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Urban typology of marine protected areas (MPAs): An exploratory methodological framework applied to the Western Mediterranean Sea

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ABSTRACT

The coastlines of Mediterranean countries are heavily developed and impacted by human activities. Marine Protected Areas (MPAs) play an essential part in protecting these urban regions and preserving their marine biodiversity. However, the implementation of effective MPAs in populated zones poses challenges and requires the creation of suitable management strategies. The first step is to define what 'urban' means within the context of the marine protection framework. This work examines 20 MPAs in the Western Mediterranean Sea. The aim of our study is twofold. Firstly, to identify urban variables that enable MPAs to be classified based on their level of urbanisation. Secondly, to establish thresholds of these variables that define the characteristics of an urban MPA. We identify nine variables derived from population metrics and satellite images and use these to create an urban indicator. We calculated the urban indicator for each MPAs and found that (1) this new urban indicator effectively clusters MPAs, (2) only 6 out of the 20 MPAs in our study can be classified as urban, (3) urban MPAs tend to be easily accessible and located near densely populated areas, while (4) non-urban MPAs may also be found in highly touristic areas. The study thus provides initial insights into the profiles of MPAs located in urban contexts. To deepen our understanding, it will be essential to analyse and compare the management and governance of urban and non-urban MPAs. This could highlight valuable management tools to enhance ecological effectiveness, tailored to the urbanisation level of each MPA.

1. Introduction

1.1. Context

Striking a balance between marine conservation and the expansion of human activities is a significant challenge due to the considerable barriers to establishing Marine Protected Areas (MPAs) along densely populated coastlines (Mouillot et al., 2024). It is essential to establish effective protection zones in biodiversity hotspots where both ecological richness and human impacts are significant, to safeguard the species present (Joppa and Pfaff, 2009). Addressing this issue requires innovative approaches to reframe our conservation strategies and meet this crucial challenge for the next decade (Ferraro et al., 2015; George et al., 2016; Howard-Grenville et al., 2014).

Human activities cause direct damage to the oceans, resulting in the loss of marine biodiversity. One of the strategies to address these challenges is the creation of MPAs. If effectively managed, MPAs can restore the balance of the food web, thereby contributing to healthier ecosystems (Giakoumi et al., 2024). However, the world's 100 largest MPAs, which account for 90 % of the global MPA coverage, are predominantly located in remote, offshore areas (Pike et al., 2024). Protection is urgently needed in vulnerable coastal ecosystems, where biodiversity is most at risk from human pressures (Joppa and Pfaff, 2009). But, the development of MPAs near urban centres, such as the Larvotto MPAs in Monaco (Ventura et al., 2024), remain lacking. In contrast with terrestrial protected areas, significant obstacles exist in the establishment of MPAs along densely populated coastlines, where marine resources are crucial for livelihoods or food security (Mouillot et al., 2024).

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MPAs offer varying levels of protection ranging from no-take zones to multiple-use areas (Claudet et al., 2020; Grorud-Colvert et al., 2021; Horta e Costa et al., 2016). A "no-take zone[1]" is an MPA or part of an MPA where fishing is prohibited, providing greater ecological benefits than partially protected MPAs or unprotected areas (Sala and Giakoumi, 2018). An MPA contributes significantly to fish community improvement (Zhao et al., 2024) and protection of threatened species (Crosti et al., 2020). Protection and its benefits begin when the MPA is implemented with active and adaptative management (Arneth et al., 2023; Grorud-Colvert et al., 2021), and assessing the quality of an MPA is essential to ensure effective protection (Sullivan-Stack et al., 2024). However, the protected areas with higher levels of protection – IUCN categories I and II – are mostly located far away from cities compared to those with lower levels of protection, in categories III and IV (Joppa and Pfaff, 2009). To establish effective, highly protected MPAs in more urban regions where they are most needed, an essential first step is to develop a tool to distinguish urban MPAs from non-urban ones.

1.2. Mediterranean Sea

The Mediterranean Sea is a biodiversity hotspot: though it covers less than 1 % of the ocean's surface, it harbours between 4 % and 18 % of global marine species (Bianchi and Morri, 2000) and 20 % of species are endemic(Coll et al., 2010).

Fisheries in the Mediterranean Sea started in Antiquity, and were reported in Greek, Egyptian and Roman civilizations. The first nets were woven in Egypt around 3000B.C. Mediterranean countries are oriented towards the sea with many fishing villages and small ports on the coastline of each country. Fisheries and seafood consumption are part of the cultural landscape of the Mediterranean (Pérez-Lloréns et al., 2021). Fishing also plays a significant social and economic role by offering employment opportunities (FAO, 2020).

However, current levels of commercial fishing in the Mediterranean Sea indicate high levels of over-exploitation. Today, more than 90 % of the stock assessed are above sustainable biological limits. Especially in the Western Mediterranean areas, the ecosystem sustainability of fisheries is very low due to the high levels of fishing pressure and the practice of targeted fishing for particular species, which overexploits stocks (Colloca et al., 2017). Mediterranean fisheries and ecosystems are in an alarming situation because of overfishing, combined with pollution (chemical, noise, light or waste). The presence of invasive species (Kletou et al., 2016) also compromises ecosystem health, leading to functional or species extinction, locally and regionally. Globally, climate change and ocean acidification have ushered in the mass extinction of species and an unprecedented decline in global biodiversity (Lee et al., 2023; Sala and Knowlton, 2006).

The Mediterranean Sea is also impacted by a growing trend: urbanisation. Half the world's population lives less than 100 km from the coast (Daeden, 2015; Todd et al., 2019), which extends human activities into the ocean (von Glasow et al., 2013). In the Mediterranean, coastal areas are becoming increasingly populated (Li et al., 2024): coastal population density is on average 10 % higher than inland, reaching a peak of 50 % in some countries like Spain (European Environment Agency, 2006). The coastline is also becoming more artificial: the rate at which natural coastal areas are being converted into artificial ones is outpacing population growth (Salvati et al., 2014). Mediterranean cities are becoming increasingly "dispersed" due to urban sprawl around urban areas (Schneider and Woodcock, 2008). The Mediterranean basin, currently one of the world's hotspots for urban sprawl, faces significant environmental consequences. The high and increasing human pressure, coupled with important changes in soil and climate, increase the ecological fragility of surrounding landscapes (Salvati et al., 2012).

