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RESEARCH PAPER

The Mediterranean Sea under siege: spatial overlap between marine biodiversity, cumulative threats and marine reserves

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ABSTRACT

Aim A large body of knowledge exists on individual anthropogenic threats that have an impact on marine biodiversity in the Mediterranean Sea, although we know little about how these threats accumulate and interact to affect marine species and ecosystems. In this context, we aimed to identify the main areas where the interaction between marine biodiversity and threats is more pronounced and to assess their spatial overlap with current marine protected areas in the Mediterranean.

Location Mediterranean Sea.

Methods We first identified areas of high biodiversity of marine mammals, marine turtles, seabirds, fishes and commercial or well-documented invertebrates. We mapped potential areas of high threat where multiple threats are occurring simultaneously. Finally we quantified the areas of conservation concern for biodiversity by looking at the spatial overlap between high biodiversity and high cumulative threats, and we assessed the overlap with protected areas.

Results Our results show that areas with high marine biodiversity in the Mediterranean Sea are mainly located along the central and north shores, with lower values in the south-eastern regions. Areas of potential high cumulative threats are widespread in both the western and eastern basins, with fewer areas located in the south-eastern region. The interaction between areas of high biodiversity and threats for invertebrates, fishes and large animals in general (including large fishes, marine mammals, marine turtles and seabirds) is concentrated in the coastal areas of Spain, Gulf of Lions, north-eastern Ligurian Sea, Adriatic Sea, Aegean Sea, south-eastern Turkey and regions surrounding the Nile Delta and north-west African coasts. Areas of concern are larger for marine mammal and seabird species.

Main conclusions These areas may represent good candidates for further research, management and protection activities, since there is only a maximum 2% overlap between existing marine protected areas (which cover 5% of the Mediterranean Sea) and our predicted areas of conservation concern for biodiversity.

Keywords
Cumulative impacts, human threats, marine biodiversity, marine conservation, marine protected areas, Mediterranean Sea.

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INTRODUCTION

The Mediterranean Sea is the largest and deepest enclosed sea on earth. Located between Africa, Europe and Asia, it is a hotspot of terrestrial and marine biodiversity (Bianchi & Morri, 2000; Myers *et al.*, 2000; Coll *et al.*, 2010). Currently it is known to host more than 17,000 described marine species and contributes an estimated 7% to the world's marine biodiversity, including high percentages of endemic species (Coll *et al.*, 2010). Emblematic species of conservation concern, such as the bluefin tuna, *Thunnus thynnus*, and the Mediterranean monk seal, *Monachus monachus* (e.g. Groombridge, 1990; Reijnders *et al.*, 1997; Bearzi *et al.*, 2004; Mackenzie *et al.*, 2009), as well as several unique, endangered and sensitive habitats, such as the seagrass meadows of the endemic *Posidonia oceanica* (e.g. Blondel & Aronson, 2005; Ballesteros, 2006; IUCN-Med, 2009), occur in the basin.

This rich ecosystem has been altered in many ways throughout its history. Temporal trends indicate that overexploitation and habitat loss are the main human drivers of historical changes (Lotze *et al.*, 2011). However, since the Industrial Revolution and ensuing improvements in technology and a human population explosion, these pressures have grown exponentially (Coll *et al.*, 2010; Lotze *et al.*, 2011). At present, habitat loss and degradation, as well as extraction, pollution, eutrophication and the introduction of alien species, and recently climate change, are the most important threats that affect the greatest number of taxonomic groups occurring in the Mediterranean Sea (Coll *et al.*, 2010; Costello *et al.*, 2010).

Within the context of high biodiversity and high impacts of human activities, there is a need to move towards a fine-scale analysis of spatial congruencies between the cumulative impact of multiple threats and marine biodiversity across taxa in order to identify critical areas and thus future conservation needs. Anthropogenic pressures on marine ecosystems in the Mediterranean Sea are predicted to increase in the future (Coll *et al.*, 2010), especially those posed by climate change, habitat degradation and exploitation, as they may do world-wide (Butchart *et al.*, 2010). Though a large body of knowledge exists on these impacts on Mediterranean marine resources (e.g. Galil, 2000; Danovaro, 2003; Bianchi, 2007; Tsounis *et al.*, 2007; Abdulla & Linden, 2008; Stergiou *et al.*, 2009; Coll *et al.*, 2010; Lasram *et al.*, 2010, and references therein), little is known about their cumulative effects and their synergistic impact on marine species, communities and ecosystems. This limits environmental analyses, which usually consider few anthropogenic threats, and which may therefore lack realism, especially in highly affected areas such as the Mediterranean Sea (Costello *et al.*, 2010).

In the Mediterranean Sea, similarly to most of coastal ecosystems across the world, marine protected areas (MPAs) have become the primary tool for *in situ* habitat and biodiversity conservation with more than 100 MPAs that cover approximately 5% of the continental shelf (Abdulla *et al.*, 2008; MEDPAN, 2010). In addition, there is a growing consensus that MPAs protect the structure and function of ecosystems (Mouillot *et al.*, 2008; Libralato *et al.*, 2010) and rebuild and sustain fisheries (Russ *et al.*, 2004), particularly artisanal fisheries in the Mediterranean (Forcada *et al.*, 2009). However, Mediterranean MPAs have been set up following local sociopolitical decisions instead of ecological considerations (Francour *et al.*, 2001; García-Charton *et al.*, 2008) and the ability of this MPA network to protect most of the marine biodiversity from multiple threats is still unknown. A move towards sustainable management and planning requires spatial mapping of human impacts and protection efforts to assess their overlap with marine biodiversity. Similar initiatives have been developed in other regional seas (e.g. Selkoe *et al.*, 2009; Benn *et al.*, 2010) and at global scales (Halpern *et al.*, 2008) analysing the overlap between cumulative threats and marine ecosystems, or between MPA networks and marine biodiversity (Hamilton *et al.*, 2010).

Under an ecosystem-based approach, there is an increasing need to manage resources while ensuring their sustainable use. At the same time, regional, national and European agencies call for a better understanding of the impact of human activities on marine ecosystems. Therefore, quantifying biodiversity patterns in and threats to the biologically rich Mediterranean Sea is a major step forward in determining the possible responses of its ecosystems to anthropogenic impacts and global change.

In this context, our work had the aim of: (1) identifying the principal areas of conservation concern in the Mediterranean Sea, where interaction between marine biodiversity and threats may be more pronounced, and (2) quantifying the overlap between these areas and current protected sites. Firstly, we identified areas of high biodiversity in the Mediterranean Sea using available information on species distribution of marine mammals, marine turtles, seabirds, fishes and commercial or well-documented invertebrates (henceforth simply called 'invertebrates'). Secondly, we mapped potential areas of high anthropogenic threats where several such threats occur simultaneously. Finally, we quantified the areas of high conservation concern for biodiversity by looking at how biodiversity-rich areas spatially overlap with those of high cumulative threats, and with those currently protected.

MATERIALS AND METHODS

The Mediterranean Sea

The Mediterranean Sea has narrow continental shelves and a large area of open water (Fig. 1). It covers approximately 2,500,000 km^2 (excluding the Black Sea) with an average depth of 1460 m and a maximum of 5267 m. The Mediterranean Sea connects through the Strait of Gibraltar to the Atlantic Ocean in the west, and through the Strait of Bosphorus to the Sea of Marmara and the Black Sea in the north-east, while in the south-east the Suez Canal links the Mediterranean to the Red Sea and the Indian Ocean. The Strait of Sicily divides the sea into two distinct basins, the western (0.85 million km^2) and the eastern (1.65 million km^2).

