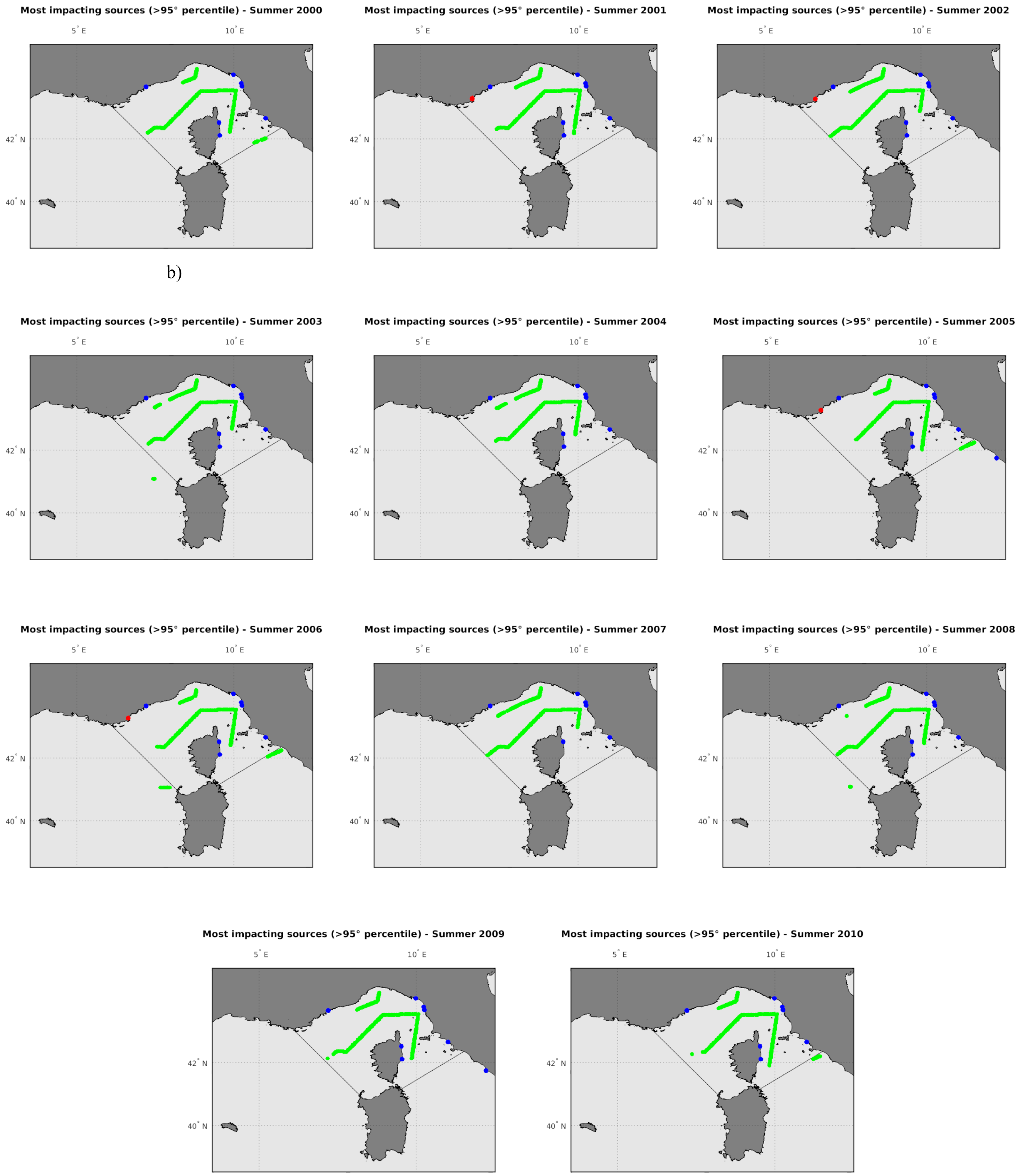

Figure B.4:Yearly maps of the most impacting sources, defined as those that exceeded the 95° percentile of the overall distribution of source contribution on the Pelagos Sanctuary.

