Impact of the marine litter pollution on the Mediterranean biodiversity: a risk assessment study with focus on the marine protected areas.

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Abstract

In this paper a novel methodology to assess the risk of marine litter (ML) pollution in the Mediterranean Sea is implemented. In this approach, the hazard component is estimated using a state-of-the-art 3D modeling system, which allows the simulation of floating and sinking ML particles; the exposure component is defined from biodiversity estimates; and the vulnerability is related to ML ingestion rates of each species. The results show that the hot-spots for the ML risk concentrate in the coastal regions, and are mainly conditioned by the biodiversity in the region. A dedicated analysis on the marine protected areas shows that the risk therein is controlled by the proximity to ML sources and that their present-day protection levels are not effective in the case of ML pollution. Only a reduction of ML at the sources could reduce the impact of ML pollution in protected areas.

1. Introduction.

The Mediterranean Sea is one of the most diverse areas and has been identified as a marine biodiversity hot spot with approximately 17,000 species corresponding to between 4-18% of the world marine species (Bianchi and Morri, 2000; Coll et al., 2010). Considering its unique geographic position and narrow connection to the Atlantic Ocean, the Mediterranean Sea is also home to several endemic and emblematic species to the region (Boudouresque, 2004). However, plastic pollution is a growing threat on marine diversity with interaction with plastic pollution evident throughout the region through entanglement and ingestions studies highlighting how widespread this issue is (Alomar et al., 2020; Consoli et al., 2019; Darmon et al., 2017). Studies based on both observations and numerical models indicate that the ML concentration in the Mediterranean is among the highest of the world, with values comparable to those found in the great garbage patches of the Pacific subtropical gyres (Cózar et al., 2015; Law et al., 2014; Liubartseva et al., 2018; Soto-Navarro et al., 2020). Consequently, the ML pollution poses a major threat to the biodiversity of the basin.

Within the context of the European Marine Strategy Framework Directive (Directive 2008/56/EC), the establishment of Marine Protected Areas (MPAs) by countries within the European Union is a strategy to achieve Good Environmental Status in addition to an affordable way to mitigate and promote adaptation to climate change (Pérez-Ruzafa et al., 2017; Roberts et al., 2017). Mediterranean MPAs have a range of site-specific restrictions and range in protective status from limited navigations, no-take areas, fishing limitations, among others, to reduce the human pressures on the marine environment. Despite this, MPAs are still subject to multiple threats, including coastal and ocean-based impacts and pollution, trawling and dredging, exploitation of marine resources, maritime activities and climate change (Coll et al., 2010). Currently in the Mediterranean Sea, there are initiatives and transversal actions aimed at examining MPAs. The Plastic Busters MPAs project (EU-Interreg co-funded by the European Regional Development Fund) aims at monitoring and assessing marine litter in MPAs across the Mediterranean Sea through mitigation and preventive measures established among the consortium MPAs such as the Pelagos Sanctuary (Italy), the Tuscan Archipelago National Park (Italy), the National Marine Park of Zakynthos (Greece) and the Cabrera Archipelago Maritime-Terrestrial National Park (Spain). These MPAs have all identified some form of ML present in the area whether it be on the sea surface (Baini et al., 2018), in biota (Panti et al., 2015) or on the seafloor (Alomar et al., 2016).

Ecological risk analyses have been widely used as an essential tool for ecosystem-based management. By quantifying the probability of an undesirable event or impact, the risk assessment is very useful to establish mitigation measures aiming at prevent or hinder those impacts (Holsman et al., 2017). However, the risk estimation strongly relies on the specific methodology applied for its computation, particularly on the definition of the different parameters characterizing the risk. Previous studies in the global ocean and the Mediterranean Sea have addressed the estimation of ML pollution risk using different methodologies and/or definitions of the factors involved in the risk estimation. Nonetheless, although the methodologies differ, all studies share common aspects. The risk is based on a combination of indicators for hazard, exposure, and vulnerability. The hazard definition is usually very similar for all of them since the presence/absence of ML is the key starting point in any ML pollution study. Determining the amount of ML present in the area of study is crucial and very difficult. The available observational data is spatially and temporally discontinuous, hence insufficient to provide accurate information about the ML distribution over extended regions and time periods.

To solve this problem, most studies rely on indirect methods and numerical models. For instance, Wilcox et al. (2013) evaluated the risk of entanglement in abandoned fishing nets for sea turtles in Northern Australia, combining observations in beaches and bycatch records with Lagrangian numerical models to estimate the density of lost fishing gear in their area of study. On a global scale, Wilcox et al. (2015) and Schuyler et al. (2016) analyzed the risk of plastic ingestion for seabirds and sea turtles, respectively. Both works used ML concentrations based on Lagrangian simulations run over drifter derived current fields obtained from the Global Drifter Program. In the Mediterranean, Darmon et al. (2017) studied the co-presence of sea turtles and ML patches in the Mediterranean and Atlantic French waters, analyzing aerial observations. Compa et al. (2019) elaborated risk maps of the whole Mediterranean basin for several species using the global model of Lebreton et al. (2012) to calculate the ML concentration in the basin. Finally, Fossi et al. (2017) and Guerrini et al. (2019) studied the impact of plastic pollution on the fin whale feeding grounds at the Pelagos Sanctuary (northwestern Mediterranean) using the current fields from regional simulations to compute the ML concentration in their region of study.

Unlike the hazard, the definitions of exposure and vulnerability found in the literature are more subjective and strongly depend on each study's specific scope. When it is focused on only one species such as Fossi et al. (2017) and Guerrini et al. (2019) on the fin whale, the definition of vulnerability is unnecessary because this parameter is used precisely to distinguish the impact of the ML pollution on different species. In this case, the authors compute the risk as to the product of the average ML concentration given by their models (hazard) and the presence/absence of fin whales in their area of study, inferred from the habitat suitability model of Druon et al. (2012). Wilcox et al. (2015) and Schuyler et al. (2016) use a more sophisticated method to define the risk factors. First, they carry out an extensive literature review to gather all the available observations of ML impact on the species of interest for the study (188 seabirds and seven turtle species, respectively). Afterwards, they retrieve the global distribution of seabirds and sea turtles' populations from on-line open-access datasets. Then, the exposure is defined as the probability of encountering the individual species with the marine debris, which their respective ML spread models give concentration. Finally, the risk is defined as the probability of ingestion, estimated using a binomial model that includes the biological characteristic of the different species such as life-history traits and body size. Thus, these models implicitly include the vulnerability of each species analyzed. Compa et al. (2019) follow this methodology to assess the risk for marine species in the Mediterranean. After an exhaustive literature search, the species for which there are observations of plastic ingestion were included in the study. A total of 84 species, pelagic and demersal, were selected. Generalized Additive Models (GAM) with binomial distribution were used to determine the exposure and the risk of each species, defined as the ingestion rate taking into account biological characteristics (motility, body size, class, or habitat). The total risk for the whole ensemble was estimated as the sum of each species' individual risks.

The objective of this study is to move forward in the ML risk assessment of the Mediterranean Sea by developing a new methodology that seeks to complement and improve the previous efforts in this area. To this aim, a very high-resolution 3D ML dispersion model is used to estimate the concentration of ML particles with neutral and negative buoyancy to define the hazard for different ML types. Complementary, a dataset of more than 2000 species will be used to estimate exposure and vulnerability. Special attention is paid to the impact of the ML pollution in the Mediterranean Marine Protected Areas (MPAs) by focusing the results on more than 1400 MPAs. The paper is organized as follows: section 2 describes the methodology applied for the definition of the risk factors and the different sources of data. In section 3 the results are presented and discussed in section 4. The main conclusions of the study are summarized in section 5.

2. Methodology.

In order to evaluate the risk of ML pollution in the Mediterranean, three parameters have to be defined and estimated: hazard, exposure, and vulnerability. In our case, the hazard is defined as the average concentration of ML in a particular area, the exposure is related to the diversity of species present in the area (normalized number of species within the area), and the vulnerability is related to the probability of plastic ingestions by those species.

2.1 Hazard: Marine Litter concentration

The United Nations Environmental Program (UNEP) defines marine litter (ML) as any persistent, manufactured or processed solid material that is discarded, disposed of or abandoned in the marine or coastal environment (UNEP, 2009). These materials accumulate in both shallow and deep waters, and especially in closed basins such as the Mediterranean Sea (Barnes et al., 2009; Cózar et al., 2015). The most recent estimates show that between 4.8 and 12.7 million tons of plastic waste were dumped into the ocean in 2010, an amount that is expected to increase by one order of magnitude by 2025 if no measures are implemented to improve the waste management systems. In the case of the Mediterranean, it is estimated that around one hundred thousand tons of plastic waste enter each year (J. R. Jambeck et al., 2015). This definition of ML is the one adopted in this study. Therefore, the ML concentrations analyzed correspond to the macro-plastic (> 5 mm) dumped in the Mediterranean introduced in the Mediterranean basin as a result of the human activities.

The ML concentration in the Mediterranean basin is estimated from the outputs of a modeling system comprised of a high resolution Regional Circulation Model (RCM) and a Lagrangian model coupled to the RCM current field, which simulates the 3D trajectories of the ML. A complete description of the modelling system and the experiments can be found in Soto-Navarro et al. (2020), so here we summarize the main characteristics. This modeling system is used to run 120 year-long simulations starting the first day of each month and covering the period 2003 – 2013. In each simulation, 41872 particles are released, corresponding to the estimated 100k tons of ML dumped into the Mediterranean every year (J. Jambeck et al., 2015). Three different ML sources are considered: cities with a population larger than 25k inhabitants, major rivers and shipping lanes with dense maritime traffic. The particles are distributed among these three types of sources according to the ratio 50:30:20%, respectively. The 50k tons of ML per year corresponding to the cities are distributed in proportion to their population, the 30k tons of the rivers according to their climatological average discharge between 1980 and 2012 and the annual 20k tons corresponding to the shipping lanes are uniformly distributed over the regions with higher concentrations of maritime traffic (fig. S1). Due to the lack of information, the ML inputs from the Atlantic Ocean through the Strait of Gibraltar and from the Black Sea through the Dardanelles strait have not been included in the simulations. This might has resulted in an underestimation of the ML concentrations in the Alboran Sea and Northern Aegean.

Two sets of experiments were carried out, the first one considered ML particles with neutral buoyancy (NP), meaning that their density is exactly the same as the density of the seawater surrounding them and, hence, their vertical movements depend only on the RCM vertical velocities. This experiment aims at mimicking the evolution of polymers with density similar to seawater density (for instance, some polystyrene utensils and nylon fishing nets or ropes). Nonetheless, as shown by Soto-Navarro et al. (2020), the spatial patterns of the concentration of neutral and floating ML particles is very similar. Therefore, the results for the NP can be considered representative of the first 100 m of the water column.