1.3. Definition of urban

The definition of the concept of 'urban' remains regularly debated among geographers and sociologists. It is ambiguous, with boundaries that depend on the local context and the chosen approach. To effectively integrate protected areas in urban contexts, it is essential to define the specific implications of 'urban' coastal settings for adjacent marine protected zones (Marty-Gastaldi et al., 2025).

Urbanisation, the movement of people from rural areas to cities, is a worldwide phenomenon associated with the increasing population. The definition of a city varies across regions, incorporating variables such as population size and density, the physical extent of the urban area, and the city's economic or political significance, or a combination thereof (Stébé, 2022). In 2020, the United Nations (UN) Statistical Commission approved a methodology for delineating cities, as well as urban and rural areas, known as the degree of urbanisation (Dijkstra et al., 2021). In densely populated areas, such as large cities, urban infrastructure is built to meet the needs of the human population. For example, the presence of factories in the area surrounding a protected zone is evidence of a past or present urban activity (Daumalin et al., 2021). A city requires essential infrastructure such as sewage outlets (Affre et al., 2015), which act as gateways for anthropogenic discharges (pollutants and contaminants) into the sea (Claeys et al., 2016; Umasangaji, 2018). In addition, the global population growth poses a challenge for sustainable food production. Aquaculture development is viewed as a solution to this demand for food security, despite its environmental impacts (Trottet et al., 2022). Aquaculture is considered urban when the production is located immediately in front of urban areas (Bunting and Little, 2015). The presence of aquaculture farms around MPAs can therefore be seen as an urban indicator.

When studying urbanisation, it is essential to consider the impact of tourism. The intensification of tourism is accompanied by the development of infrastructure to accommodate the growing number of visitors (and sometimes the construction of secondary residences). The expansion of tourism infrastructure contributes significantly to urbanisation (Gohar, 2021; Pitarch-Garrido and Zornoza-Gallego, 2023). Increased tourism can put pressures on and threaten the marine environment through increased consumption of resources such as water, electricity, and marine species. In the context of MPAs, a significant influx of tourists to the nearby city could also result in increased visits to the protected area, potentially harming the ecosystem (Barot et al., 2019).

Tourism, which impacts the landscape and transforms land use (Pitarch-Garrido and Zornoza-Gallego, 2023), often occurs in coastal areas (Navalón-García, 2023). Marine tourism is defined as a form of tourism that is intrinsically linked to the sea and the marine environment (sailing, nautical sports, scuba diving, fishing, etc.). Coastal tourism is a type of tourism connected to the sea, but it also encompasses beach-based tourism (swimming, sunbathing, etc.) (Papageorgiou, 2016). The duration of coastal and marine tourism in the Mediterranean depends on the latitude, as it is seasonal. Some coastal tourist villages close to the MPA are built for tourists. They are completely empty in winter and resemble ghost towns, while in summer they are overcrowded. This phenomenon can be observed throughout the Mediterranean, including in Cyprus, Greece, Albania, Spain and France (Koutra and Karyopouli, 2013; Šuštar and Laškarin Ažić, 2019). The Land Use and Land Cover (LULC) methodology is used to evaluate the percentage of human land use and to define "built up" areas (Salvati et al., 2014).

An urban place must be accessible if it is to be inhabited and populated. Moreover, more accessible areas are expected to have less protection, as the majority of protected areas are "high and far" from roads

[1] "A No Take Zone (NTZ) is a MPA […], where all methods of fishing and extraction of natural materials, dumping, dredging or construction activities are prohibited, from which the removal of any resources, living or dead is prohibited. NTZs can be used alongside conventional fisheries and wildlife conservation management measures in order to protect marine wildlife and heritage and safeguard or improve local fish stocks for future generations to enjoy." FAO definition

and cities (Joppa and Pfaff, 2009; Mouillot et al., 2024). Accessibility is one of the most crucial variables in the planning of tourism development in natural destinations (Tverijonaite et al., 2018). This ease of access to a protected space has consequences: the rise in visitor numbers, especially in national parks, leads to high traffic and significant environmental impacts. Balancing the development of recreation and tourism with biodiversity conservation is a challenging task (Juutinen et al., 2011). Indeed, the more accessible and nearby the protected area is, the more likely it is that human activities will occur (Williams et al., 2022). The frequency of visits to a protected area is influenced by the distance to the city and the ease of access (Li et al., 2023). To link land use and MPA boundaries, the percentage of coastline accessible to humans could be an indicator of their urban character. Access to an MPA can be achieved *via* maritime routes, such as by boat. Ports, whether industrial or marinas, serve as urbanizing factors by providing means of transport and acting as gateways to connect and promote Mediterranean tourism (Ballester, 2017), despite their polluting nature (Sharaan et al., 2017). Contemporary cities are increasingly oriented towards their ports, integrating them as an essential part of the urban space (Herbert and Gibout, 2018). Another way of connecting is by air. The proximity of an airport to a city significantly influences its economic growth (Sheard, 2019) and urban development by facilitating mobility (Florida et al., 2015). Airports create connections between cities and increase the number of visits, thus reflecting the urban dimension of the area (Blonigen and Cristea, 2015). Access to an MPA can be achieved by terrestrial routes, either on foot or by motorized vehicles. If the MPA is adjacent to a developed area with pedestrian access points or with roads and parking facilities, it is easier to visit this protected site (Li et al., 2024).

The definition of an MPA as an urban entity is thus contingent upon its position within an urban context, as well as the presence of multiple characteristics enumerated in this section. Furthermore, meeting or exceeding specific levels of these variables is also a prerequisite for an MPA to be classified as urban (Marty-Gastaldi et al., 2025).