D.1 Risk maps obtained with potential suitable habitat exposure (species-specific for fin whales)

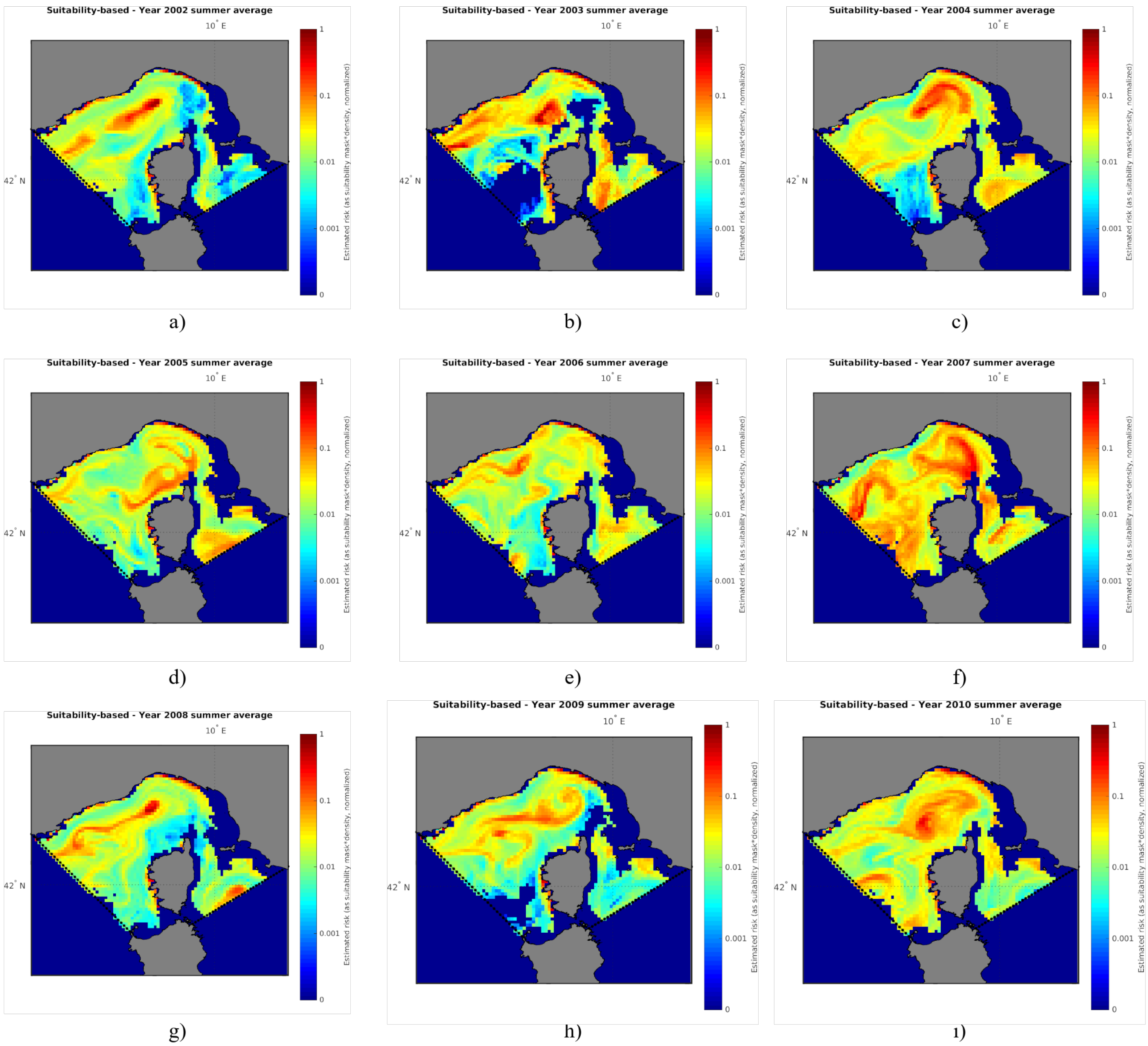

*Figure D.1: Average risk of exposure to plastic obtained applying the potential habitat criteria after Druon et al. (2012). Habitat data is available for 2002-2010, as MODIS chlorophyll-a measurements started in late June 2002 (*https://oceandata.sci.gsfc.nasa.gov/MODIS-Aqua/*).*