The second set of simulations considers ML particles with negative buoyancy (SP), which density is higher than seawater and therefore have a negative component in the vertical velocity that makes them sink. The same number of particles are released using the same ML sources distribution and over the same time period. The difference is that in these runs the vertical motion of the particles is constraint. A nominal sedimentation velocity of the particles of -10^{-3} m/s is considered. It has to be noted that this sedimentation velocity is lower than the those obtained in laboratory experiments for particles with densities slightly higher than the water density (Khatmullina and Isachenko, 2017). These authors estimated sinking velocities between 0.005

and 0.127 m/s for items in the density range of 1130 – 1168 kg/m^3. We have selected a sedimentation velocity lower than the observed in laboratory in order establish an upper limit for the horizontal dispersion of sinking ML. In any case, this experiment should not be considered as an exhaustive representation of the ML sedimentation process, but as an approximation to the upper range of the possible evolution of the denser ML particles. Most of the polymers used in the fabrication of plastic items are denser than the seawater (GESAMP, 2019). In consequence, most of the ML (70%) is hypothesized to lie in the seafloor (UNEP, 2009). The SP simulations aims at representing the spatial distribution of these large fraction of ML.

In summary, the two types of particles represented in this work correspond to ML manufactured with polymers with densities in the range of seawater (1020-1040 kg/m^3, neutral particles) and denser than seawater (>1040 kg/m^3, sinking particles).

At each grid point, the hazard is defined as the average ML concentration, which is computed on a regular grid of 0.25° x 0.25° resolution for both the neutral and sinking particles. Taking into account that NP will affect the species that feed on the upper layers of the water column (pelagic) and the SP to those that feed near the seafloor (demersal and benthic), two different hazards are defined, one for each type of particles. Finally, the hazard values are normalized between 0 and 1, by dividing the concentration values by the maximum of the NP and SP concentration, i.e., the maximum of the two concentrations maps. This way the normalization is common for the two types of particles so the index value for the NP and SP can be compared.

2.2. Exposure: species distribution

We relate the exposure to the probability of occurrence of different species. To quantify it we use the spatial distributions of the probability of occurrence of all the Mediterranean species available in the FishBase (www.fishbase.se) and SeaLifeBase (www.sealifebase.ca) datasets. These datasets have been retrieved from the Aquamaps website (https://www.aquamaps.org/) (Kaschner et al. 2019) in May 2020. This includes a wide range of marine diversity including chitons, echinoderms, hydrozoans, sponges, tunicates, among others (see table S1 for complete list). The most common phylums were: Chordata (29.1 %) including pinnipeds, reptiles, sea turtles, fish, sharks, whales and dolphins; Mollusca (22.7 %) including bivalves, cephalopods, gastropods, etc.; arthropoda (12.0 %) sea spiders and crustaceans; and Annelida (10.7 %) consisting of mainly polychaetes. The exposure of each species at a particular location is defined as its probability of occurrence at that point. It is hazard-dependent, meaning that pelagic species are not exposed to ML in the bottom and benthic species are not exposed to ML existing in the upper layer. A total of 2170 species are considered (table S1). The data is originally provided in a regular grid with a spatial resolution of 0.25° x 0.25°, and has been interpolated into the same grid as the hazards.

Since the exposure is defined as a probability, its values range between 0 and 1. Once the exposure for all the species is computed, the metric defined to represent the average exposure is the sum of all the probabilities of the species appearing at a given grid point normalized by the total number of species. This way, the exposure will be higher in regions where many species are present, even though their probability is not very high, than in regions with very few species with higher probability of occurrence. In other words, the exposure is defined as a proxy of the biodiversity. More diverse regions contain a larger number of species and hence are more exposed to the ML pollution and vice versa.

It is important to point out that the diversity definition adopted here is limited to the species included in the Aquamaps dataset (table S1). This definition does not include phytoplankton, zooplankton or bacteria. In ecological terms, our definition is framed in the alpha-diversity, as we consider the number of species locally, normalizing the probability by the total number of species at each grid point of the domain. A second point to be considered is that the abundance of each species have not been taken into account in the risk estimation. Clearly, regions with low diversity but hosting very abundant species could be considered as very exposed, since the ML would likely impact a very large number of individuals. However, our approach is based on the inclusion of the largest possible number of species. Unfortunately, currently there is no information on population dynamics for the 2170 species considered. Moreover, by only considering the abundance for the species for which that information available, we would be introducing a bias in the results. These limitations should be taken into account in the interpretation of the results of this study and considered when the terms diversity or biodiversity are mentioned.

2.3. Vulnerability: probability of ingestion

The vulnerability is defined as the probability of plastic ingestion by the species present in a certain location. However, the lack of information makes unfeasible the estimation of the ingestion rate for each of the 2170 Mediterranean species analyzed in this work. Therefore, here we rely on the work of (Fossi et al., 2018) who have characterized the ingestion rates by habitats, and assign a ingestion rate to each species depending on the habitat they belong to.

Namely, (Fossi et al., 2018) authors carried out an exhaustive bibliographic research of all the previous works on plastic ingestion in Mediterranean species, finding 48 papers analyzing a total of 91 species. Then they defined an index of ML ingestion as the fraction (in %) of ingestion occurrence observed for the species belonging to different types of marine habitats. We have selected the median value of the distribution of percentage of ingestions for each habitat (see fig. 3 of Fossi et al. 2018) as an indicator of the species ingestion rate. Using this approximation, we are aware that the uncertainty associated to individual species could be large but, as we work in an aggregated framework, the expected error in the final results will be minimized. The habitat assigned to each of the species is summarized in table S1. Table 1 shows the ingestion rate assigned to each of the ten different habitats included in the ensemble of species. It is important to notice that the vulnerability is defined taking into account the position of the habitats in the water column. For this study, pelagic habitats are vulnerable to the hazard due to NP, while benthic and demersal habitats are vulnerable to the hazard due to SP. The vulnerability index is defined as the ingestion rate given as a fraction of unity, hence ranges between 0 and 1. The average vulnerability of a particular location is computed separately for the NP hazard (only affecting pelagic species) and the SP hazard (only affecting benthic and demersal species), as the sum of the vulnerability of each species at each grid point divided by the total number of species (423 for NP and 1823 for SP).

Habitat	Ingestion rate for NP (%)	Ingestion rate for SP (%)	N species	
Pelagic	43.3	0	182	Pelagic
Bathypelagic	43.3	0	74	
Pelagic-Neritic	43.3	0	38	
Pelagic-Oceanic	43.3	0	53	
Benthopelagic	24.1	24.1	77	
Benthic	0	2.1	903	Benthic/demersal
Demersal	0	10.6	395	
Bathydemersal	0	10.6	44	
Reef-Associated	0	2.1	87	
Sessile	0	2.1	317	

Table 1. List of habitats and assigned ingestion rate for the hazard due to neutral particles (NP) and sinking particles (SP). The last column is the number of species included in each habitat, indicating which are considered pelagic (affected by NP) and benthic or demersal (affected by SP).

2.4 Risk estimation

Once the hazard, exposure and vulnerability are defined, the risk by ML at each grid point and for each species is computed as follows:

$$R = \begin{cases} \frac{1}{3}(H + E + V)\,, & H \wedge E \wedge V > 0 \\ 0 & , H \vee E \vee V = 0 \end{cases} \qquad (1)$$

where *R*, *H* and *E* are matrices of dimensions *lon x lat x species* and *V* is the vulnerability assigned to each of the 2170 species' habitat. So, the risk index is defined as the average of the three components, except if one of them is 0, when the risk is considered 0 (e.g. if no ML is present in a certain region, then the hazard will be 0 and so the risk).

This computation is done for each species, so to represent the total risk in a particular location, we use a similar metric than for the exposure and vulnerability. The total risk is computed at each grid point as the sum of the risk for each species divided by the total number of species. Complementarily, the specific risks for pelagic (only affected by NP) and benthic and demersal (only affected by SP) species are computed as the sum of their individual risks divided by the number of species belonging to each habitat type (423 for pelagic and 1823 for benthic and demersal).

This methodology assigns higher risk to regions with larger number of species. I.e: since we normalize dividing by the total number of species, for different regions subject to the same hazard (i.e. ML concentration), those regions hosting many species with low vulnerability will show higher risk than regions with less biodiversity but with more vulnerable species. Also, computing the risk as the average of H, E and V (only in the points where the three factors are higher than zero), prevents the result from being unbalanced by a very high or low value of one of the factors.

2.5 Marine protected areas

The estimated risk has been summarized for the different Marine Protected Areas of the Mediterranean (MPAs) of the Mediterranean. MPAs data from the Natura2000 network was downloaded from the European Environmental Agency (EEA) (www.eea.europa.eu). A total of 1448 MPAs distributed across the Mediterranean basin are included in the Natura 2000 network. The information from the MPAs includes boundaries, surface and habitats hosted. The averaged values of the hazards, exposure, vulnerability and risk at each of the MPAs were computed. All the information is summarized in table S2.

3. Results

3.1 Risk assessment of the Mediterranean basin

3.1.1 Hazard

The regions of higher NP hazard (i.e., higher concentrations of ML in the water column) in the Western Mediterranean are located in the Gulf of Lions and the northeastern slope of the Iberian Peninsula (fig. 1a). In this sub-basin, the regions with lower particle accumulation are located in the southern Tyrrhenian Sea (southeast of Sardinia), Ligurian and the Alboran Sea. North of the Algerian current and in the Balearic Sea, the average concentrations are moderate. In the Eastern

Mediterranean, the higher NP hazard is found in the proximities of the Sicily Strait and the Gulf of Gabes, the Adriatic Sea and the slopes of the Levantine basin from Egypt to Turkey. On the other hand, the northern Aegean, northern Ionian and center region of the Levantine basin show the lowest ML concentrations. Throughout the rest of the Eastern Mediterranean, the concentrations are moderate. It is worth pointing out that, according to the results of Soto-Navarro et al. (2020), the average concentration of the NP in the basin is 2.3 kg·km^{-2}, the highest values reach 6.5 kg·km^{-2} and the lowest below 1.5 kg·km^{-2}. The authors also concluded that the average depth across the whole basin at which NP are found is 35 m, with more than 80% of the particles remaining inside the photic layer (fig. S2). In the Western Mediterranean the NP depth distribution is quite homogeneous, with values close to the whole basin average [20 – 30 m]. In the Eastern Mediterranean the mean depth distribution is more heterogeneous with regions as the southern Aegean, offshore the slope of the Gulf of Gabes and some areas of the Ionian Sea and the Levantine basin where the average depth reaches values higher than 45 m.

The distribution of the hazard due to sinking particles is completely different (fig. 1b). Even though the sedimentation speed of the particles is relatively small, most of them remain close to location where they were released. As a result, the average concentration map for the SP highly resembles the initial concentrations, with very high values at these positions (compare fig. 1b with fig. S1 and see Soto-Navarro et al., 2020 for a thorough description of the ML distribution of both NP and SP).