General oceanographic conditions in the Mediterranean Basin have been previously described in detail (e.g. Hopkins,

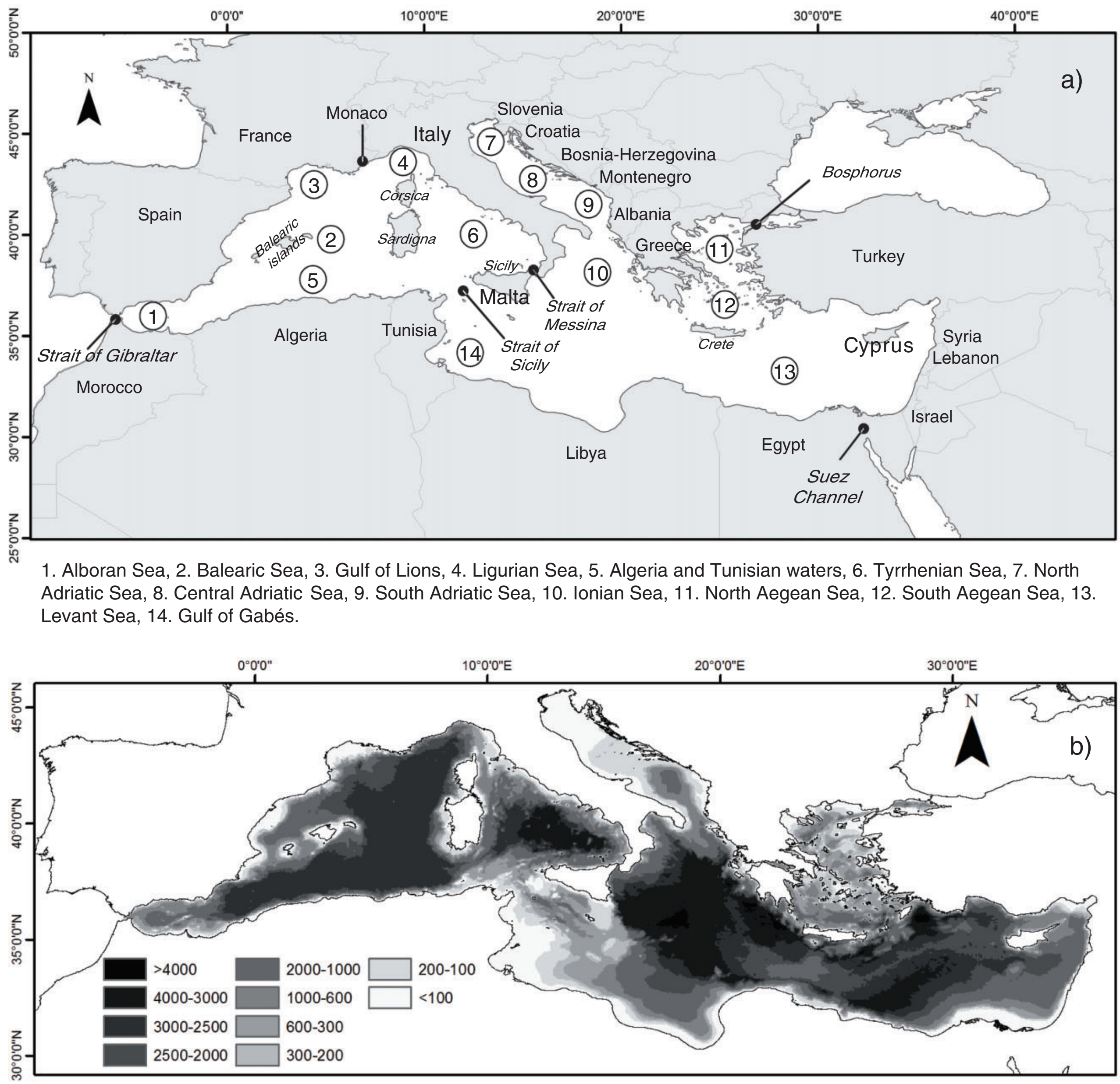

Figure 1 The Mediterranean Sea: (a) main biogeographic regions, basins and administrative divisions, and (b) maximum average depth (m).

1985; Pinardi *et al.*, 2006). The basin is characterized by strong environmental gradients making the eastern end more oligotrophic than the western end. Local features enrich coastal areas through changing wind conditions, temporal thermoclines, currents and river discharges and municipal sewage (Estrada, 1996; Bosc *et al.*, 2004). The annual mean sea surface temperature shows a high seasonality and important gradients from west to east and north to south (Hopkins, 1985). The biological production decreases from north to south and west to east and is inversely related to the increase in temperature and salinity (Danovaro *et al.*, 1999). This illustrates that the Mediterranean Sea is highly heterogeneous.

Mapping marine biodiversity

We collected available data on species diversity distribution of marine mammals, marine turtles, seabirds, fishes and invertebrates (data modified from Coll *et al.*, 2010) to identify areas of high species biodiversity (Table 1). Also, we mapped the distribution of large predators (species that are likely to have predator roles due to their body size and trophic behaviour) using the information from large fishes, marine mammals and turtles, and seabirds. Species included in the above-mentioned groupings and data sources are listed in Appendix S1 in the Supporting Information. This information is also now freely available

Table 1 Information used to map marine biodiversity in the Mediterranean Sea. The resolution of all data sets was 0.1° latitude by 0.1° longitude. Further information in Appendix S1.

Biodiversity	Number of species	Description	Time frame	Sources
Fish species	625	Main fish species	1990s	Lasram *et al.* (2009), Lasram & Mouillot (2009), Coll *et al.* (2010)
Marine mammals	9	Resident	1990s–2000s	Coll *et al.* (2010)
Marine turtles	3	Resident	1990s–2000s	Coll *et al.* (2010)
Seabirds	19	Breeding and non-breeding	1990s–2000s	Sea Around Us project database
Invertebrates	50	Commercial or well-studied	1950s–2000s	Sea Around Us project and FAO databases (Appendix S1)
Large predators	80	Predatory fish, marine mammals, turtles and seabirds	1990s–2000s	Lasram *et al.* (2009), Lasram & Mouillot (2009), Coll *et al.* (2010), Sea Around Us database

through SeaLifeBase (http://www.sealifebase.org; Palomares & Pauly, 2010), FishBase (http://www.fishbase.org; Froese & Pauly, 2010) and through the Sea Around Us project website (http://www.seaaroundus.org; Pauly, 2007)[1].

We used the above detailed spatial data, mostly available in the form of expert-drawn maps or sighting locations, to map spatial patterns of invertebrate and vertebrate species using geographical information system (GIS) software (ArcGIS v.9.3, Environmental Systems Research Institute). Following the methodology by Coll *et al.* (2010), we estimated species richness of different species groupings as the sum of the species co-occurring by overlapping distribution maps at fine-scale resolution (0.1° × 0.1° grid cells).

With the above information, we defined and mapped five species groupings: (1) invertebrates, (2) fishes, (3) marine mammals and marine turtles, (4) seabirds, and (5) large predators; we re-expressed known occurrences in relative terms between 0 (no species present) and 1 (100% of species present). Marine mammals and marine turtles were grouped together due to the low species diversity of marine turtles residing in the Mediterranean Sea (Groombridge, 1990).

Cumulative anthropogenic threats

We gathered from a variety of sources the available data on 18 direct and indirect anthropogenic threats in the Mediterranean Sea (Table 2). We considered all those human activities with available data documenting both direct and indirect impacts on marine species (Coll *et al.*, 2010). Specific information on sources and analysis for developing threat layers is provided in Appendix S2.

With the above data on threats, we created six layers of potential cumulative anthropogenic threats (Table 2):

1. Coastal-based impacts: cumulative effects from inorganic and organic coastal pollution, nutrient runoff and hypoxia, aquaculture activities and the presence of invasive species.

2. Trawling and dredging disturbance: cumulative (historical to present) high disturbance on the sea floor by bottom fishing gear operations (from 1950 to 2006).