1.4. Objectives

No study has yet considered all these urban variables in relation to MPAs. The lack of consideration of urban dimensions in existing studies motivated us to develop innovative urban variables for MPA assessments and an urban indicator. This allows us to classify MPAs according to their levels of urbanisation. Our study facilitates a tangible transition from theoretical frameworks in geography and sociology to practical applications, by identifying appropriate urban variables to distinguish between urban and non-urban MPAs. The second objective was to establish relevant thresholds that define the characteristics of an 'urban MPA'. An 'urban index' is then developed that includes several variables, with scores based on the thresholds. These variables and thresholds have been tested in different Mediterranean MPAs located in the Western side of the basin. Given the novel nature of the concept of urban MPA, there is clearly room for improvement regarding the clarity of definitions and the rigour of the methodology. MPAs have been the subject of extensive research; however, those located near urban areas, facing distinct issues and challenges, remain to be fully delineated. The present study proposes a novel research direction by addressing significant gaps in the extant literature.

The importance of defining an urban indicator in the MPA framework lies in the potential application of its specific characteristics to management strategies. An overuse of the area, unregulated tourism or an uncontrolled diversity of activities can lead to social consequences such as spatial conflicts, as well as ecological impacts. Categorising MPAs using the urban indicator will enable the early identification of potential threats and provide a framework for benchmarking existing solutions in the Mediterranean that can be adapted to local contexts through tailored management strategies. Good practice in managing urban MPAs can be shared with managers who are dealing with similar issues. Managing activities such as regulating boat anchoring in a mooring zone will differ according to whether the MPA is in a place where there are no boats, where there is seasonal tourism, or where there are large numbers of people all year round. Implementing effective management practices that are widely accepted by all relevant stakeholders is not always a straightforward process. When planning a new MPA, stakeholders should be aware of the specific challenges they face depending on the degree of urbanisation. From the design process to long-term management, the use of an urban indicator to gain novel insights into MPAs will allow for more effective MPA management. Thus, our study gives a new perspective on MPA in the Mediterranean, which may be useful for MPA managers and Marine Spatial Planning (MSP) practitioners (Papageorgiou, 2016).

2. Methodology

To define the level of urbanisation of an MPA, we have created an urban indicator based on 9 urban variables. For each urban variable, thresholds are defined based on the literature to obtain a scoring system from 1 to 5. The mean value the urban variable scores for each MPA is its urban indicator. The selection of MPAs, the study area and the urban variables are described below. The choice of the urban variables and the details of the thresholds are described in Supplementary Material 1.

2.1. MPA selection

Our study area covers the Western Mediterranean Sea. The following criteria were used to select MPAs:

a) MPA with a nearby city: Each MPA in the study was associated with the most populated nearby town (within 10 km), from which data were collected. Our focus was on MPAs at a local scale, i.e., within 1 km of the border of the MPA. We examined the activities within the MPA and its immediate perimeter, rather than at the national level or within MPA networks as it is the case in the literature. Most studies aim to assess the impact of urban areas or threats on a large scale using 1 km^2 grid cells (Cinner et al., 2018; Micheli et al., 2013; Portman and Nathan, 2015).
b) MPA with ecological data available: The selected MPAs were those with readily accessible ecological data. The research relied on the willingness of MPA managers to collaborate. The MPAs must also have been in existence for at least five years to provide meaningful results on their ecological effectiveness (Giakoumi et al., 2017; Seytre and Francour, 2009).
c) MPA with full level of protection: No-take marine reserves provide greater ecological benefits than partially protected MPAs or unprotected areas (Sala and Giakoumi, 2018). For this reason, we chose only MPAs with at least one "no-take zone" inside.
d) MPA with an existing, clearly defined and implemented management plan. We wanted to avoid, as much as possible, to including "paper parks"[2] in our research (Beuret and Cadoret, 2021). The content of management plans were indicative of the level of protection of the MPAs (Portman and Nathan, 2015).

2.2. Study area

To avoid differences in governance frameworks or management implementation, we selected exclusively European MPAs (Claudet et al., 2020). Applying our selection criteria, we identified 20 MPAs among

[2] "a legally established protected area where experts believe current protection activities are insufficient to halt degradation." (Dudley and Stolton, 1999). In the marine context, a paper park is an established MPA that lacks sufficient management and enforcement to implement regulations and management plans and achieve conservation goals effectively. Dehens and Fanning, 2018 define paper parks as "legally designated but do little for conservation".

these European MPAs, ranging from Spain to Greece (see Fig. 1. and Table S1, Supplementary Material 1), with careful consideration given to selecting MPAs located near cities.

2.3. Urban indicators

To assess the degree of urbanisation within the MPAs and identify differences across the Mediterranean Sea, we defined nine urban variables, developing tools to measure them and establishing thresholds to systematically convert the measurements into scores.

Our approach included population-based metrics:

- Population size: the number of people living in the city;
- Population density: the number of inhabitants in the city per km^2;
- Level of tourism: the ratio between the number of tourists visiting the city each year and the number of residents.

We then considered variables derived from satellite images. Using the QGIS software (3.36.2), we measured factors such as accessibility, land use and human use, with the variables:

- "Transport Access": number of car parks and bus stops alongside the coastline in front of the MPA;
- "Footpath Access": number of footpaths to connect the land and the sea;
- "Coast Access": accessibility of the MPA coast by all ways of transport;
- "Distance": length between the MPA and its city;
- "Land Cover": proportion of urban space along the coastline in front of the MPAs' surface;
- "Infrastructure": The presence of ports, wastewater treatment plants, aquaculture farms, airports, and industrial activities in and 1 km around the MPA.