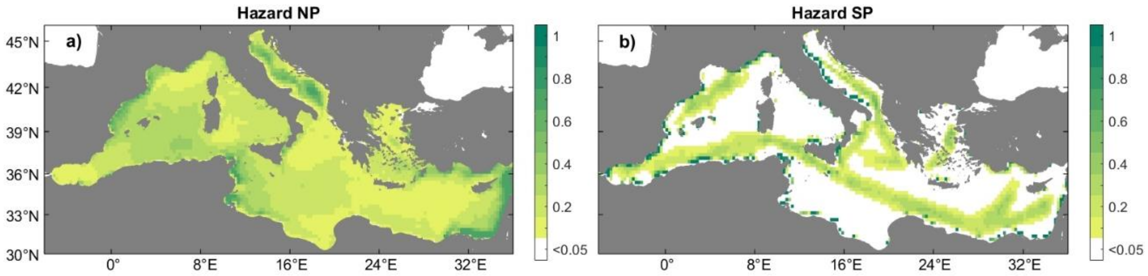

Figure 1. Neutral particles (a) and sinking particles (b) hazard distribution computed as the average concentration (see text). Values are normalized and adimensional.

3.1.2 Exposure

The spatial pattern of the average exposure is represented in figure 2a. As pointed out in section 2.2, this index is proportional to the number of species that can be found at each grid point, therefore, it can be interpreted as a measure of the biodiversity. The regions with higher exposure are concentrated in the coastal areas of the Western Mediterranean, the Strait of Sicily, the Adriatic and Aegean seas. In the open sea the number of species with high probability of occurrence is significantly lower, especially in the Tyrrhenian and Ligurian seas and most of the Eastern Mediterranean. This negative gradient from west to east and north to south of the Mediterranean biodiversity has been previously described and linked with differences in key environmental variables (latitude, salinity, temperature and water circulation) (Coll et al., 2010). According to these authors, the Western Mediterranean is more diverse due to its proximity to the Strait of Gibraltar which favors an influx of Atlantic species and a wider range of physicochemical conditions. On the other hand, the Levantine basin show the lowest species richness due to the unfavorable conditions in the area (such as high salinity).

From the total of 2170 species considered, 80% live in habitats close to the seafloor (benthic, demersal, bathydemersal, sessile and reef-associated) (table 1, fig. 2b). These habitats are mainly located in shallower coastal areas where the photic layer reaches the seafloor enabling the growth of seaweeds and seagrasses, which are essential in the development of multitude of ecosystems (Coll et al. 2010). The growth of these organisms occurs mainly in the continental shelves and the uppermost parts of the seamounts above 150 m depth (Ballesteros, 1994). As a consequence, the highest marine diversity is concentrated in coastal areas and continental shelves, above 200 m (Coll et al., 2010; Moranta et al., 1998). Conversely, the diversity is lower in open sea waters, which are mainly home of pelagic species as the seafloor is too deep to be reached by the sunlight and hence diversity in benthic ecosystems is lower. Unsurprisingly, the diversity distribution in the basin coincides with the spatial pattern of the primary production (Coll et al., 2010; Stambler, 2014). High productivity areas such as the Western Mediterranean and the Adriatic Sea show higher diversity, as they are important feeding and reproductive sites for numerous species. In particular, the regions of the Mediterranean with higher primary production are the continental shelves of the Gulf of Lions and the Italian and Iberian Peninsulas, the Gulf of Gabes and the North Aegean Sea, which are also areas of high biodiversity (fig. 2a). On the contrary, the Ionian Sea and the Levantine basin are the more oligotrophic regions of the basin, showing the lower biodiversity.

3.1.3 Vulnerability

Following (Fossi et al., 2018), the most vulnerable habitats are those closer to the surface (pelagic, benthypelagic, pelagic-neritic and pelagic-oceanic). These habitats show ingestion rates ranging between 24% and 43%. Benthic and demersal habitats have lower ingestion rates, ranging between 2% and 24% (table 1). As mentioned, pelagic ecosystems extend all over the basin, unlike benthic which are limited by the light availability to the shallower regions. These differences are reflected in figures 2c and 2d, which represent the average vulnerability for the neutral and sinking particles at each grid point. We see that the higher ingestion rate of the habitats closer to the surface and affected by ML in the water column (i.e. represented by NP) results in a higher value of the average vulnerability (fig. 2c). It is also evident that the pelagic species spread throughout the whole Mediterranean, so values of the average vulnerability exceed 0.15 across the whole basin. Nonetheless the most vulnerable regions are those close to the shores, where the ecosystems are richer and host many more species. On the other hand, the benthic species' lower ingestion rate results in a significantly lower average vulnerability (i.e. values lower than 0.1 everywhere). The spatial constriction of these species to the coastal areas is clear and no significant vulnerability is obtained in the open sea (fig. 2d).

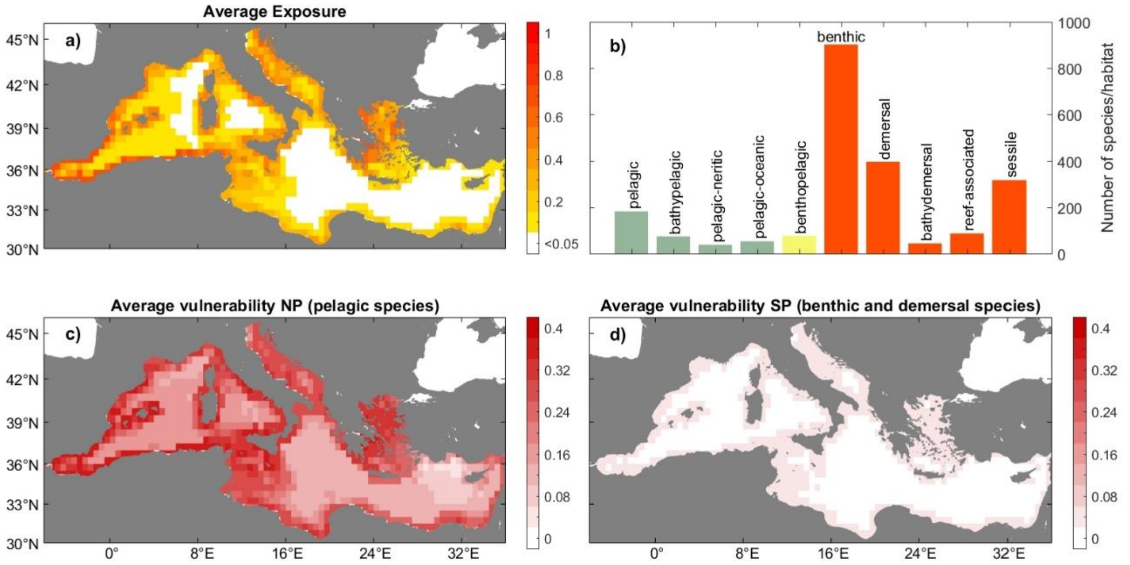

Figure 2. a) Average exposure, estimated as the sum of the probability of occurrence of each species at each grid point divided by the total number of species. b) Histogram of the number of species belonging to each of the habitats considered. The colors indicate if the habitat is affected by the hazard due to neutral particles (green), sinking particles (orange) or both (yellow). c) Average vulnerability for the neutral particles. d) Average vulnerability for the sinking particles.

3.1.4 Risk assessment

The risk maps for the hazards due to neutral and sinking particles in the whole Mediterranean are shown in figure 3. The remarkable differences between the total risk values and spatial distributions between the two types of hazards (i.e., neutral ML vs sinking ML) are evident (figs. 3a, b). For the NP the total risk is distinctly lower than for the SP, a direct consequence of the difference in the number of species affected by the two types of hazards, much larger for the latter (table 1, fig. 2b). It is important to keep in mind that the total risk for both types of hazard is computed as the sum of the risk for each species divided by the total number of species (2170). In consequence, the total risk for the hazard due to NP is much lower because it only affects 20%

of the species. This metric is defined to measure the impact of the ML pollution in the whole water column, and show the relative importance of the two hazards for the whole ensemble of species analyzed. The differences between figures 3a and 3b emphasizes that most of the Mediterranean species live in benthic/demersal habitats close to the seafloor, distributed along the coastal regions. The total risk for NP is significant (>0.02) for the whole Western Mediterranean except a small region in the Ligurian Sea (fig. 3a). In the Eastern Mediterranean, significant values are found in the Adriatic, the Aegean and the eastern Ionian. The Central Ionian and the Levantine basin do not show significant risk, with the exception of the coastal regions. For the SP, the total risk values are notably higher than for the NP (fig. 3b), but the regions affected are limited to the vicinity of the ML sources (i.e., compare to figs. 1b, S1). The total risk values are generally high in the continental slopes of the highly populated areas of the Western Mediterranean and the Adriatic. The lower vulnerability of the demersal and benthic communities reduces the impact of the strong SP hazard values in the coastal regions of the western and southern Adriatic, the Ligurian Sea and the southwestern Ionian. The higher risk values are found in the slopes of the Iberian Peninsula and the northern African coasts of the Western Mediterranean due to the presence of many highly populated cities which constitute the main source of SP (fig. 1S). In the Eastern Mediterranean, the lower exposure reduces the high impact of the coastal cities and Nile river, resulting in relatively low values of the total risk.

In order to better analyze the spatial differences across the basin, it is useful to look at the risk when only the species affected by each type of hazard are considered in the normalization. By doing that, a strong increase in the average risk is obtained for the NP hazard (fig.3c). Even though the values of the NP hazard are generally much lower than for the SP all over the basin (fig. 1), the risk associated exclusively to the pelagic species is relatively high, reaching values comparable to the SP risk, as a consequence of the higher vulnerability of the species living in these habitats (fig. 2c). The highest values are found in the coasts of the Western Mediterranean, particularly in the eastern slope of the Iberian Peninsula, the Algerian current, the Balearic Sea, and the Strait of Sicily, all of them regions with high NP concentration and exposure (figs. 1a, 2a). High values are also found in the Aegean Sea, in this case, due mainly to the high exposure of this region, as the NP concentration is relatively low in that area. The Gulf of Lions, Gulf of Gabes, Adriatic Sea and eastern slopes of the Levantine basin show relatively moderate risk, also matching with areas of moderate NP hazard and exposure. Conversely, the southern Adriatic and eastern slope of the Levantine basin, both regions with very high NP concentration, are less exposed, thus showing a moderate risk. The open sea regions of the Western and Eastern basins are the areas with lower NP risk, as expected since they show the lowest values of ML concentration and biodiversity (i.e., low exposure). On the other hand, no significant changes are observed when computing the risk for the SP considering only benthic and demersal species (fig. 3d). Since these habitats contain more than 80% of the species, the risk values remain very similar than when computed using the total number of species in the normalization.

It is worth pointing out that using the total number of species (figs. 3a, b) or only those affected by each type of hazard (figs. 3c, d) in the normalization does not affect the spatial distribution of the risk in any case. Since the same species are considered for each hazard, the regions of higher/lower risk remain similar; only the risk value changes because the results of the sum of the individual risks of each species are divided by a different number of species (423 for NP and 1823 for SP). The objective of showing the two estimations is to illustrate each type of hazard's relative relevance in the computation of the total risk. In the case of the pelagic species, their total contribution is relatively small because there are fewer species (fig. 3a). Still, individually, the lower NP concentrations are counterbalanced by these habitats' high vulnerability, resulting in high risk values in many regions of the Mediterranean. Therefore, when computing the average only considering these species the risk increases (fig. 3c). Conversely, the benthic and demersal species are the main contributors to the total risk and there is almost no difference between the computation using only them or the whole ensemble (figs. 3b, d). These species have much lower vulnerability but the SP hazard values are very high, resulting in individual risk similar to those of the pelagic species in many regions of the basin. In summary, pelagic and benthic/demersal species show similar risk values individually in the coastal regions of the Mediterranean where they cohabit, but the larger number of the latter makes them have a greater weight in the total risk of the basin.