3. Ocean-based pollution: cumulative effects from shipments of toxic substances (e.g. toxic waste, radioactive waste and fertilizers) and other ocean-based pollution from shipping traffic, deposition of heavy metals and inorganic nitrogen.

4. Exploitation of marine resources by fisheries: information relative to recent industrial or semi-industrial demersal and pelagic catches (both including low and high by-catch, and low or high habitat modification) and artisanal fisheries.

5. Maritime activities: cumulative effects from maritime traffic due to shipping and other transport and the presence of oil rigs.

6. Climate change: cumulative effects from changes in sea water temperature, in the intensity of ultraviolet radiation and in water acidification.

We used ArcGIS 9.3 software and a 0.1° × 0.1° grid cell resolution to map patterns of anthropogenic impacts and estimate the presence or absence of each threat to create cumulative threat layers (or threat models). Each continuous threat was first log(x + 1)-transformed and then normalized (expressed between 0 and 1) in order to compare the intensity of threats.

For each species biodiversity grouping, i.e. invertebrates, fishes, marine mammals and turtles, seabirds and large predators, we built a spatial cumulative threat model (equation 1 below) equal to a weighted sum of each of the six cumulative threat layers (Table 2). Vulnerability weights (Table 3) applied to each threat layer were estimated using published data on specific taxa and expert opinions (Coll *et al.*, 2010). Specifically, experts involved in the previous study were asked to rank main threats affecting the diversity of species groupings under their expertise using data available to them and personal experience. The threats were ranked from 0 to 5, taking into account the relative importance of each threat to biodiversity (i.e. 0 no importance, 5 highest in importance). The original scores are available elsewhere (Coll *et al.*, 2010) and Table 3 presents the relative weights of individual threats for different species groupings used in this study.

Each cumulative threat model (T_L) for each species biodiversity grouping (i) was expressed as a weighted average of individual threats ($T_{L,i}$):

$$T_{L,i} = \sum_{n=1}^{N} (L_n \cdot w_n) \qquad (1)$$

where L_n is the nth threat layer, w_n is the weight of layer L_n and $N = 6$ is the number of the threat layer (1, coastal-based impacts;

[1]This information is available under Mediterranean LME: ecosystems information.

Table 2 Information used to map cumulative anthropogenic threats to marine biodiversity in the Mediterranean Sea.

Threat layers	Description & combined sub-layers	Resolution (degrees)	Time frame	Sources
1. Coastal-based impacts	Inorganic pollution (non-point, urban runoff)	0.5 × 0.5	2000–01	Halpern *et al.* (2008)
	Organic pollution (non-point, pesticides)	0.5 × 0.5	1992–2001	
	Nutrients (fertilizers)	0.5 × 0.5	1993–2002	
	Hypoxia sites	0.1 × 0.1	1990s–2000s	Diaz & Rosenberg (2008)
	Invasive species (fish species)	0.1 × 0.1	1990s	Lasram *et al.* (2009), Lasram & Mouillot (2009)
	Fish and shellfish aquaculture (location and nature of pens)	0.1 × 0.1	2004–06	P. Trujillo, *et al.*, submitted (Appendix S2)
2. Trawling and dredging disturbance	Benthic disturbance from fishing	0.5 × 0.5	1950–2006	Sea Around Us project database
3. Ocean-based pollution	Poison shipments	0.1 × 0.1	1979–2001	In.fondo.al.mar (2010)
	Ocean-based pollution (from shipping traffic and port data)	0.5 × 0.5	1999–2005	Halpern *et al.* (2008)
	Deposition of heavy metals (Cd, Pb, Hg)	0.1 × 0.1	2007	Ilyin *et al.* (2009)
	Inorganic nitrogen deposition	0.5 × 0.5	2000	Dentener *et al.* (2006)
4. Exploitation of marine resources by fisheries	Demersal and pelagic high and low by-catch and high and low habitat modification	0.5 × 0.5	2000–06	Watson *et al.* (2006a, b)
	Artisanal fishing	0.5 × 0.5	1999–2003	Sea Around Us project database
5. Maritime activities	Commercial shipping lanes	0.5 × 0.5	2004–05	Halpern *et al.* (2008)
	Benthic oil rig structures	0.5 × 0.5	2003	Halpern *et al.* (2008)
6. Impacts of climate change	Sea surface temperature anomalies	0.5 × 0.5	2000–05 vs. 1985–90	Halpern *et al.* (2008)
	UV increase	0.5 × 0.5	1996–2004	
	Ocean acidification	0.5 × 0.5	1870 vs. 2000–09	

Table 3 Weights of each threat layer by biodiversity grouping to create the threat models by group (the sum of the weights by biodiversity grouping is equal to 1).

	1. Coastal-based impacts	2. Trawling and dredging disturbance	3. Marine pollution	4. Exploitation of marine resources	5. Maritime activities	6. Climate change
Invertebrates	0.16	0.27	0.16	0.22	0.05	0.14
Fishes	0.11	0.28	0.17	0.28	0.06	0.11
Marine mammals and marine turtles	0.07	0.14	0.29	0.21	0.14	0.14
Seabirds	0.08	0.00	0.31	0.38	0.08	0.15
Large predators	0.09	0.16	0.24	0.29	0.09	0.13

2, trawling and dredging disturbance; 3, marine pollution; 4, exploitation of marine resources; 5, maritime activities; 6, climate change).

The total cumulative threat model was calculated as the sum of each cumulative threat model ($T_{L,i}$) for each biodiversity grouping i:

$$T_{L,total} = \sum_{i=1}^{I} (T_{L,i}) \quad (2)$$

where $I = 4$ is the number of biodiversity groupings (1, invertebrates; 2, fishes; 3, marine mammals and turtles; 4, seabirds).

To explore how the weighting factors w_n of equation 1 could affect the overall results, we performed a sensitivity analysis and developed alternative results using (1) equal weighting and (2) randomly assigned weightings to threat layers. We compared these new results with results obtained using available weighting factors (Table 3).

Areas of conservation concern for biodiversity and overlap with MPAs

Spatial distributions of biodiversity by group and the cumulative threat models were used to identify important areas of conservation concern, i.e. areas where high biodiversity and high cumulative threats occurred simultaneously. We calculated a new index of overlap (OI) as follows:

$$OI_r = (BI_r + T_{L,\text{total},r})/2 \quad (3)$$

where *BI* is the biodiversity index (the sum of all the species or diversity by group normalized over space and scaled between 0 and 1), and $T_{L,\text{total}}$ is the threat index (equation 2 above, ranging between 0 and 1). *OI* values ranged from 1, indicating high concern, to 0, low or no concern using $r = 4$ intervals: < 25%, ≥ 25%, ≥ 50% and ≥ 75%. Therefore, the *OI* was calculated for areas where both species diversity and the intensity of cumulative threats were < 25%, ≥ 25%, ≥ 50% and ≥ 75% (thus, we calculated the $< OI_{25}$, OI_{25}, OI_{50} and OI_{75}, respectively). For example, OI_{25} identifies areas where diversity is equal to or higher than 25% and threat intensity is equal to or higher than 25%, and we excluded the cases where combinations of lower diversity and higher threats, or vice versa, would provide similar results.

We used the Spatial Analyst Toolbox of ArcGIS v.9.3 to calculate the total area of all regions that displayed a high degree of overlap between cumulative threat intensity and high species diversity. We expressed these areas as a percentage of the total surface of the Mediterranean Sea using the North Pole Lambert Azimuthal Equal Area Conic projection to minimize area distortions, and we plotted the maps using the World Geodetic 1984 coordinate system (WGS1984).