Thresholds were defined for each variable from the literature. The details of the methodology can be found in Supplementary Material 1 (Text S1). Based on the thresholds, each MPA was assigned a score from 1 to 5 for each variable. Then an overall average was calculated to determine a final score for each MPA, namely the urban indicator, which is intended to measure urbanisation in the MPAs and their surrounding environments.

$$\text{Urban indicator} = \bar{x}\ \text{urban score} = \Sigma\,\text{urban variables scores} / \Sigma\,\text{no. of variables}$$

2.4. Data analysis

All statistical analyses were conducted in R v4.4.1 (https://www.R-project.org). To group similar MPAs together, we performed clustering with dendrograms using the Manhattan distance because our data consists of discrete scores with a focus on small differences between MPAs for each variable. The Manhattan distance is calculated by adding only the absolute difference between the elements, a process which is advantageous for this category of data. Furthermore, the Manhattan Distance method has been shown to be more effective in the handling of high-dimensional data by virtue of its emphasis on individual coordinate

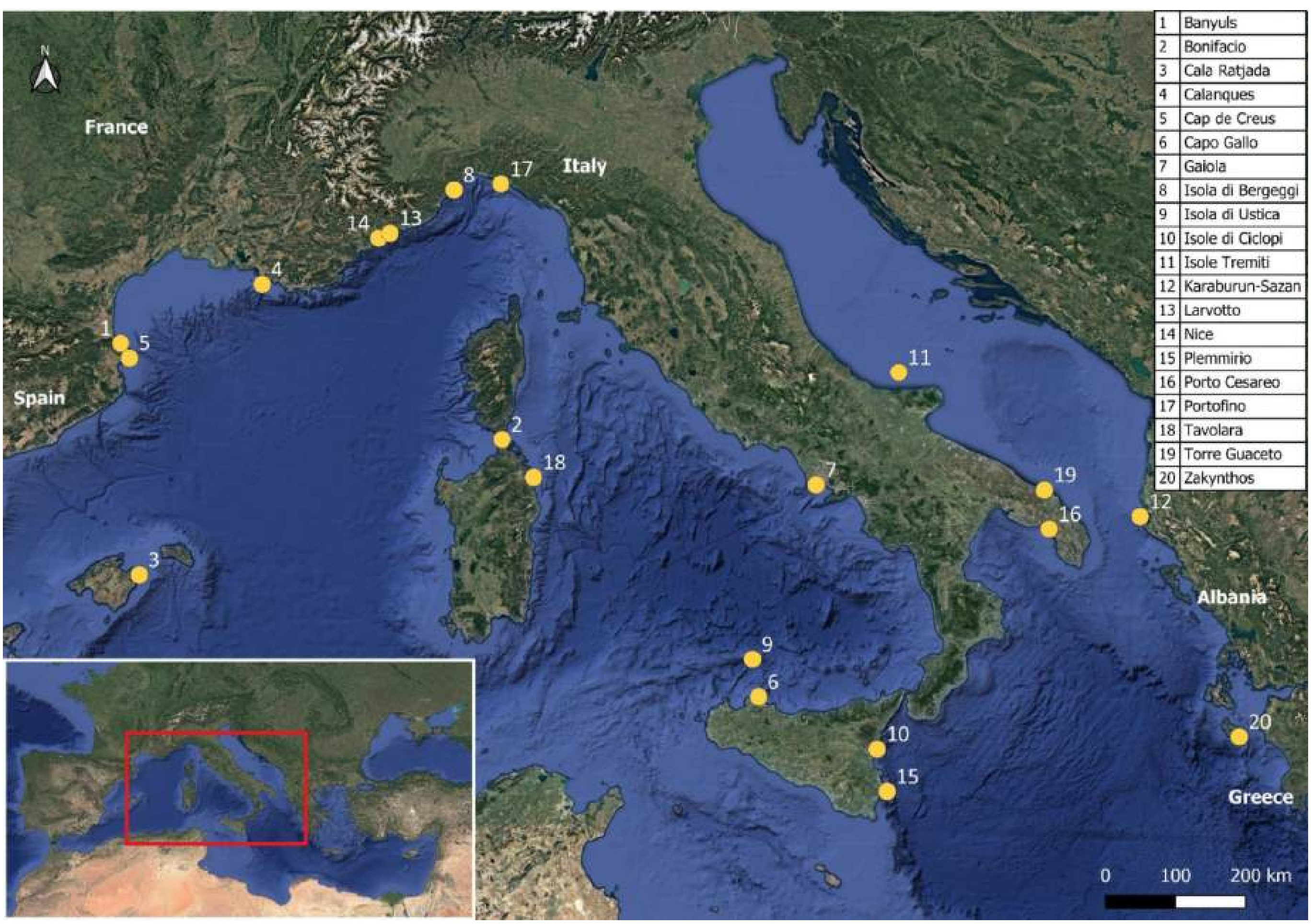

Fig. 1. Location of the Mediterranean marine protected areas (MPAs) included in the present study. For details on each MPA see Supplementary Material 1, Table S1. The map was generated using the open source QGIS software version 3.36.2. Base layer: Google Satellite in 2024; EPSG: 3857 (http://qgis.org).

differences. In higher dimensions, where the Euclidean distance may be ineffective, the method remains capable of discriminating between points. We employed the complete-linkage clustering method to obtain well-defined groups. Univariate tests were performed to compare variable scores for the different MPAs in the urban and non-urban categories. After checking for normality (Shapiro tests), we compared the median urban scores of the MPAs (Kruskal-Wallis test). To complement this test, the Man Whitney *U* test was performed to assess the differences between the two categories.

Multivariate tests were performed to compare urban categories with the matrix formed by the 9 variables (urban indicators) and the 20 sites (MPAs). The matrix was analysed using permutational analysis of variance (PERMANOVA). This analysis was performed on a dissimilarity matrix calculated using the Manhattan index. Dissimilarity values were visualized using a non-metric multidimensional scaling (nMDS), to visualize the differences between MPAs depending on their urban variables.

3. Results

3.1. Urban vs non-urban MPAs

The 20 MPAs analysed had urban indicators ranging from 1.22 to 4.22 (Fig. 2). The average across the 20 MPAs is 2.47. There is significant heterogeneity in urbanisation levels among the MPAs, with values increasing progressively from Tremiti, the least urbanised, to Nice, the most urbanised. Substantial variability is observed in the scores of variables for a given MPA, resulting in highly dispersed data, as seen in Bonifacio, Banyuls, and Porto Cesareo, where scores range from 0 to 5. The analysis of the urban characteristics of the 20 MPAs with the clustering dendrogram reveals a clear separation into two distinct groups, as shown by the formation of two branches (Fig. 3).