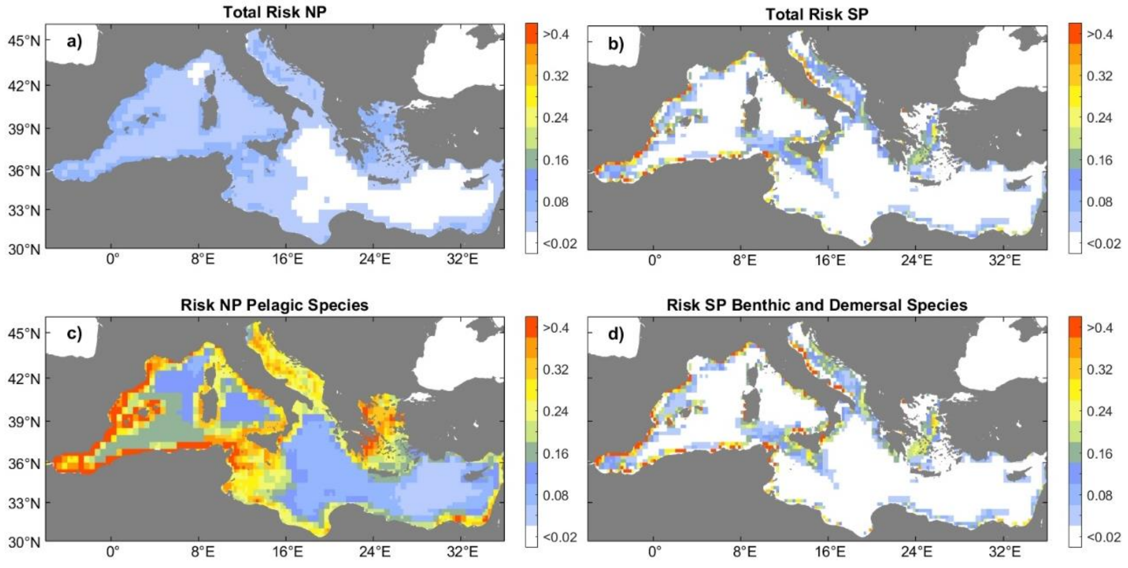

Figure 3. Total risk for neutral (NP) (a) and sinking (SP) (b) marine litter particles. The partial risk for (c) neutral particles/pelagic species and (d) sinking particles /benthic and demersal species.

3.2 Risk of the MPAs

The spatially averaged values of the hazards, exposure, vulnerability and total risk for the 1448 MPAs included in the Natura2000 network are summarized in table S2. For the sake of clarity, here the analysis of the results will focus on the ten largest MPAs, distributed over the Western Mediterranean and the Aegean Sea. The values of the different terms of the analysis for these MPAs are represented in figure 4 and summarized in table 2. Also for clarity, the MPAs have been numbered; their names and assigned numbers can be consulted in the caption of figure 4. Hereinafter we will be referring to each of them using the notation *MPAn*, where *n* is the number of the MPA (MPA1, MPA2, etc.).

MPA		Exposure	Hazard NP	Vuln. NP	Risk NP	Hazard SP	Vuln. SP	Risk SP
MPA1	Sur de Almería - Seco de los Olivos	0.73	0.19	0.38	0.18	0.44	0.05	0.47
MPA2	Plataforma-talud marinos del Cabo de la Nao	0.41	0.39	0.31	0.16	0.23	0.03	0.25
MPA3	Espacio marino del Delta de l'Ebre-Illes Columbretes	0.28	0.46	0.21	0.10	0.22	0.02	0.14
MPA4	Canal de Menorca	0.45	0.27	0.32	0.14	0.13	0.04	0.26
MPA5	Grands dauphins du Golfe du Lion	0.34	0.34	0.30	0.13	0.01	0.03	0.07
MPA6	Camargue	0.23	0.31	0.18	0.08	0.001	0.02	0.06
MPA7	Oiseaux marins de l’Agriate	0.16	0.14	0.19	0.06	0.02	0.02	0.05
MPA8	Plateau du Cap Corse	0.34	0.20	0.30	0.10	0.02	0.04	0.06
MPA9	Korinthiakos Kolpos	0.22	0.22	0.11	0.05	0.29	0.01	0.10
MPA10	Ethniko Thalassio Parko Alonnisou – Voreion Sporadon, Anatoliki Skopelos	0.41	0.11	0.32	0.13	0	0.03	0

Table 2. Summary of the risk factors for the 10 MPAs analyzed in this section.

The histogram of figure 4a represents the total risk (considering all the species) distribution of the MPAs. It summarizes the average risk of figures 3a and 3b in the MPAs areas. As for the whole basin and for the reasons already stated, the risk to NP pollution in the MPAs is much lower than the SP pollution. Almost all of the MPAs (95%) are affected by NP pollution, and only a few of them (60) show zero risk to this hazard (table S2). Most of them (85%) show relatively moderate values (between 0 and 0.15), the rest (10%) having a relatively high risk (> 0.15). In the case of the pollution due to SP, the risk values are higher, but the number of MPAs affected is much lower (47%). This is a direct consequence of the proximity of the MPAs to the ML sources. The dense ML particles sink very close to their sources and most protected areas are located far from cities and polluted river mouths, hence safe from the SP pollution. Among the MPAs affected, 29% show relatively low risk (between 0.1 and 0.3), 10% moderate risk (between 0.4 and 0.6) and 8% high risk values (between 0.7 and 0.9).

The spatially averaged exposure, vulnerability, hazard and total risk for NP and SP pollution of the ten largest MPAs are represented in figures 4b-h. All MPAs are located in coastal regions, where the values of exposure and vulnerability are higher (figs 2, 4b-d). The exposure factor appears to be the most determining in the risk for both neutral and sinking particles. The MPAs with higher exposure are MPA1, MPA2 and MPA4 in the Western Mediterranean, and MPA10 in the Aegean (fig. 4b, table 2). Those MPAs are also the most vulnerable for both NP and SP (fig. 4c-d, table 2), and have the higher risk to NP pollution (fig. 4g; table 2). However, the hazard factor plays a crucial role modulating the risk. For instance, MPA10 has a relatively low NP hazard value (fig. 4e) that reduces its NP risk, which is the lowest among the MPAs with higher exposure and vulnerability. On the contrary, MPA3 has very low exposure and vulnerability but very high NP hazard, resulting in a NP risk comparable to MPA10. On the other hand, the MPAs with lower risk to NP pollution are MPA6, MPA7 and MPA9, which are also those with lower exposure and vulnerability, despite the relatively high NP hazard in some of them (i.e., MPA6). The impact of the hazard in the risk for SP pollution is stronger. Since the dense ML particles remain in the surrounding of their sources, the MPAs located far from cities and river mouths are much better protected from their impact. That is the case of MPA5,6,7,8 and 10, which has very low (<0.03) SP hazard (fig. 4f) and hence very low or no significant risk for SP pollution (fig. 4h). Conversely, the MPAs located in the vicinity of important ML sources (fig. S1) show the highest SP hazard and risk values (i.e., MPA1, MPA2).

In summary, the analysis of the selected MPAs point to the exposure, i.e. the biodiversity, as the main contribution to the risk for ML pollution. The sensitivity to the exposure was already commented in the previous section, where we saw that the number of species used in the normalization of the total risk has a very strong impact in its final value. Here we confirm that, according to our metrics, the diversity of a region largely determines the impact of the ML pollution on it. Nonetheless, this impact is modulated by the hazard value, and this is particularly true with the dense ML particles. Most MPAs are located in coastal areas of high biodiversity and host numerous ecosystems so their exposure and vulnerability are similar. However, some of them are more isolated from ML sources than others or are in regions where the NP concentration is lower. The differences in the hazard values, which is a consequence of the MPAs position, is hence key in the risk for ML in the MPAs. These results are valid for the whole ensemble of 1440 MPAs of the Natura2000 network (table S2).