Furthermore, we compared how areas of high conservation concern overlapped with currently established MPAs. For this analysis we used data on existing national and international MPAs in the Mediterranean Sea (Abdulla *et al.*, 2008; MEDPAN, 2010) and complemented them with information from other Mediterranean institutions (see Appendix S3). We excluded from the analysis those sites that had only been formally declared as MPAs (e.g. those at present only proposed).

RESULTS

Areas of high marine biodiversity

High-biodiversity areas were primarily located in the coastal areas of Spain, France and Italy, including the Balearic Islands, Corsica, Sardinia and Sicily, the north-western coast of Africa, the eastern Adriatic Sea, and coastal regions of the Ionian and the Aegean Sea (Fig. 2).

Invertebrate species were of higher concentration in the coastal waters and over the continental shelf areas of the Mediterranean Sea, especially of the western area, the Adriatic and Aegean seas, and the coasts of Tunisia, Egypt and Israel (Fig. 2a). The Adriatic Sea exhibited the highest species richness of invertebrates (Fig. 2a). Fish were of highest species richness around Sicily, followed by the coastal and shelf areas of the western Mediterranean and the Ionian Sea (Fig. 2b).

Eight of the nine resident marine mammals were found in the western Mediterranean and were concentrated especially in the eastern Adriatic, in the waters of Alboran, Balearic, Ligurian, Aegean and Ionian seas, and along the coasts of western Africa and Israel (Fig. 2c). Seabird species distribution was concentrated over coastal areas throughout the Mediterranean region, especially around river deltas (Fig. 2d). Highest seabird species richness was found in the Ebro and Rhone deltas, southern Spain, southern Corsica and Sardinia and over coastal waters of the Aegean Sea. The diversity of large predators was higher in the western Mediterranean and in the Aegean Sea (Fig. 2e).

In general, species diversity declined from north to south and from west to east and was concentrated in coastal and shelf areas (Fig. 2f). This finding may highlight the heterogeneous nature of species distribution in the Mediterranean Sea, but it may also be a result of the lack of data from countries of the southern and eastern regions (Coll *et al.*, 2010).

Areas of cumulative threats

Coastal-based impacts were as expected most pronounced in parts of the Mediterranean Basin with the highest population densities (Fig. 3a). Trawling and dredging disturbance, ocean-based pollution and the exploitation of marine resources by fisheries extended to the shelves and slopes of the whole basin, and showed a tendency to concentrate in the north and western Mediterranean (Fig. 3b–d). The impact of shipping and maritime traffic was prevalent mainly in the open waters of the basin, especially along traffic routes, harbours and other important commercial coastal areas (Fig. 3e). Potential impacts of climate change were more pronounced in the southern and eastern regions (Fig. 3f).

The cumulative threat models for the five diversity groupings identified several areas of high potential risk for invertebrates, fishes, marine mammals and turtles, seabirds and large predators which were widespread throughout the western and eastern parts of the Mediterranean Basin (Fig. 4). Fewer areas were located in the south-eastern Mediterranean region. Areas where cumulative impacts on invertebrates, fishes and seabirds were greater were located along the coast and over the continental shelf (Fig. 4a, b, d). On the other hand, impacts on marine mammals were also pronounced in the open sea (Fig. 4c). These areas of high potential cumulative threat were largely similar between species groupings. This is due to the widespread potential impacts of cumulative threats on marine diversity in the Mediterranean Sea and a generally low sensitivity of the cumulative models to the different impact weights (Table 3) given to the threats for each biodiversity grouping (see sensitivity analysis results in Appendix S4a).

Areas of conservation concern for biodiversity

The main areas of conservation concern for biodiversity, i.e. where there was higher spatial overlap between areas of high biodiversity and threats, were notably different among species groupings (Fig. 5, Table 4).

For invertebrate and fish species, areas of OI_{50} were primarily located in coastal regions of Spain, France, Italy, the Aegean Sea, south-east of Turkey and regions surrounding the Nile Delta and north-west African coasts (Fig. 5a, b). These areas were relatively small and represented less than 3% of the total surface

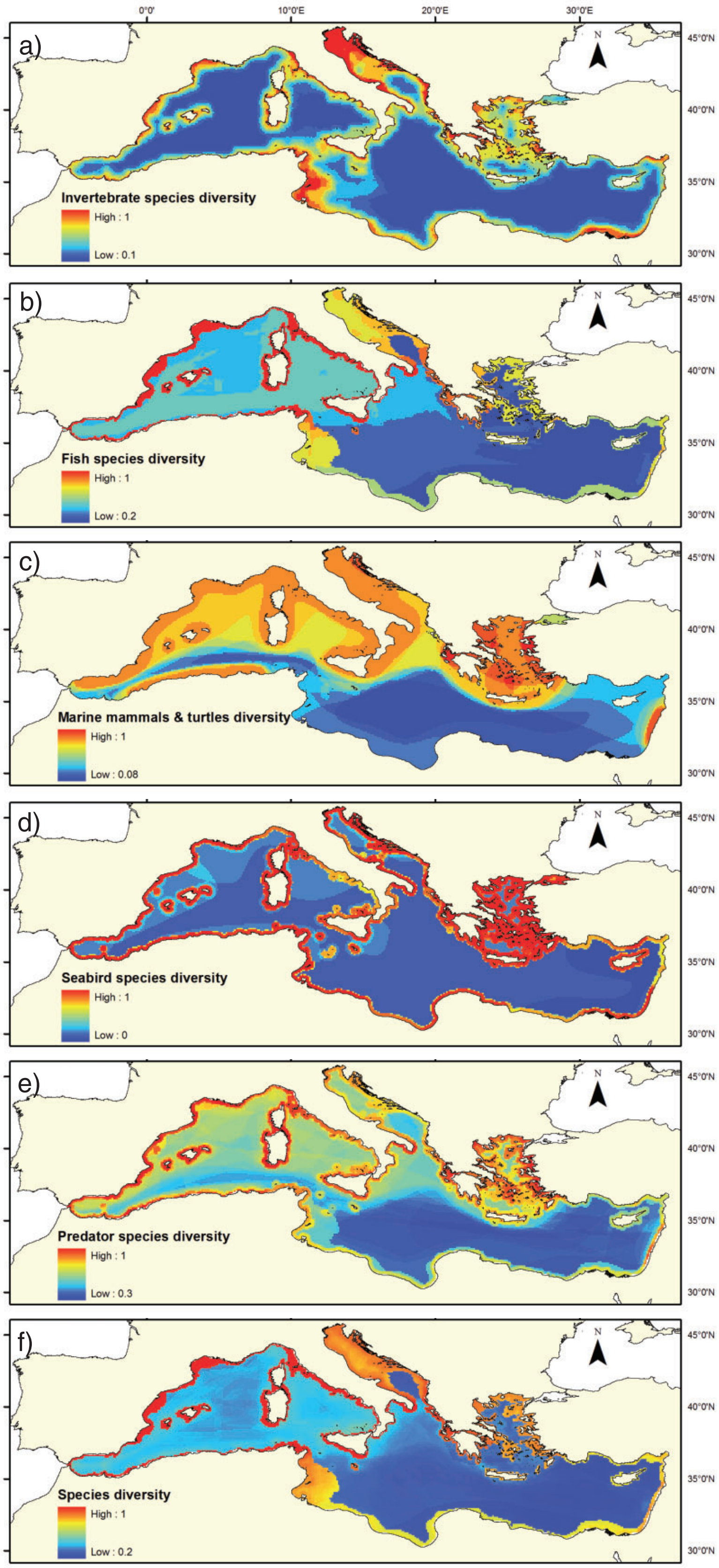

Figure 2 Species biodiversity in the Mediterranean Sea: (a) commercial or well-documented invertebrate species, (b) fish species, (c) marine mammals and turtles, (d) seabirds, (e) large predators (including large fishes, marine mammals, turtles and seabirds), and (f) all data combined. Richness is indicated as a relative amount (expressed between 0 and 1) of total species of group present.