MPAs clustered in the first branch of the dendrogram exhibit the 6 highest urban indicators, all exceeding 2.5, as shown in Fig. 2. The dendrogram classification is consistent with the boxplots of the MPA urban indicators. MPAs with an average score below 2.5, considered non-urban (14 MPAs), are highlighted in green in Fig. 3 and represent 70 % of the sampled MPAs. Those with an indicator above 2.5 are classified as urban MPAs, highlighted in red in Fig. 3. The dendrogram effectively separates the MPAs into two distinct groups, while the boxplots, showing increasing average scores, help to clearly identify the urban indicator threshold between urban (6) and non-urban (14) MPAs.

The data follow a non-normal distribution (p-value $= 5.603 \times 10^{-10}$, Shapiro Test). A significant difference in urban indicators exists among the MPAs (Kruskal-Wallis test; p-value $= 0.008$) and between the category "Non-urban MPA" with 14 MPAs and the category "Urban MPA" with 6 MPAs (Mann-Whitney *U* test; p-value $= 1 \times 10^{-7}$) when using the univariate analysis.

For the multivariate analysis, Non-metric Multi-Dimensional Scaling (nMDS) provides a 2D graphical representation, considering the 9 variables. The NMDS plot shows a separation between the 2 different urban categories (Fig. 4) with a good fit (stress value $= 0.096$). This result is statistically supported by a PERMANOVA performed on the same distance matrix, showing a significant difference between the 2 categories of MPAs: non-urban and urban (SumOfSqs $= 728.51$; $R^2 = 0.36586$; $F = 10.385$; Pvalue $= 1 \times 10^{-4}$).

3.2. Profile of the MPAs

The urban indicator is composed of nine variables, making each MPA's profile unique. However, it is possible to categorise MPAs into different groups based on the similarity of their profiles (Fig. 5). Among the 14 MPAs considered non-urban (out of a total of 20 MPAs), 6 have a distinctive feature: a score of 5 for the tourism variable (blue radar chart, Fig. 5). The other 8 non-urban and non-touristic MPAs, shown in green in Fig. 5, have low scores of urban variables. Ustica and Capo Gallo are the exception due to the association with Palermo, resulting in a high population density (score of 5).

The MPAs highlighted in red in Fig. 5 represent the urban MPAs: they all have at least two variables with a score of 5. Nice, identified as the most urbanised MPA according to the urban indicator developed in this study, has 5 out of 9 variables with a score of 5. All urban MPAs exhibit a 'Transport Accessibility' score of 5. The next section examines how the variables contribute to and influence the urban indicator.

3.3. How variables influence the profile

3.3.1. Variables influence urban indicators

The MPAs are distinctly clustered in the space defined by the first

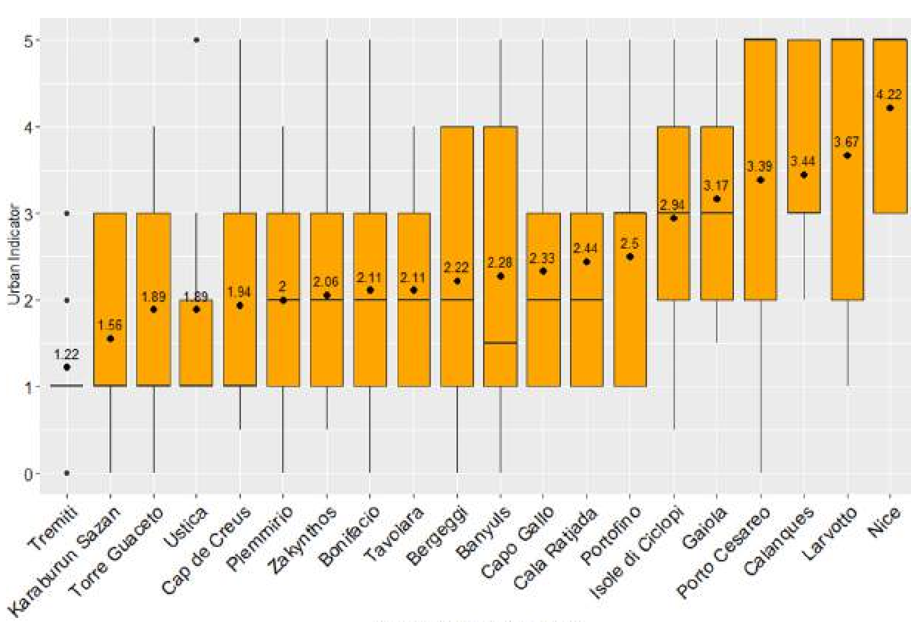

Fig. 2. Urban indicators of the 20 MPAs in the Mediterranean Sea in ascending order. Each boxplot represents one MPA. Black dots are outliers. Numbers within the plot indicate the urban indicator for each MPA, which is composed by nine urban scores from 0 to 5.