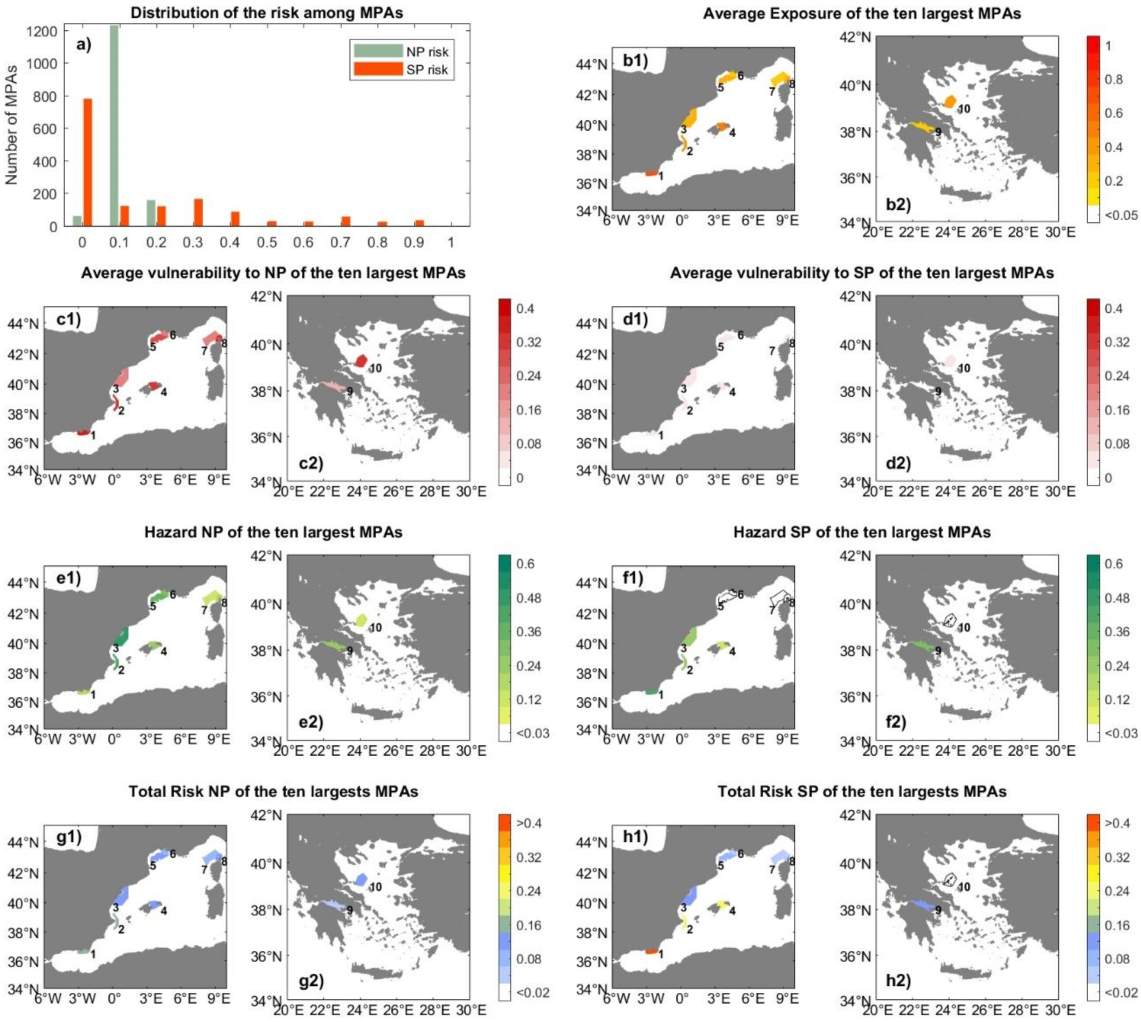

Figure 4. a) Distribution of the total risk for the 1448 Mediterranean MPAs of the Natura2000 network for neutral particles (green) and sinking particles (orange). b) Exposure, c) vulnerability to neutral particles, d) vulnerability to sinking particles, e) hazard for neutral particles, f) hazard for sinking particles, g) total risk due to neutral particles and h) total risk due to sinking particles for the ten largest MPAs of the Mediterranean in the Natura2000 network. The MPAs corresponding to each number are: 1. Sur de Almería – Seco de los Olivos. 2. Plataforma-talud marinos del cabo de la Nao. 3. Espacio marino del Desta de l'Ebre – Illes Columbretes. 4. Canal de Menorca. 5. Grands dauphins du Golfe du Lion. 6. Camargue. 7. Oiseaux marins de L'Agriate. 8. Plateau du Cap Corse. 9. Korinthiakos Kolpos. 10. Ethniko thalassio parko alonnisou - Voreion sporadon, Anatoliki skopelos.

4. Discussion

4.1 Risk definition and parameterization

In the present work, we have addressed the risk assessment of ML pollution in the Mediterranean Sea, defining it as the average of three factors: i) hazard, defined as the ML concentration over the basin for neutrally buoyant (NP) and sinking (SP) ML particles, ii) exposure, defined as the density of species in the Mediterranean (i.e., biodiversity) and iii) vulnerability, defined as the ingestion rate of the species. This approach is obviously not unique, as all the risk assessments rely on subjective aspects, especially when defining the exposure and vulnerability factors. Keeping this in mind, the approach followed in our work is based on the use of the most advanced state-of-the-art models and on a large datasets of species distribution in order to minimize that subjectivity.

One of the main improvements with respect to previous studies in the Mediterranean is the modeling system used in the estimation of the ML concentration. Fossi et al. (2017) simulated a two-month period between September and October 2014 coinciding with a field campaign in the region. They used a regional configuration of the ROMS model (at 2 km resolution) to compute the daily velocity fields, then running daily Lagrangian simulations starting from and homogeneous ML distribution over the model domain. Guerrini et al. (2019) used the velocity fields from the Copernicus Marine Environment Monitoring Service (CEMEMS) (1/16^o resolution) to run daily Lagrangian simulations covering a ten-year period (2000-2010). Their initial ML distribution considers plastic released from coastal sources uniformly distributed in their area of study, river mouths and maritime traffic. Finally, Compa et al. (2019) elaborated risk maps of the whole Mediterranean basin for several species using the model of Lebreton et al. (2012) to calculate the ML concentration in the basin. This model computes Lagrangian ML trajectories on a global scale, using realistic ML sources in cities, rivers and boat lanes. The velocity field used are the outputs of the HYCOM global model at 1/12^o resolution. In our study, we estimate the ML concentration of the Mediterranean basin using a very high resolution (1/36^o, 2-3 km) RCM velocity field as the base to run monthly Lagrangian simulations for a ten-year period (2003-2013). The ML is released at the beginning of the simulations from realistic sources (cities, river mouths and ship lanes), using indirect estimations for the total amount of plastic yearly dumped in the basin (100k tons). The increase of the spatial resolution and the use of realistic sources are two significant improvements in our hazard definition with respect to the previous works. The global simulations, as the ones used by Wilcox et al. (2015) and Schuyler et al. (2016), cannot incorporate such a high resolution due to limitations of the computing resources. Likewise, the global model of Lebreton et al. (2012) likely limits the accuracy of the estimations of ML concentration in the work of Compa et al. (2019). The authors point out that their results show a high degree of uncertainty, which can be partially attributed to the low resolution of the model. Indeed, the Mediterranean has a complex mesoscale field and high-resolution models are necessary to resolve the circulation at a local scale, which is fundamental to properly describe the ML dispersion of the basin (Soto-Navarro et al., 2020). The differences are very clear when comparing the maps of average ML concentration in the Mediterranean of Lebreton et al. (2012; fig. 3) and figure 2a. The ML spatial pattern obtained from the global model is completely different, showing wide accumulation zones in the Eastern Mediterranean that are unrealistic (Liubartseva et al., 2018; Soto-Navarro et al., 2020). Guerrini et al (2019) uses a regional model for the Mediterranean with a similar approach to ours in the ML sources distribution for the Pelagos Sanctuary region (northwestern Mediterranean). However, they use a lower resolution current field and a less realistic estimate of coastal inputs. Our results show lower ML concentration in the same area, likely due to the different sources' distribution. The only previous study based on comparable spatial resolution is the work of Fossi et al. (2017), which is restricted to a very specific region. These authors also simulate a short time period. Thus, their results should be considered with caution when describing a long term situation.

In addition to the higher resolution and realistic sources, we have considered for the first time, to our knowledge, different risk estimates for ML particles with different buoyancies, neutral and negative. Neutrally buoyant particles are distributed over the whole basin along the photic layer (between 0 and 100 m), with an average depth of 35 m (Soto-Navarro et al., 2020). These particles affect mainly pelagic species, which are less than 20% of the total analyzed. The average concentrations of NP are also much smaller than for the dense particles, since the NP spread across the whole basin while the SP remains in their sources' position. Consequently, the concentrations of SP are much higher, which is consistent with the fact that 94% of the plastic waste is estimated to be in the seafloor (Sherrington, 2016). Although their spread is limited, the SP affect a larger number of species living in benthic and demersal habitats, which constitute 80% of the total considered in our study. All the works mentioned only consider floating debris concentrations as hazard in the risk assessment. In the case of the studies focused on seabirds or pelagic species like sea turtles or fin whales this consideration could be accurate enough. On the contrary, if there is an interest on benthic or demersal species characterizing ML only with floating particles is likely overestimating the range of spread of the ML particles and underestimating the concentration close to the ML sources and hence the impact on these species.

Regarding the definition of exposure, we have a wide range of species ranging from fish, invertebrates and marine mammals and turtles (n = 2170), so we can have a reliable estimation of the spatial distribution of the basin biodiversity (Coll et al., 2010). The vulnerability is related here to the ingestion rate of ML, although as that information is only available for a very reduced number of species, we have used as a proxy the habitat-depending ingestion rates computed by Fossi et al. (2018). We are aware that this approach is less accurate than those based on the specific biological characteristic of each species (e.g. Wilcox et al. 2016; Schuyler et al. 2106; Compa et al. 2019). However, as we do not focus on individual species but we compute the total risk using the whole ensemble, we think that the impact of those inaccuracies is mitigated.

Indeed, our results show that the regions of higher/lower risk coincide with those obtained by Compa et al. (2019) using more sophisticated ingestion rate models (fig. 3). The reason is that the main factor on the risk computation is the exposure, i.e., the number of species. The vulnerability and, particularly, the hazard plays key roles in the modulation of the risk magnitude, but the spatial distribution is largely influenced by the diversity of each region. This way, both our study and Compa et al. (2019) find that the coastal regions of the Western Mediterranean, the Strait of Sicily, the Adriatic and the Aegean seas are the hotspots for the risk by ML pollution. This is for both neutral and dense particles because those are the regions of the basin with higher biodiversity. In conclusion, our methodology compensates for the lack of accuracy in the definition of the ingestion rate with the use of a very large ensemble of species. This methodology constitutes a great advantage in the risk assessment of marine regions where the samples and ML ingestion are very scarce. A second advantage is that the methodology can be updated at any time with new information on the species distribution and/or ingestion rate. As the research on the impact of ML in the different species increases, the new information can be incorporated easily into the risk assessment algorithm, gradually improving its accuracy.

It is also important to point out that the normalization used for the different factors in the risk computation reflects the relative importance of the habitat distributions. The normalization only affects the risk magnitude, which is an arbitrary adimensional quantity. The spatial distribution of the risk would be the same regarding the normalization chosen. As explained in section 3.1.4, normalizing the NP risk dividing by the total number of species reduces its magnitude since only 20% of the species are affected by this hazard (fig. 3a). When normalizing by the number of pelagic species, the risk magnitude strongly increases and the spatial patterns are clearer (fig. 3c). Thus, the normalization is arbitrary and can be chosen to highlight different aspects of the results. By using all the species in our definition of total risk we intend to highlight that the higher risk is found in the ecosystems closer to the seafloor because most of the species of the basin live in benthic or demersal habitats and the ML concentration in the seafloor is much higher than in the surface waters (figs. 3a, b).

4.2 MPAs protection

A recent paper by (Claudet et al., 2020) draws attention to the practical lack of protection of the Mediterranean MPAs regarding human activities, specially fishing. The article highlights that only 6% of the Mediterranean waters are protected (far from the objective of 10% for 2020 agreed by the States Parties to the Convention of Biological Diversity; CBD, 2010). Among this protected area, only 3.4% has a high or full level of protection and for 72.6% of the MPAs no difference exists between the regulations imposed inside to those outside. In the specific case of the ML pollution, our results show that the risk associated to the MPAs is completely dependent on their location and is site-specific. By definition, the exposition and vulnerability of the MPAs is very high since they are located in regions of high biodiversity, one of the reasons there is interest in their protection. Considering the results from this study, those factors are determinant in the risk, so the MPAs are by definition very sensitive to the ML pollution. Therefore, the hazard factor, i.e. the ML concentration in the area, is the key element that shapes the MPAs risk. Those MPAs isolated from important ML sources such as big cities and river mouths are better protected, particularly to SP pollution. Likewise, those MPAs that are far from important ML sources and located in regions with weaker circulation are better protected for NP pollution because they import less ML from other regions. That is the case of the Aegean Sea, a sub-basin with relatively weak circulation, little exchange with the rest of the Mediterranean, which prevents the NP input from other regions, and affected by less important ML sources than other regions of the basin. Conversely, those MPAs located within the vicinity of ML sources or in regions under the influence of important boundary currents such as the Northern or the Algerian currents show higher risks. Conversely, those MPAs located within the vicinity of ML sources or in regions under the influence of important boundary currents such as the Northern or the Algerian currents show higher risks.

In summary, it is clear that the legislation used to protect MPAs is not useful to avoid the risk of impacts by ML. The only effective way of properly protecting all the MPAs from the risk of ML pollution is to reduce the inputs of ML at basin scale. Local measures will only be effective for those MPAs that are not reached by ML particles transported from the rest of the basin.