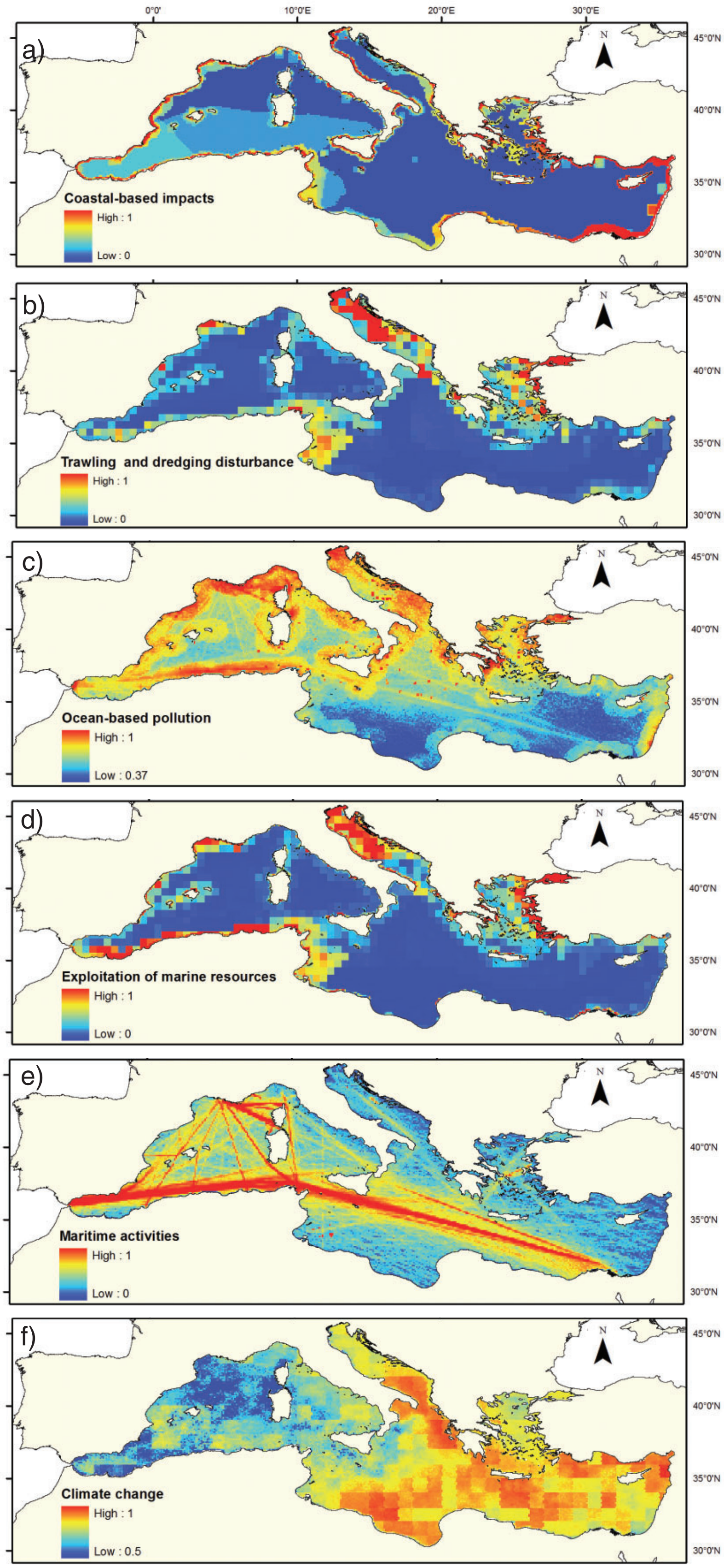

Figure 3 Human threats with potential impact on marine biodiversity in the Mediterranean Sea: (a) coastal-based impacts, (b) trawling and dredging disturbance, (c) ocean-based pollution, (d) exploitation of marine resources, (e) maritime activities, and (f) climate change impact. Each continuous threat was first $\log(x + 1)$-transformed and then normalized (expressed between 0 and 1) in order to compare the intensity of threats (see text for details).

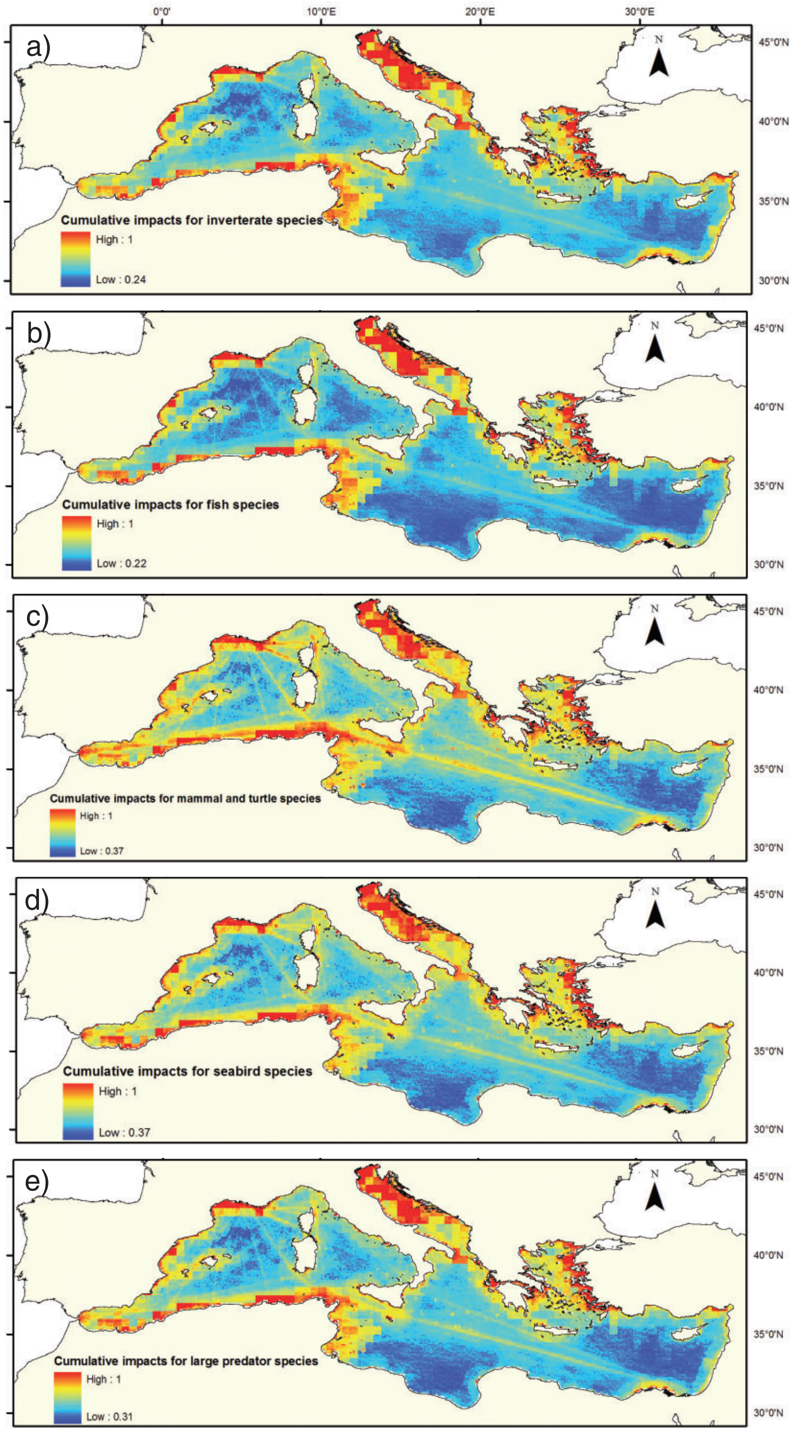

Figure 4 Areas of cumulative threats (expressed as relative values between 0 and 1) with potential impact on marine biodiversity in the Mediterranean Sea: (a) commercial or well-documented invertebrate species, (b) fish species, (c) marine mammals and turtles, (d) seabirds, and (e) large predators (including large fishes, mammals, turtles and seabirds). Cumulative threat (from equation 1) is equal to a weighted sum of each of the six cumulative threat layers (data sources from Fig. 3 and weighting factors on Table 3).