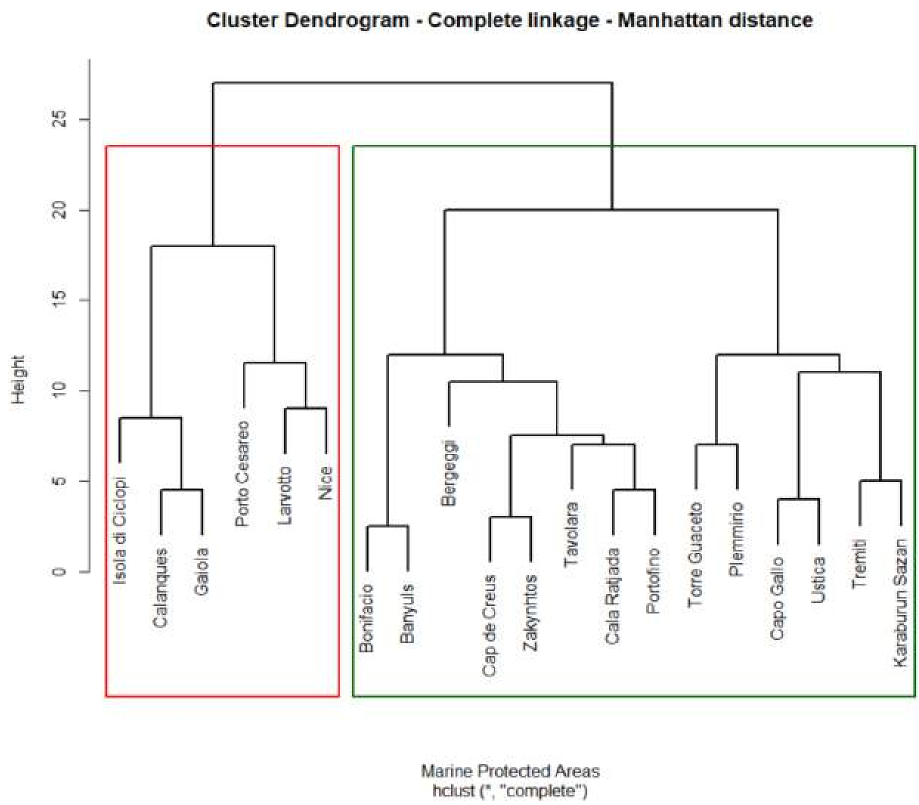

Fig. 3. Dendrogram clustering of the 20 MPAs using Manhattan distance and a complete linkage representation.

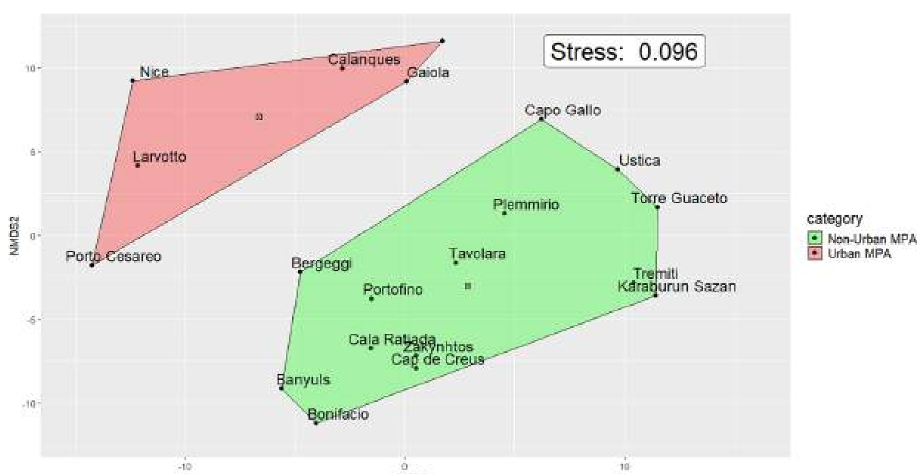

Fig. 4. Non-metric multidimensional scaling (nMDS) plot showing differences in the urban indicator of Non-urban MPA and Urban MPA categories. Points represent MPAs and polygons represent the categories of urban MPAs in red and non-urban MPAs in green. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

two components, suggesting that they can be differentiated based on urban characteristics (Fig. 6). Principal component 1 (PC1) accounts for 39.11 % of the variance in the dataset and the variables "Footpath Accessibility" and "Transport Accessibility" contribute 21.8 % and 20.7 %, respectively, to this component (Table SM1. Supplementary material 2). This suggests that these variables are among the most significant factors distinguishing the observations in this analysis. The variable vectors "Land Cover" and "Coast Access" also point in the same direction in the graphical representation and contribute 20.3 % and 12.9 % respectively, to the first component. These 4 variables can be grouped into the category "Access" which positively influences the urban indicator.

The second principal component (PC2) accounts for 28.25 % of the variance. The two variables that contribute most to the explained variance of this component are "Population Size" (25 %) and "Population Density" (26.8 %) (Table SM1. Supplementary material 2). They can be grouped into the category of "Population", which also positively influences the urban indicator.

The "Tourism" and "Distance" and "Infrastructure" vectors contribute negatively to PC2 and point in a different direction than the "Access" and "Population" categories. Tourism contributes to the variance of the first principal component with 22.6 %, while distance contributes to both components: 12.3 % for PC1 and 17.2 % for PC2. The vector size for "Infrastructure" is graphically much smaller compared to

Fig. 5. Radar charts for the 20 selected MPAs with the nine urban scores (from 1 to 5) as the axes. A) Green radar charts correspond to non-urban, non-touristic MPAs; B) blue radar charts correspond to non-urban, touristic MPAs and C) red radar charts correspond to urban MPAs. *Pop.Density = Population Density; Pop.Size = Population Size; F.Access = Footpath accessibility; T.Access = transport accessibility; Coast.Access = Coast accessibility.* (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