D.1 Risk maps obtained with Net Primary Production exposure

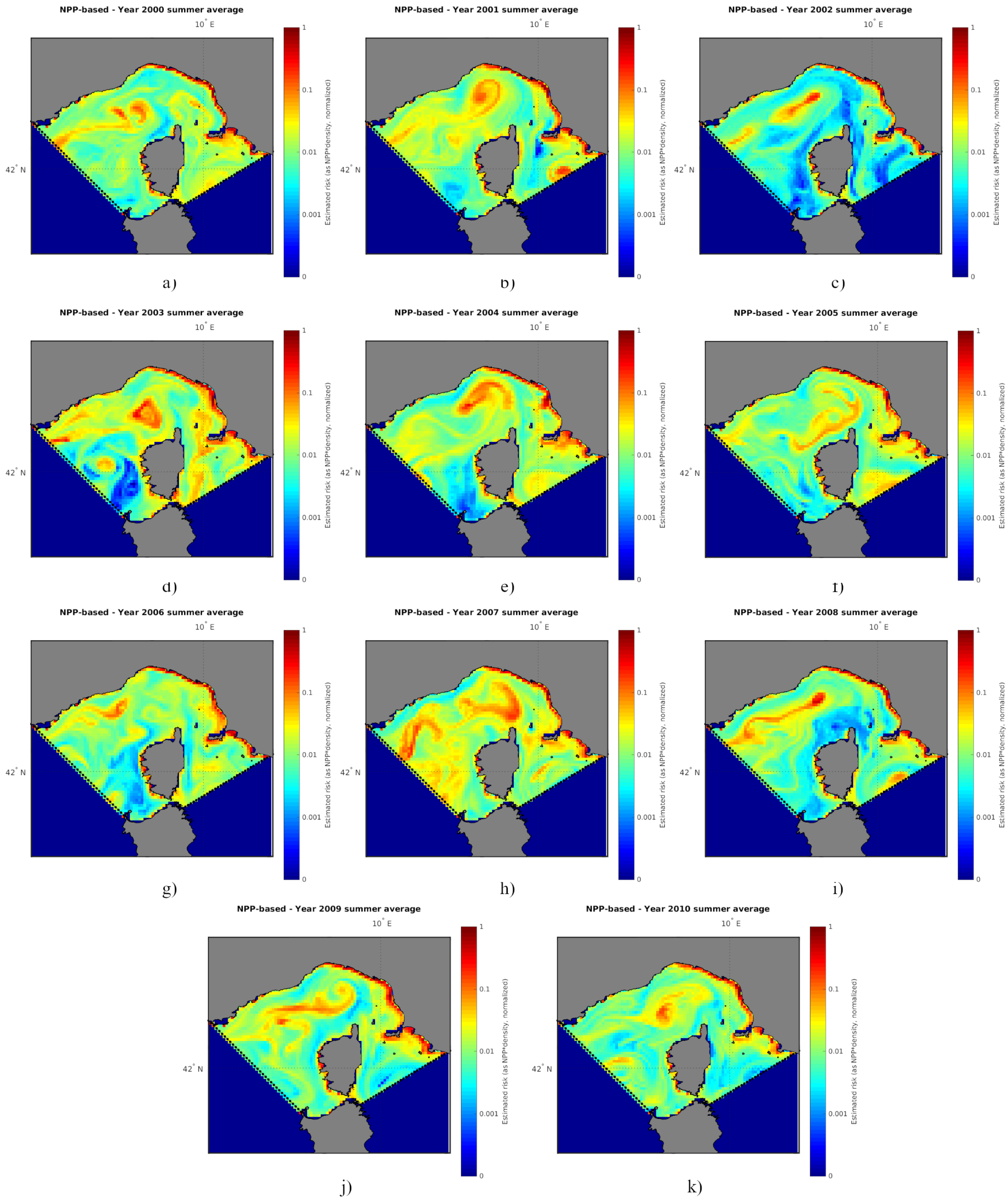

Figure D.2: Average risk of exposure to plastic obtained applying NPP as proxy of ecosystem size for the years 2000-2010.