In this study, we have developed an ecological risk framework that can provide value information for management in coastal areas surrounding the Mediterranean Sea, in particular for the MPAs. For instance, information on seafloor concentrations can be very expensive and costly while removal is nearly impossible. However, considering the regions where benthic marine diversity is at high risk of coming into contact with ML, managers of coastal cities nearby can contribute to the reduction of ML entering the marine environment by identifying point sources (i.e., river mouths or industry outlets) to mitigate and reduce the ML inputs in the surroundings of MPAs. In addition, identifying hotspot areas of risk for endangered or vulnerable species and increasing protection for them may serve as an umbrella for the protection of other species that, although not currently under threat, are in risk of being affected by ML pollution.

5. Conclusions

In this paper we develop and apply a methodology for the risk assessment of ML pollution in the Mediterranean Sea, focusing on the risk on the Marine Protected Areas of the basin. We compute the risk as the average of three factors: hazard, exposure and vulnerability. The hazard is defined as the average ML concentration, which is estimated using the outputs of a very high resolution 3D modeling system (Soto-Navarro et al., 2020) describing the evolution of realistic sources of ML. The capacity of the modeling system to resolve the 3D trajectories of the ML particles has allowed, for the first time, the analysis of the hazards due to ML particles with neutral (NP) and negative (SP) buoyancy. The exposure is defined as the probability of occurrence of 2170 species at each grid point. The vulnerability of each species is assigned in function of its habitat, according to the observations-based results of Fossi et al. (2018).

The results show that the higher risk is concentrated in the coastal areas, particularly in the Western Mediterranean, the Eastern Adriatic, and the Aegean Sea, for both NP and SP. The most determining factor in this distribution is the biodiversity, i.e., the exposure. The regions hosting a larger number of species show higher risk, and vice-versa. Nonetheless, the hazard factor also has an important role as a modulator of the risk. The regions closer to coastal ML sources show higher values than those more isolated. As the SP rapidly sink to the seafloor very close to their sources, their concentrations are much higher at those locations than the concentration NP in the rest of the basin. In addition, most of the species included in the database are benthic or demersal species (80%). As a consequence, the risk linked to SP is much higher than the risk linked to NP in the regions close to ML sources, particularly in the coastal regions. On the other hand, NP spread along the whole basin, and so does their associated risk.

The focus on the MPAs shows that they are, by definition, exposed and vulnerable areas. Thus, their risk strongly depends on the hazard's values, i.e., the ML concentration, at their location. Namely, the factor determining a higher or lower risk appears to be the proximity to ML sources. In consequence, their present-day protection levels are not effective in the case of ML pollution. The risk values reached inside the MPAs are similar to those reached in the surrounding areas. Thus, the only effective way to protect MPAs from the risk of ML pollution is to reduce the ML dumped into the whole Mediterranean.

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References

Alomar, C., Deudero, S., Compa, M., Guijarro, B., 2020. Exploring the relation between plastic ingestion in species and its presence in seafloor bottoms. Mar. Pollut. Bull. 160, 111641. https://doi.org/10.1016/j.marpolbul.2020.111641

Alomar, C., Estarellas, F., Deudero, S., 2016. Microplastics in the Mediterranean Sea: Deposition in coastal shallow sediments, spatial variation and preferential grain size. Mar. Environ. Res. 115, 1–10. https://doi.org/10.1016/j.marenvres.2016.01.005

Baini, M., Fossi, M.C., Galli, M., Caliani, I., Campani, T., Finoia, M.G., Panti, C., 2018. Abundance and characterization of microplastics in the coastal waters of Tuscany (Italy): The application of the MSFD monitoring protocol in the Mediterranean Sea. Mar. Pollut. Bull. 133, 543–552. https://doi.org/10.1016/j.marpolbul.2018.06.016

Ballesteros, E., 1994. The Deep-Water Peyssonnelia Beds from the Balearic Islands (Western Mediterranean). Mar. Ecol. 15, 233–253. https://doi.org/10.1111/j.1439-0485.1994.tb00055.x

Barnes, D.K.A., Galgani, F., Thompson, R.C., Barlaz, M., 2009. Accumulation and fragmentation of plastic debris in global environments. Philos. Trans. R. Soc. B Biol. Sci. 364, 1985–1998. https://doi.org/10.1098/rstb.2008.0205

Bianchi, C.N., Morri, C., 2000. Marine biodiversity of the Mediterranean Sea: Situation, problems and prospects for future research. Mar. Pollut. Bull. 40, 367–376. https://doi.org/10.1016/S0025-326X(00)00027-8

Boudouresque, C.-F., 2004. Marine biodiversity in the mediterranean; status of species, populations and communities. Trav. Sci. du Parc Natl. Port-Cros 20, 97–146.

CBD, 2010. Convention on Biological Diversity. COP 10 Decis. X/2. Strateg. Plan Biodivers. 2011-2020.

Claudet, J., Loiseau, C., Sostres, M., Zupan, M., 2020. Underprotected Marine Protected Areas in a Global Biodiversity Hotspot. One Earth 2, 380–384. https://doi.org/10.1016/j.oneear.2020.03.008

Coll, M., Piroddi, C., Steenbeek, J., Kaschner, K., Lasram, F.B.R., Aguzzi, J., Ballesteros, E., Bianchi, C.N., Corbera, J., Dailianis, T., Danovaro, R., Estrada, M., Froglia, C., Galil, B.S., Gasol, J.M., Gertwage, R., Gil, J., Guilhaumon, F., Kesner-Reyes, K., Kitsos, M.S., Koukouras, A., Lampadariou, N., Laxamana, E., de la Cuadra, C.M.L.F., Lotze, H.K., Martin, D., Mouillot, D., Oro, D., Raicevich, S., Rius-Barile, J., Saiz-Salinas, J.I., Vicente, C.S., Somot, S., Templado, J., Turon, X., Vafidis, D., Villanueva, R., Voultsiadou, E., 2010. The biodiversity of the Mediterranean Sea: Estimates, patterns, and threats. PLoS One 5. https://doi.org/10.1371/journal.pone.0011842

Compa, M., Alomar, C., Wilcox, C., van Sebille, E., Lebreton, L., Hardesty, B.D., Deudero, S., 2019. Risk assessment of plastic pollution on marine diversity in the Mediterranean Sea. Sci. Total Environ. 678, 188–196. https://doi.org/10.1016/j.scitotenv.2019.04.355

Consoli, P., Romeo, T., Angiolillo, M., Canese, S., Esposito, V., Salvati, E., Scotti, G., Andaloro, F., Tunesi, L., 2019. Marine litter from fishery activities in the Western Mediterranean sea: The impact of entanglement on marine animal forests. Environ. Pollut. 249, 472–481. https://doi.org/10.1016/j.envpol.2019.03.072

Cózar, A., Sanz-Martín, M., Martí, E., González-Gordillo, J.I., Ubeda, B., Á.gálvez, J., Irigoien, X., Duarte, C.M., 2015. Plastic accumulation in the mediterranean sea. PLoS One 10, 1–12. https://doi.org/10.1371/journal.pone.0121762

Darmon, G., Miaud, C., Claro, F., Doremus, G., Galgani, F., 2017. Risk assessment reveals high exposure of sea turtles to marine debris in French Mediterranean and metropolitan Atlantic waters. Deep. Res. Part II Top. Stud. Oceanogr. 141, 319–328. https://doi.org/10.1016/j.dsr2.2016.07.005

Druon, J.N., Panigada, S., David, L., Gannier, A., Mayol, P., Arcangeli, A., Cañadas, A., Laran, S., Méglio, N. Di, Gauffier, P., 2012. Potential feeding habitat of fin whales in the western Mediterranean Sea: An environmental niche model. Mar. Ecol. Prog. Ser. 464, 289–306. https://doi.org/10.3354/meps09810

Fossi, M.C., Pedà, C., Compa, M., Tsangaris, C., Alomar, C., Claro, F., Ioakeimidis, C., Galgani, F., Hema, T., Deudero, S., Romeo, T., Battaglia, P., Andaloro, F., Caliani, I., Casini, S., Panti, C., Baini, M., 2018. Bioindicators for monitoring marine litter ingestion and its impacts on Mediterranean biodiversity. Environ. Pollut. 237, 1023–1040. https://doi.org/10.1016/j.envpol.2017.11.019

Fossi, M.C., Romeo, T., Baini, M., Panti, C., Marsili, L., Campani, T., Canese, S., Galgani, F., Druon, J.-N., Airoldi, S., Taddei, S., Fattorini, M., Brandini, C., Lapucci, C., 2017. Plastic Debris Occurrence, Convergence Areas and Fin Whales Feeding Ground in the Mediterranean Marine Protected Area Pelagos Sanctuary: A Modeling Approach. Front. Mar. Sci. 4, 1–15. https://doi.org/10.3389/fmars.2017.00167

GESAMP, 2019. Guidelines for the monitoring and assessment of plastic litter in the ocean. GESAMP Reports Stud. 99, 130.

Guerrini, F., Mari, L., Casagrandi, R., 2019. Modeling plastics exposure for the marine biota: Risk maps for fin whales in the Pelagos Sanctuary (North-Western Mediterranean). Front. Mar. Sci. 6, 1–10. https://doi.org/10.3389/fmars.2019.00299

Holsman, K., Samhouri, J., Cook, G., Hazen, E., Olsen, E., Dillard, M., Kasperski, S., Gaichas, S., Kelble, C.R., Fogarty, M., Andrews, K., 2017. An ecosystem-based approach to marine risk assessment. Ecosyst. Heal. Sustain. 3. https://doi.org/10.1002/ehs2.1256

Jambeck, J., Geyer, R., Wilcox, C., Siegler, T.R., Perryman, M., Andrady, A., Narayan, R., Law, K.L., 2015. Plastic waste inputs from land into the ocean. Science (80-.). 347. https://doi.org/10.1126/science.1260352

Jambeck, J.R., Gayer, R., Wilcox, C., Siegler, R.T., Perryman, M., Andrady, A., Narayan, R., Law, L.K., 2015. The ocean. Clim. Chang. 2014 Impacts, Adapt. Vulnerability Part B Reg. Asp. Work. Gr. II Contrib. to Fifth Assess. Rep. Intergov. Panel Clim. Chang. 347, 1655–1734. https://doi.org/10.1017/CBO9781107415386.010

Khatmullina, L., Isachenko, I., 2017. Settling velocity of microplastic particles of regular shapes. Mar. Pollut. Bull. 114, 871–880. https://doi.org/10.1016/j.marpolbul.2016.11.024

Law, K.L., Morét-Ferguson, S.E., Goodwin, D.S., Zettler, E.R., Deforce, E., Kukulka, T., Proskurowski, G., 2014. Distribution of surface plastic debris in the eastern pacific ocean from an 11-year data set. Environ. Sci. Technol. 48, 4732–4738. https://doi.org/10.1021/es4053076

Lebreton, L.C.M., Greer, S.D., Borrero, J.C., 2012. Numerical modelling of floating debris in the world’s oceans. Mar. Pollut. Bull. 64, 653–661. https://doi.org/10.1016/j.marpolbul.2011.10.027

Liubartseva, S., Coppini, G., Lecci, R., Clementi, E., 2018. Tracking plastics in the Mediterranean: 2D Lagrangian model. Mar. Pollut. Bull. 129, 151–162. https://doi.org/10.1016/j.marpolbul.2018.02.019