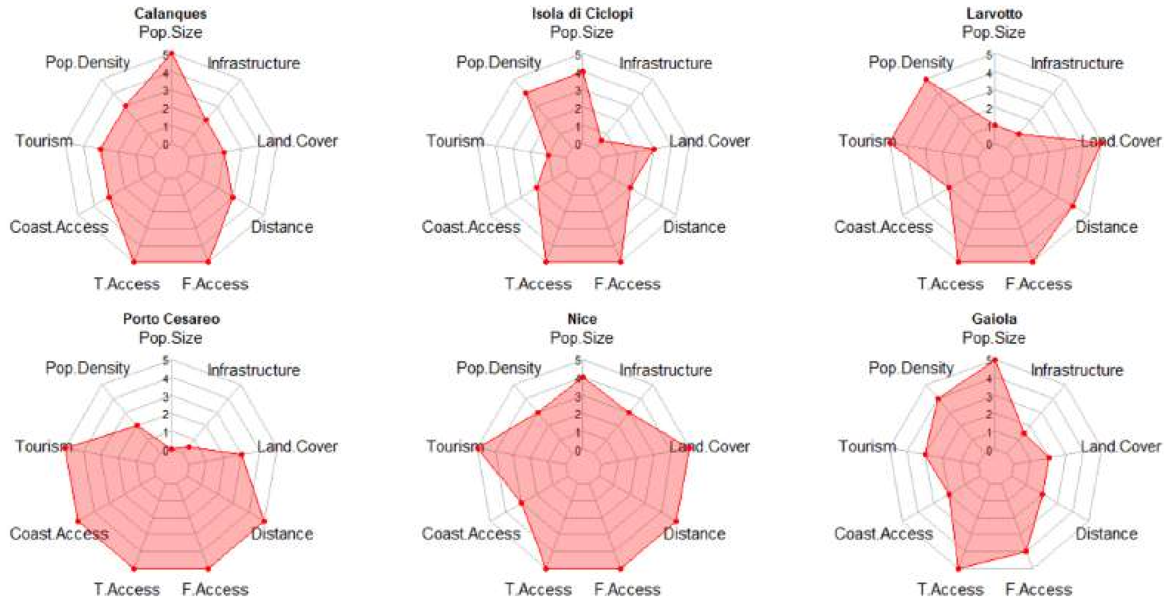

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Fig. 5. (*continued*).

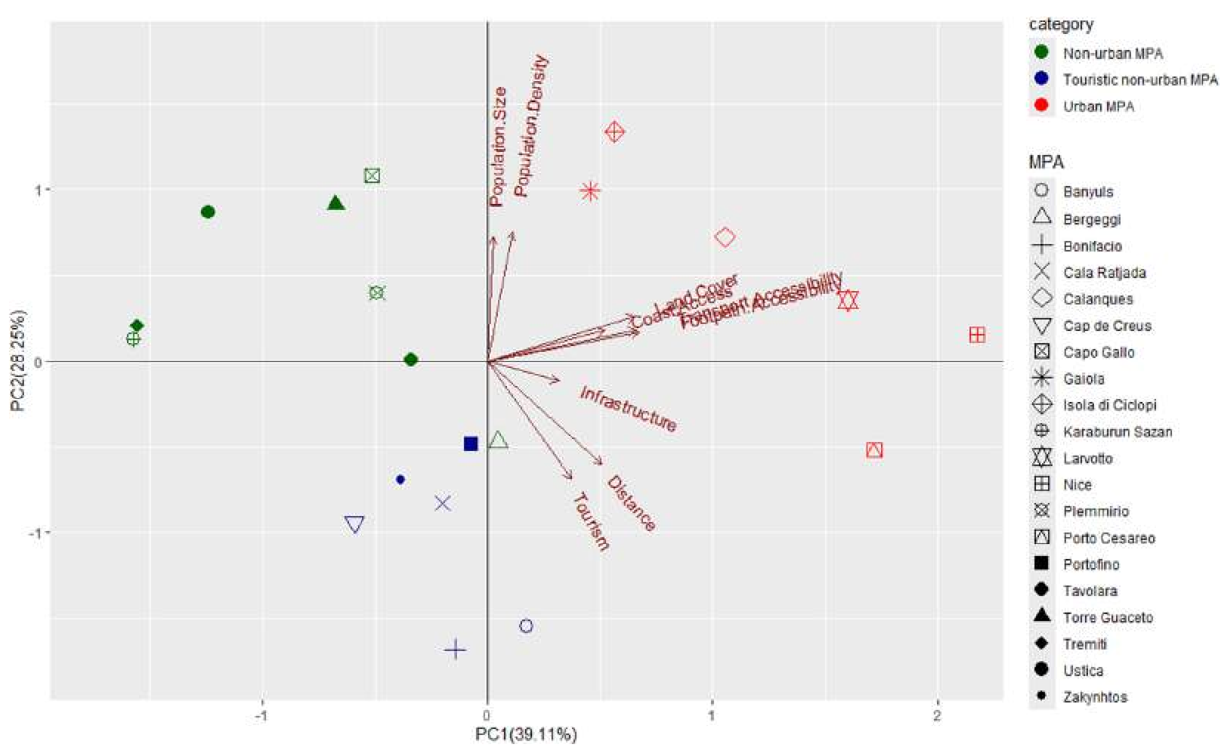

Fig. 6. Principal component analysis (PCA) of the 20 MPAs and the 9 variables of the urban indicator.

the other variables. Its contribution is minimal for both components, with values of 4.8 % for PC1 and 0.7 % for PC2 (Table SM1. Supplementary material 2).

The urban MPAs are predominantly clustered in the upper right quadrant of the graph (Fig. 6), except for Porto Cesareo. Gaiola and Isola di Ciclopi are positioned near variables within the “Population” and “Access” categories, indicating that these MPAs have high scores for these variables, confirmed by their profile in Fig. 5. The score of the Nice MPA, located near the x-axis and furthest to the right, suggests that all urban-related variables significantly influence its final scores. Porto Cesareo MPA, situated below the x-axis, indicates that “Population” variables have little influence on its urban indicator, though factors related to “Distance” or “Tourism” do; its position high along the x-axis suggests that “Access” variables exert an influence. Conversely, non-urban MPAs are primarily distributed across the left half of the graph, with non-touristic MPAs clustered in the upper left quadrant (except for

Bergeggi MPA). Touristic, but non-urban MPAs, are in the lower left quadrant, apart from Banyuls, which appears in the lower right quadrant due to the influence of “Access” variables.

3.3.2. Variables that define urban characteristics of an MPA

Population variables

No significant difference exists between urban and non-urban MPAs for the population variables: population size and population density (Fig. 7). The largest population size recorded in a non-urban MPA is 629,000 inhabitants for this study, corresponding to a score of 5. Conversely, an urban MPA may be located near a city with only 4500 residents, corresponding to a score of 0; however, the surrounding geographical context can result in a high score for other variables, ultimately categorising the MPA as urban (see Supplementary Material 1, Text S1 and Table S2).