of the Mediterranean Sea (Table 4). Areas of OI_{50} for marine mammals were much larger (Fig. 5c) and represented 30% of the Mediterranean. OI_{50} areas for seabird species and large predators were located closer to coastal regions and showed intermediate extension (Fig. 5d, e, Table 4). OI_{75} areas were much smaller (Table 4) and primarily concentrated in the Gulf of Lions, the northern Adriatic Sea, the Aegean Sea and Tunisian waters, while areas with OI_{25} were large, especially for fishes and large predators (Fig. 5b, e), and were found over coastal waters, particularly for invertebrate species and seabirds (Fig. 5a, d). The identification of these areas showed low to moderate sensitivity to the impact weights given to the threats for each diversity group, especially for invertebrates, fishes and large predatory species (see sensitivity results in Appendix S4b). However, when using equal weighting and randomly assigned weighting, *OI* areas for marine mammal species and seabirds were smaller than *OI* areas calculated with weights assigned by experts (Appendix S4b).

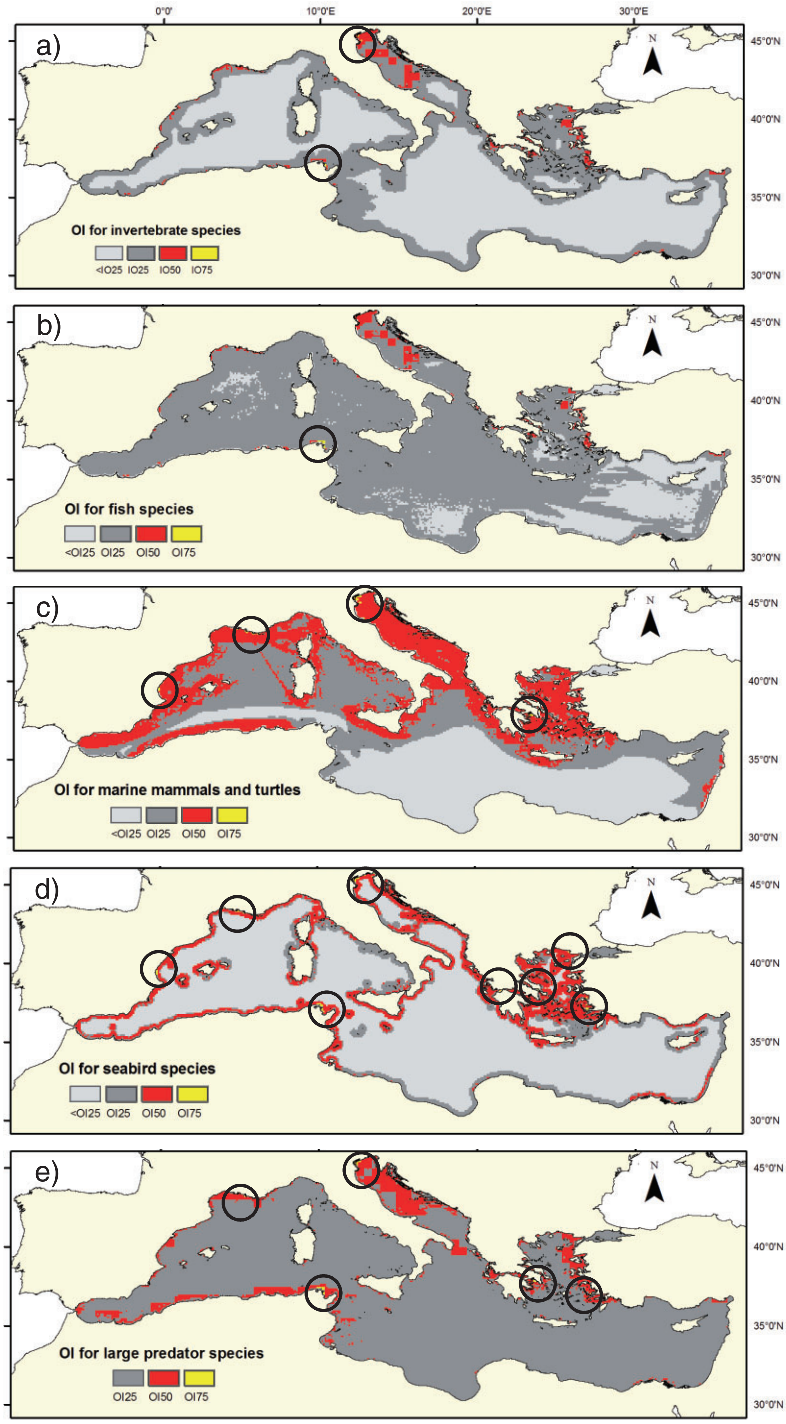

Figure 5 Identification of areas of conservation concern for biodiversity in the Mediterranean Sea, where high diversity and high threat overlap for: (a) commercial or well-documented invertebrate species, (b) fish species, (c) marine mammals and turtles, (d) seabirds, and (e) large predators (including large fish, marine mammals, turtles and seabirds). The overlap index (*OI*) indicates areas where both species diversity and intensity of cumulative threats were < 25% ($< OI_{25}$), ≥ 25% (OI_{25}), ≥ 50% (OI_{50}) and ≥ 75% (OI_{75}). Black circles indicate where values of OI_{75} occur.

For all species combined, total OI_{50} areas were identified over the Spanish Mediterranean shelf, the Gulf of Lions, the north-eastern Ligurian Sea, the north and central Adriatic Sea, the Aegean Sea, and regions of Tunisia and the western coast of Africa as areas of greatest conservation concern (Fig. 6b). These areas covered 1.3% of the Mediterranean Sea and were characterized by high species diversity as well as high cumulative threats. Threats were particularly high for four species groupings in this analysis (i.e. invertebrates, fishes, marine mammals and turtles, and seabirds; see Table 5). The OI_{50} areas for one or two biodiversity grouping out of the four groupings were larger (13–16%; Table 5). Areas of total OI_{25} were widespread along the coastal areas of the western Mediterranean, and the Adriatic and Aegean Seas, and the eastern coastal zone of Turkey, Syria, Lebanon, Israel and Egypt (Fig. 6a). They covered 13% to 32% of the Mediterranean Sea depending on how many groupings were included

Table 4 Quantification of areas of conservation concern for biodiversity in the Mediterranean Sea (results are expressed in % area). The overlap index (*OI*) indicates areas where both species diversity and intensity of cumulative threats were ≥ 25% (OI_{25}), ≥ 50% (OI_{50}) or ≥ 75% (OI_{75}). These areas are represented in Fig. 5.