Moranta, J., Stefanescu, C., Massutí, E., Morales-Nin, B., Lloris, D., 1998. Fish community structure and depth-related trends on the continental slope of the Balearic Islands (Algerian basin, western Mediterranean). Mar. Ecol. Prog. Ser. 171, 247–259. https://doi.org/10.3354/meps171247

Panti, C., Giannetti, M., Baini, M., Rubegni, F., Minutoli, R., Fossi, M.C., 2015. Occurrence, relative abundance and spatial distribution of microplastics and zooplankton NW of Sardinia in the Pelagos Sanctuary Protected Area, Mediterranean Sea. Environ. Chem. 12, 618–626. https://doi.org/10.1071/EN14234

Pérez-Ruzafa, A., García-Charton, J.A., Marcos, C., 2017. North East Atlantic vs. Mediterranean marine protected areas as fisheries management tool. Front. Mar. Sci. 4, 1–13. https://doi.org/10.3389/fmars.2017.00245

Roberts, C.M., O'Leary, B.C., Mccauley, D.J., Cury, P.M., Duarte, C.M., Lubchenco, J., Pauly, D., Sáenz-Arroyo, A., Sumaila, U.R., Wilson, R.W., Worm, B., Castilla, J.C., 2017. Marine reserves canmitigate and promote adaptation to climate change. Proc. Natl. Acad. Sci. U. S. A. 114, 6167–6175. https://doi.org/10.1073/pnas.1701262114

Schuyler, Q.A., Wilcox, C., Townsend, K.A., Wedemeyer-Strombel, K.R., Balazs, G., van Sebille, E., Hardesty, B.D., 2016. Risk analysis reveals global hotspots for marine debris ingestion by sea turtles. Glob. Chang. Biol. 22, 567–576. https://doi.org/10.1111/gcb.13078

Sherrington, C., 2016. Plastics in the Marine Environment. Eunomia Res. Consult. Ltd 13.

Soto-Navarro, J., Jordá, G., Deudero, S., Alomar, C., Amores, Á., Compa, M., 2020. 3D hotspots of marine litter in the Mediterranean: A modeling study. Mar. Pollut. Bull. 155, 111159. https://doi.org/10.1016/j.marpolbul.2020.111159

Stambler, N., 2014. The Mediterranean Sea -- Primary Productivity, in: Goffredo, S., Dubinsky, Z. (Eds.), The Mediterranean Sea: Its History and Present Challenges. Springer Netherlands, Dordrecht, pp. 113–121. https://doi.org/10.1007/978-94-007-6704-1_7

UNEP, 2009*, Marine Litter A Global Challenge, Nairobi: UNEP. 232 pp.*

Wilcox, C., Hardesty, B.D., Sharples, R., Griffin, D.A., Lawson, T.J., Gunn, R., 2013. Ghostnet impacts on globally threatened turtles, a spatial risk analysis for northern Australia. Conserv. Lett. 6, 247–254. https://doi.org/10.1111/conl.12001

Wilcox, C., Van Sebille, E., Hardesty, B.D., Estes, J.A., 2015. Threat of plastic pollution to seabirds is global, pervasive, and increasing. Proc. Natl. Acad. Sci. U. S. A. 112, 11899–11904. https://doi.org/10.1073/pnas.1502108112

Impact of the marine litter pollution on the Mediterranean biodiversity: a risk assessment study with focus on the marine protected areas.

J. Soto-Navarro[1], G. Jordá[2], M. Compa[2], S. Deudero[2], C. Alomar[2], and M.C. Fossi[3]

Tables

Habitat	Ingestion rate for NP (%)	Ingestion rate for SP (%)	N species	
Pelagic	43.3	0	182	Pelagic
Bathypelagic	43.3	0	74	
Pelagic-Neritic	43.3	0	38	
Pelagic-Oceanic	43.3	0	53	
Benthopelagic	24.1	24.1	77	
Benthic	0	2.1	903	Benthic/demersal
Demersal	0	10.6	395	
Bathydemersal	0	10.6	44	
Reef-Associated	0	2.1	87	
Sessile	0	2.1	317	

Table 1. List of habitats and assigned ingestion rate for the hazard due to neutral particles (NP) and sinking particles (SP). The last column is the number of species included in each habitat, indicating which are considered pelagic (affected by NP) and benthic or demersal (affected by SP).

MPA		Exposure	Hazard NP	Vuln. NP	Risk NP	Hazard SP	Vuln. SP	Risk SP
MPA1	Sur de Almería - Seco de los Olivos	0.73	0.19	0.38	0.18	0.44	0.05	0.47
MPA2	Plataforma-talud marinos del Cabo de la Nao	0.41	0.39	0.31	0.16	0.23	0.03	0.25
MPA3	Espacio marino del Delta de l'Ebre-Illes Columbretes	0.28	0.46	0.21	0.10	0.22	0.02	0.14
MPA4	Canal de Menorca	0.45	0.27	0.32	0.14	0.13	0.04	0.26
MPA5	Grands dauphins du Golfe du Lion	0.34	0.34	0.30	0.13	0.01	0.03	0.07
MPA6	Camargue	0.23	0.31	0.18	0.08	0.001	0.02	0.06
MPA7	Oiseaux marins de l’Agriate	0.16	0.14	0.19	0.06	0.02	0.02	0.05
MPA8	Plateau du Cap Corse	0.34	0.20	0.30	0.10	0.02	0.04	0.06
MPA9	Korinthiakos Kolpos	0.22	0.22	0.11	0.05	0.29	0.01	0.10
MPA10	Ethniko Thalassio Parko Alonnisou – Voreion Sporadon, Anatoliki Skopelos	0.41	0.11	0.32	0.13	0	0.03	0

Table 2. Summary of the risk factors for the 10 MPAs analyzed in this section.

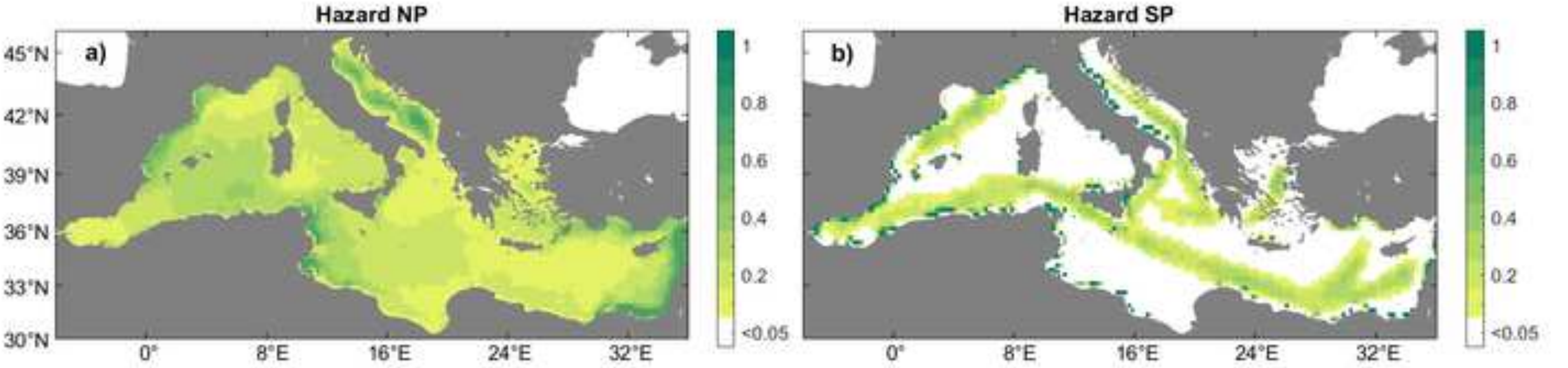

Hazard NP
a)
45°N
42°N
39°N
36°N
33°N
30°N
0°
8°E
16°E
24°E
32°E
1
0.8
0.6
0.4
0.2
<0.05
Hazard SP
b)
0°
8°E
16°E
24°E
32°E
1
0.8
0.6
0.4
0.2
<0.05

Figure_2

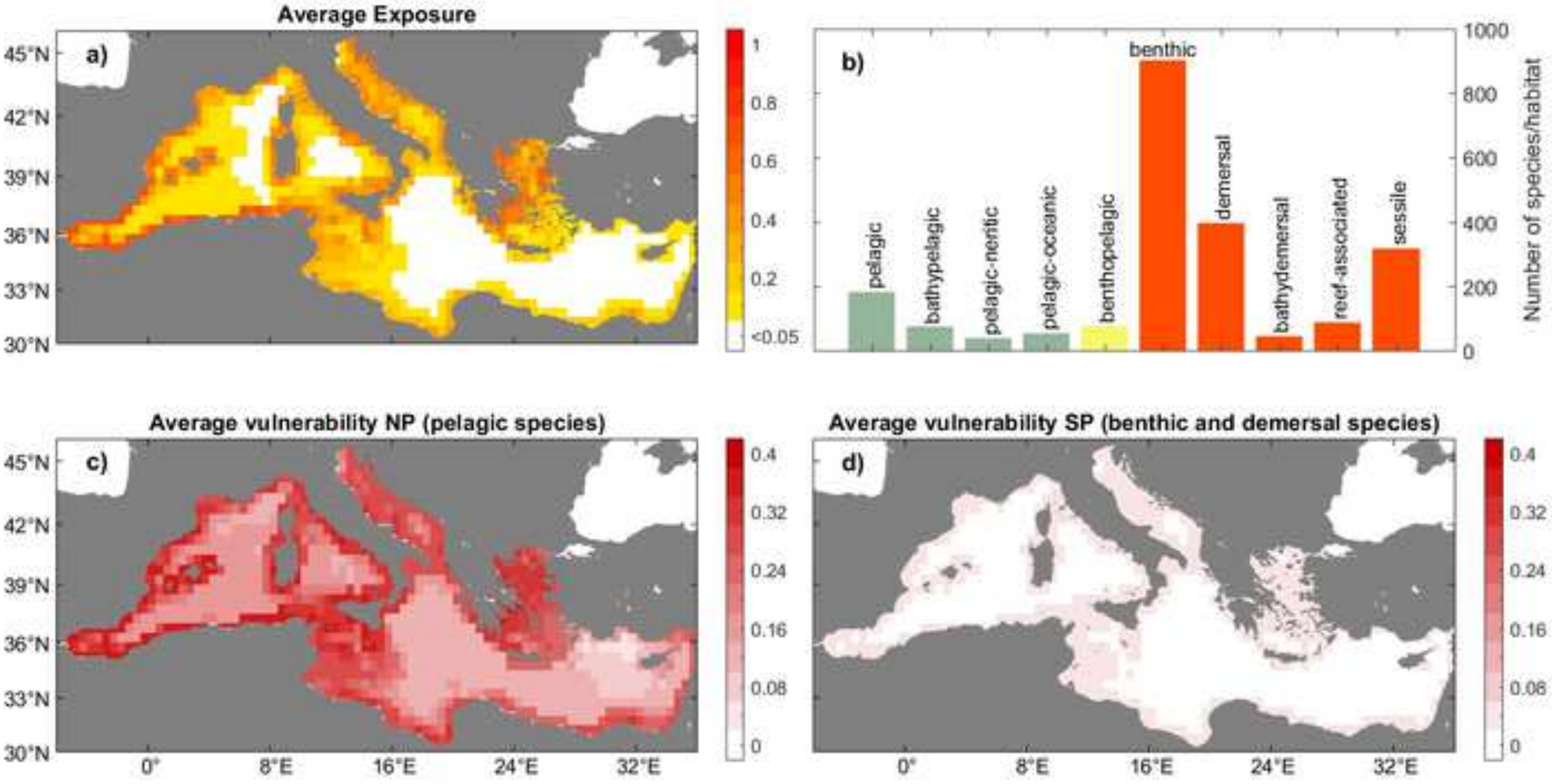

Average Exposure
a)
45°N
42°N
39°N
36°N
33°N
30°N
1
0.8
0.6
0.4
0.2
<0.05
b)
benthic
pelagic
bathypelagic
pelagic-neritic
pelagic-oceanic
benthopelagic
demersal
bathydemersal
reef-associated
sessile
1000
800
600
400
200
0
Number of species/habitat
Average vulnerability NP (pelagic species)
c)
0.4
0.32
0.24
0.16
0.08
0
0°
8°E
16°E
24°E
32°E
Average vulnerability SP (benthic and demersal species)
d)