OI_{25}: Areas of conservation concern with ≥ 25% diversity and ≥ 25% threats (%)	
Invertebrates	35.9
Fishes	82.8
Marine mammals and turtles	34.3
Seabirds	10.6
Large predators	90.8
OI_{50}: Areas of conservation concern with ≥ 50% diversity and ≥ 50% threats (%)	
Invertebrates	2.7
Fishes	1.9
Marine mammals and turtles	29.2
Seabirds	17.0
Large predators	9.1
OI_{75}: Areas of conservation concern with ≥ 75% diversity and ≥ 75% threats (%)	
Invertebrates	0.0
Fishes	0.0
Marine mammals and turtles	0.1
Seabirds	0.1
Large predators	0.1

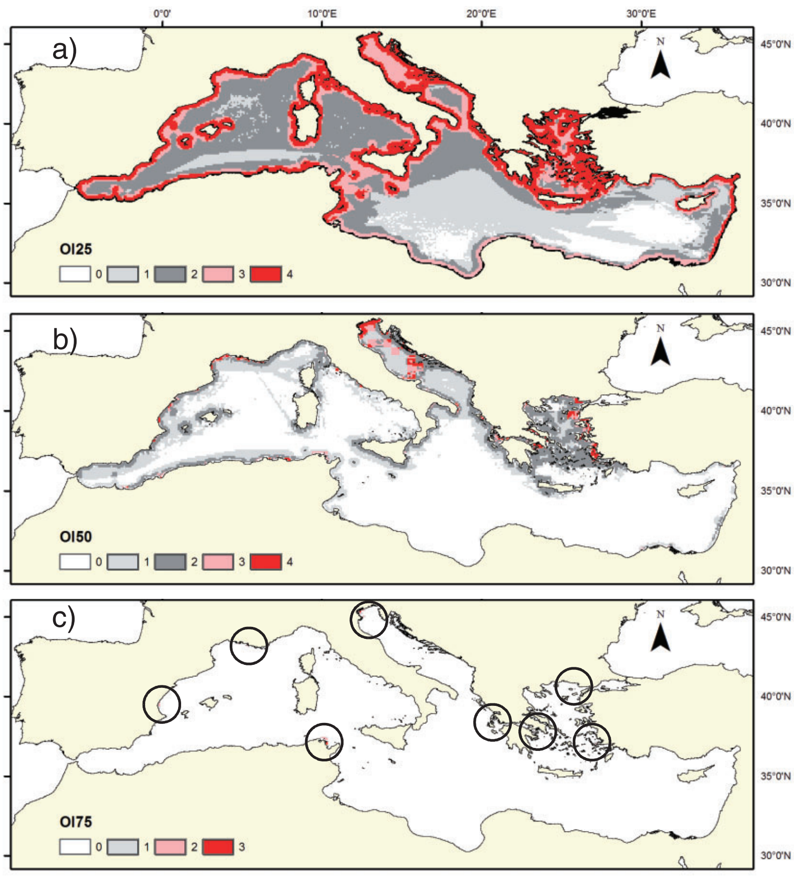

Figure 6 Global areas of conservation concern in the Mediterranean Sea where high biodiversity of invertebrates, fishes, marine mammals and turtles, and seabirds, and high threats overlap. The overlap index (*OI*) indicates areas where both species diversity and intensity of cumulative threats were: (a) ≥ 25% (OI_{25}), (b) ≥ 50% (OI_{50}) and (c) ≥ 75% (OI_{75}). 0 = no groups (of the four biodiversity groupings studied: invertebrates, fishes, marine mammals and turtles, and seabirds) show high diversity and high cumulative threats; 1 = only one group shows high diversity and high threats; 2 = two groups of the four show high diversity and high threats; 3 = three groups of the four show high diversity and high threats; and 4 = all groups show high diversity and high threats. Black circles indicate cells with data.

(Table 5). Areas of total OI_{75} were mainly confined to six coastal areas along the Mediterranean Sea (eastern coast of Spain, south coast of France, northern coast of Tunisia, northern Adriatic Sea, Ionian Sea, and coastal areas of the western, north-eastern and south-eastern Aegean Sea; Fig. 6c).

Overlap between protected areas and areas of conservation concern

Currently, MPAs cover less than 5% of the Mediterranean Sea when including the Pelagos Sanctuary in the Ligurian Sea, which

Table 5 Quantification of areas of conservation concern for biodiversity in the Mediterranean Sea that include high diversity and threats for one to four of the groupings studied (invertebrates, fishes, marine mammals and turtles, and seabirds) (results are expressed in % area). The overlap index (*OI*) indicates areas where both species diversity and intensity of cumulative threats were ≥ 25% (OI_{25}), ≥ 50% (OI_{50}) and ≥ 75% (OI_{75}). These areas are represented in Fig. 6.

OI_{25}: Areas of conservation concern with ≥ 25% diversity and ≥ 25% threats		OI_{50}: Areas of conservation concern with ≥ 50% diversity and ≥ 50% threats		OI_{75}: Areas of conservation concern with ≥ 75% diversity and ≥ 75% threats	
One grouping	23.8	One grouping	16.4	One grouping	0.1
Two groupings	32.1	Two groupings	12.9	Two groupings	0.1
Three groupings	12.9	Three groupings	1.3	Three groupings	0.0
Four groupings	22.0	Four groupings	1.3	Four groupings	0.0

Table 6 Overlap of marine protected areas (see Appendix S3) with areas of conservation concern for biodiversity in the Mediterranean Sea (from Fig. 6) for one to four of the groupings studied (invertebrates, fishes, marine mammals and turtles, and seabirds) (results are expressed in % of conservation concern areas in existing MPAs). The overlap index (*OI*) indicates areas where both species diversity and intensity of cumulative threats were ≥ 25% (OI_{25}), ≥ 50% (OI_{50}) and ≥ 75% (OI_{75}).

Total area (%) under protection*: 5%/0.45%[1];

Overlap of protected areas with areas of concern (*OI*):

≥ OI_{25}		≥ OI_{50}		≥ OI_{75}	
One grouping	0.0	One grouping	1.6	One grouping	0.0
Two groupings	1.6	Two groupings	1.1	Two groupings	0.0
Three groupings	0.6	Three groupings	0.0	Three groupings	0.0
Four groupings	2.0	Four groupings	0.1	Four groupings	–

*UNEP database, 1 without Pelagos Sanctuary.

is by far the largest protected area in the Mediterranean Sea (Abdulla *et al.*, 2008) and which is mainly dedicated to the conservation of marine mammals (Notarbartolo-Di-Sciara *et al.*, 2008). Without considering the Pelagos Sanctuary, the Mediterranean waters under protection are less than 0.5% (Appendix S3).

Less than 2% of the areas with OI_{25} coincide with existing protected areas (Table 6). Overlap with existing MPAs is lower (< 1.6%, Table 6) when considering areas of OI_{50} and OI_{75}. Areas of high conservation concern currently protected are mainly within the Pelagos Sanctuary. If we exclude the Pelagos Sanctuary, the overlap between protected and high conservation concern areas is lower than 0.2%.

DISCUSSION

The mapping of areas of high diversity is very important. Biodiversity is not just one element of natural ecosystems, but is of overarching importance both for science and society as a whole (McCann, 2007; Vira & Adams, 2009). Indeed, it is fundamental and critical for the understanding of biogeographic patterns and of evolutionary history; also it is linked to ecosystem functioning (e.g. Danovaro *et al.*, 2008; Duffy, 2009). Biodiversity is also related to ecosystem services and available resources for humans, to which we give monetary, recreational or other values (Pearce & Moran, 1994; Bengtsson *et al.*, 1997; Oksanen, 1997; Costanza *et al.*, 1998; Tilman, 2000).

Several threats that affect efforts to conserve biodiversity in the Mediterranean Sea were previously identified (Coll *et al.*, 2010). Our study expands on this issue by: (1) identifying the areas where these threats are more prevalent, and (2) quantifying the degree of overlap between anthropogenic threats and marine biodiversity, and the latter with MPAs. The quantification of overlap between cumulative threats and marine biodiversity is fundamental to understanding how biodiversity is affected by human activities and identifying future conservation needs. This is especially relevant in the Mediterranean Sea as a strongly impacted large marine ecosystem (Costello *et al.*, 2010).

Our results show a substantial overlap between regions with high biodiversity and high cumulative threats in the Mediterranean Sea, and are in line with other regional studies that investigated areas of ecological importance in the basin (e.g. Aguilar & De La Torriente, 2008). We show that anthropogenic threats to marine diversity in the Mediterranean Sea are diverse and extend from coastal areas to the open seas. The most important threats to diversity at present, i.e. pollution and eutrophication, habitat degradation and exploitation of marine resources (e.g. Danovaro, 2003; Tsounis *et al.*, 2007; Abdulla & Linden, 2008; Stergiou *et al.*, 2009), are mainly concentrated in the coastal and shelf areas; additional threats to diversity that are expected to substantially increase in the future and that are predicted to have an important effect on marine resources and fisheries in the Mediterranean Sea, such as climate change and invasive species (Galil, 2000; Bianchi, 2007; Cheung *et al.*, 2009, 2010; Lasram *et al.*, 2010), are widely distributed.

We evaluated alternative weighting formulations for threats and found that the areas of strong overlap between biodiversity and threats were robust to the weighting assumption (Appendix S4), indicating that the spatial patterns we identified are not an artefact of our methodology. Our results document the complex situation in the Mediterranean Sea, where both local and global stresses affect marine resources at a regional scale. These areas of conservation concern may be good candidates for future in-depth studies, and specific protection and management actions. They also represent important case studies for a further analysis of the impacts of cumulative anthropogenic threats on marine communities and food webs using a combination of advanced data analysis and modelling tools (e.g. Brown *et al.*, 2010).

Our study also shows that cumulative threats to marine biodiversity in the Mediterranean Sea tend to be concentrated in coastal areas and on shelves, and are higher for seabirds, fishes and invertebrate species in coastal regions. Threats that occur in the open sea are especially important to the diversity of marine mammals, marine turtles and large predatory fish, which are under high pressure in the entire Mediterranean Basin (e.g. Bearzi *et al.*, 2003; Abdulla, 2004). In our study, these organisms also scored highest regarding the area of high cumulative threats that overlapped with high-diversity areas (OI_{25}, OI_{50} and OI_{75}, Table 4).

We also show that the areas of highest concern are concentrated in the northern region of the Mediterranean Sea. This may reflect the higher impact that human populations pose in the northern parts of the basin, and the key role northern countries, most of them members of the European Community, have in the management and conservation of Mediterranean marine biodiversity as well as in policy initiatives. Since only a very small proportion of the areas of conservation concern for biodiversity are currently under protection (Table 6), this study illustrates that a significant amount of effort is still required to protect and manage marine biodiversity in the Mediterranean Sea.

This study is the first step towards a detailed analysis of biodiversity 'hot spots' in the Mediterranean Sea, and may also be relevant to map biodiversity 'cold spots' (Kareiva & Marvier, 2003). The comparison of our results with previously identified 'hot spots' for Mediterranean vertebrate species of special conservation concern (including critically endangered, endangered, vulnerable or near-threatened species of marine mammals, turtles and fishes) (Coll *et al.*, 2010, Table 3) suggests that areas of conservation concern for biodiversity are complementary to those areas identified as biodiversity 'hot spots' for vertebrate species under threat. Thus, they should be considered together when directing conservation efforts towards the Mediterranean Sea. For example, the Alboran Sea, in the south-western part of the Mediterranean Sea, hosts a large concentration of listed vertebrate species, as well as some invertebrates, but may not be considered as an area of biodiversity concern in terms of maximizing the number of species per unit area. Therefore, other important criteria to take into account when identifying areas for the conservation of marine biodiversity in the Mediterranean Sea are the occurrence of rare, endemic and endangered species, non-resident species that may still require large areas, the preservation of functional and phylogenetic traits, the protection of species that require large areas to survive or areas that represent migratory paths, the consideration of important ecosystem services, and important socio-political and economical factors that play key roles in ensuring the maintenance of diversity (Kareiva & Marvier, 2003).

Our analysis of protected areas did not take into account the trawling ban below depths of 800–1000 m established by the General Fisheries Council for the Mediterranean (WWF/IUCN, 2004), since its establishment is limited to bottom trawling activities (and not to all fishing fleets) and its compliance is not assessed. Moreover, this work faced data limitations and uncertainties that need to be taken into account when interpreting results. As highlighted previously (Coll *et al.*, 2010), the availability of biodiversity data from the Mediterranean Sea is highly heterogeneous and is limited in southern and eastern regions of the basin. This limitation may render conservative our identification of areas of conservation concern for biodiversity in the south-eastern regions of the basin. Moreover, available data regarding biodiversity of the Mediterranean Sea as well as threats were collected during an extended period of time (about 20 years) so they represent an average situation rather than the most up-to-date assessment. There is thus a need to revise the spatial distribution in these areas with data that are current. Data available on changes of species assemblages due to human activities are scarce, and this study assumes that changes have not occurred during the period from which most of our data originate (1980–2000). However, available analysis on the impacts of climate change on fish species distributions illustrates that climate change has already instigated some noticeable changes in species distributions (e.g. Sabatés *et al.*, 2006) and is likely to have an important impact in the near future (Lasram *et al.*, 2010). Therefore, the turnover rate of species assemblages may be important and may accelerate in the future due to cumulative human activities, which means that distribution changes should be included in future analysis of global change in the Mediterranean.

The availability of spatial data on anthropogenic threats has increased exponentially in the last decade and such data are abundant in the Mediterranean context. However, the resolution of these data precluded an analysis at finer scales than the large-regional focus adopted here. Detailed information on deep sea activities, such as submarine communication cables, marine research or historical dumping of radioactive waste, are difficult to access or are absent from the region, although a detailed study from the adjacent north-east Atlantic floor illustrated that these activities had moderate impacts compared to the impact of bottom trawling (included in our analysis), which was 'an order of magnitude greater than the total extent of all the other activities' (e.g. Benn *et al.*, 2010). In addition, available data on other threats such as commercial shipping and fishing may be underestimated due to recreational activities and underreporting of commercial fishing. We assumed a linear relationship between driver magnitude and impact on marine biodiversity, which allowed for direct comparison between threats, but ignored the existence of thresholds that are likely conditioning the way anthropogenic impacts act in the ocean and the historical development of anthropogenic threats. This type of information is still extremely scarce. Finally, our analyses did not include dynamic changes in marine biodiversity such as annual variation in production and migration and of threats due to dispersion by oceanographic currents, and neither did they include the direct impact of environmental factors. These dynamics may be important in some cases and should be considered when future analyses are developed.

Despite these limitations, this study provides a first step towards the identification of important areas for conserving marine species biodiversity in the complex Mediterranean Sea, and should be seen as the best understanding of the situation with the current available data. Our results also set a baseline for the comparison of future projections, and are useful to identify actions of research and changes in the future. As new and more detailed data become available, these analyses will be hopefully refined and most certainly improved.

CONCLUSIONS

To move towards an ecosystem approach in the Mediterranean Sea we need to improve the available data on human activities and how they spatially accumulate and interact to have an impact on marine species, communities and ecosystems. In this paper we mapped for the first time how areas with high species diversity overlap with areas that suffer high anthropogenic threats in the Mediterranean Sea. These overlaps are widespread and can be used to identify priority areas for biodiversity protection. Since current MPAs hardly cover any of these priority areas, identified areas may be good candidates to consider during future research tasks, management activities and conservation plans. They should be considered in addition to areas that host high number of endangered, endemic or rare species, transient species, areas that represent biodiversity highways, and important areas to preserve functional or evolutionary traits and ecosystem services.

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SUPPORTING INFORMATION

Additional Supporting Information may be found in the online version of this article:

Appendix S1 List of species included in each biodiversity layer and data sources.
Appendix S2 Description of threat layers used to document anthropogenic impacts on diversity.
Appendix S3 Marine protected areas existing in the Mediterranean Sea.
Appendix S4 Results of the sensitivity analysis on areas of cumulative threats and areas of conservation concern for biodiversity.

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BIOSKETCH

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