Figure_3

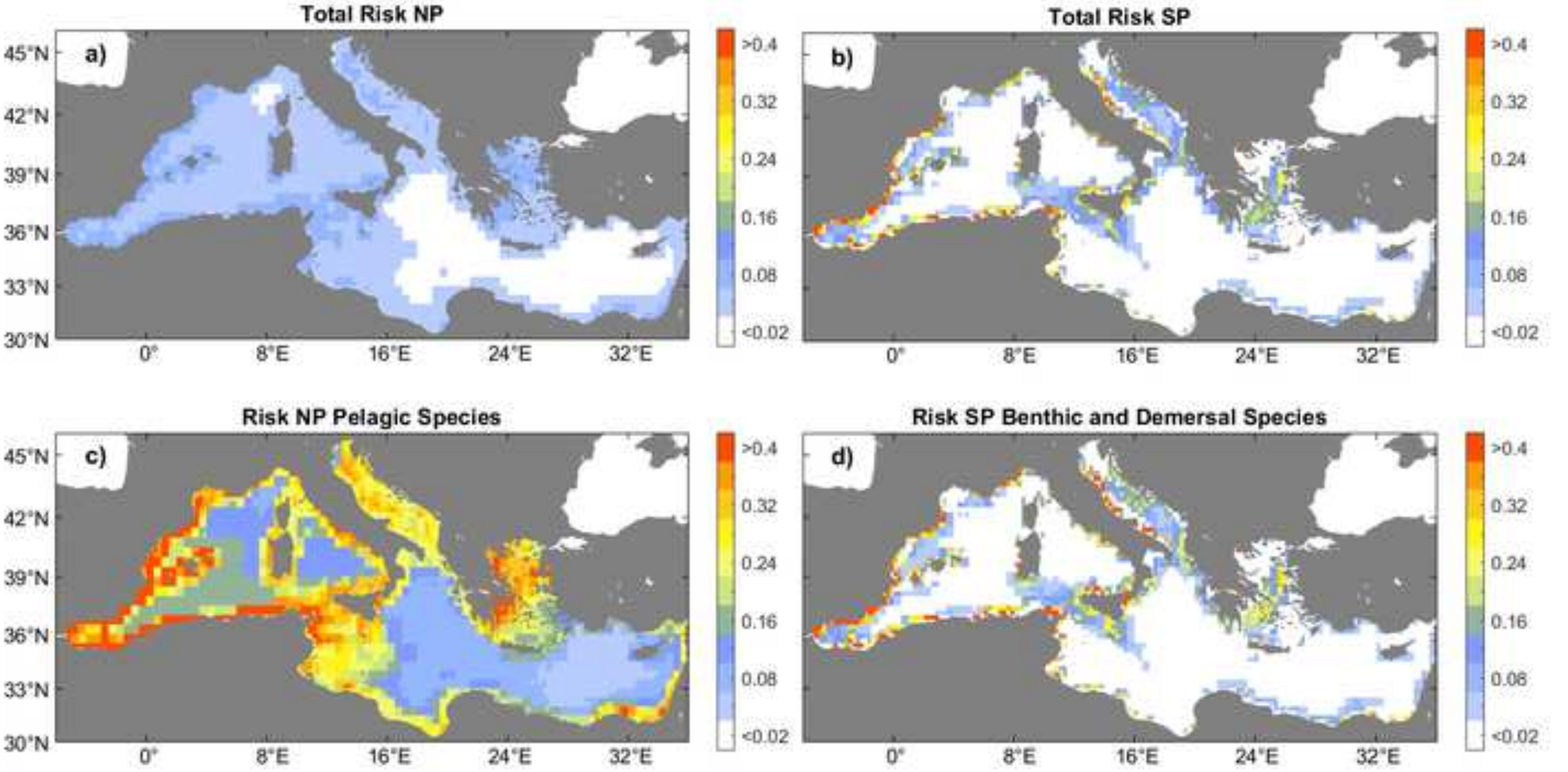
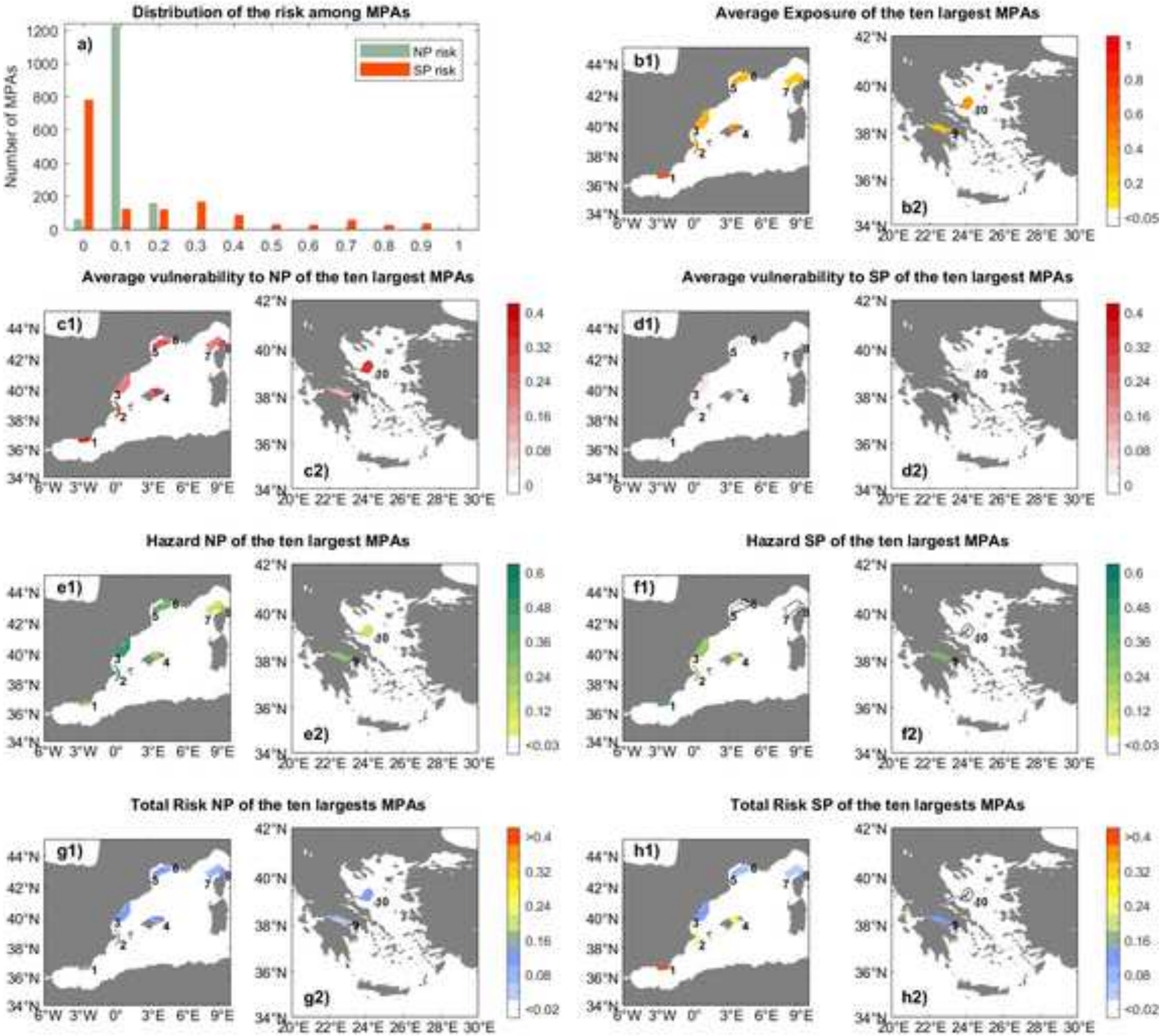

Total Risk NP
a)
Total Risk SP
b)
Risk NP Pelagic Species
c)
Risk SP Benthic and Demersal Species
d)
45°N
42°N
39°N
36°N
33°N
30°N
0°
8°E
16°E
24°E
32°E
>0.4
0.32
0.24
0.16
0.08
<0.02

Figure_4


Distribution of the risk among MPAs
a)
Number of MPAs
1200
1000
800
600
400
200
0
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
NP risk
SP risk
Average Exposure of the ten largest MPAs
b1)
b2)
1
0.8
0.6
0.4
0.2
<0.05
Average vulnerability to NP of the ten largest MPAs
c1)
c2)
Average vulnerability to SP of the ten largest MPAs
d1)
d2)
0.4
0.32
0.24
0.16
0.08
0
Hazard NP of the ten largest MPAs
e1)
e2)
Hazard SP of the ten largest MPAs
f1)
f2)
0.6
0.48
0.36
0.24
0.12
<0.03
Total Risk NP of the ten largests MPAs
g1)
g2)
Total Risk SP of the ten largests MPAs
h1)
h2)
>0.4
0.32
0.24
0.16
0.08
<0.02
44°N
42°N
40°N
38°N
36°N
34°N
6°W
3°W
0°
3°E
6°E
9°E
20°E
22°E
24°E
26°E
28°E
30°E
1
2
3
4
5
6
7
8
9
10

Supplementary_table_S1

Supplementary Data

Suplemmentary_material_Soto-Navarro_et_al_Table_S1_R1.pdf

Sumplementary_table_S2

Sumplementary_figures

Declaration of Interest Statement

Declaration of interests

☒ 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.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Impact of the marine litter pollution on the Mediterranean biodiversity: a risk assessment study with focus on the marine protected areas.

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Credit authors statement

JSN co-designed the methodology, conducted the numerical simulations, analyzed the data and co-wrote the manuscript. GJ co-designed the methodology, co-wrote the manuscript and supervised the data analysis. MC, SD and CA contributed to the design of the methodology, collaborated in the data analysis and in the writing, review and editing of the manuscript. MCF collaborated in the design of the methodology.