Access variables

For the variables “Coastline accessibility”, “Transport accessibility”, “Footpath accessibility” and “Land Cover”, significant differences exist between urban MPAs and non-urban MPAs (Man Whitney *U* test, p-value respectively = 0.005; 0.0005; 0.006; 0.0006) (Fig. 7). Non-urban MPAs (except one) have less than 40 % of the coastline accessible (Supplementary Material 1, Table S5) and half of them have just 20 % meaning that non-urban MPAs face wilderness areas. All urban MPAs receive a score of 5 for transport accessibility, meaning that, on average, there is a parking area, or a bus stop every kilometre or less (Supplementary Material 1, Text S1 and Table S7). Similarly, for footpath accessibility, all urban MPAs (except one) have a footpath every 500 m or less (Supplementary Material 1, Text S1 and Table S6). Non-urban MPAs have a land cover score of 1, signifying that less than 20 % of the territory facing the MPA is developed (Supplementary Material 1, Text S1 and Table S9). Urban MPAs, on the other hand, exhibit more varied land cover, with scores ranging from 2 to 5. The median score is 3, meaning that in 50 % of urban MPAs, at least 41 % of the territory within one kilometre of the coastline is urbanised.

Other variables

No significant difference exists between the urban and non-urban MPAs for the “Tourism”, “Distance” and “Infrastructure” variables. The tourism score for non-urban MPAs ranges from 1 to 5, indicating that even non-urban areas are affected by tourism. It is important to note that the tourism score is derived from the ratio of the number of tourists to the local population. For example, if the number of tourists is six times the local population, the score is 3 (Supplementary Material 1, Text S1 and Table S4). The distance between an MPA and a city varies significantly. A non-urban MPA may have a score of 5, indicating it is less than 1 km away from the city, as is the case for Bonifacio, while another non-urban MPA may have a score of 1, meaning it is more than 10 km away from the city, for example Torre Guaceto or Capo Gallo (Supplementary Material 1, Text S1 and Table S8). None of the non-urban or urban MPAs has large or numerous infrastructure (scores are less than 3) (Supplementary Material 1, Text S1 and Table S10).

4. Discussions

Typology of MPAs

The urban indicator developed in this study successfully classifies Marine Protected Areas (MPAs) into two categories (Fig. 3). The differences between urban and non-urban MPAs are statistically significant (Fig. 4). This paper defines the key characteristics of an urban MPA. The PCA biplot reveals a slight clustering of MPAs with similar average urban scores, consistent with the dendrograms in Fig. 3 and the NMDS plot in Fig. 4, which also distinguish between urban and non-urban MPAs. An urban MPA is characterised by an urban indicator value up to 2.5 (Fig. 2). It is typically associated with a city that has a large population and high population density (Fig. 5). An urban MPA is linked to a touristic city, where the median value for tourism is 4, indicating that the tourist population exceeds the local population by more than six-fold (Fig. 7): Nice, with a resident population of 340,000, attracts 5 million tourists annually. Urban MPAs are highly accessible, with 5 out of 6 MPAs featuring footpaths that are no more than 500 m apart, allowing easy access from land. Additionally, 100 % of urban MPAs are

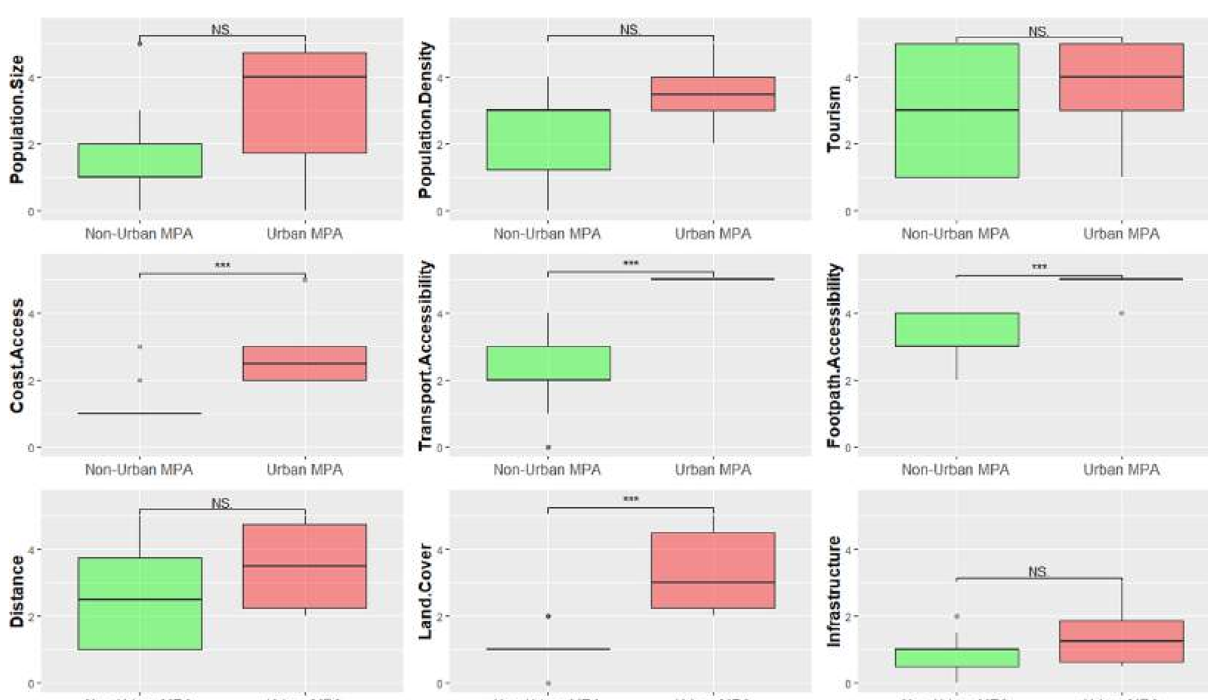

Fig. 7. Boxplots comparison for the 9 urban variables. Note: Green boxplots represent the distribution of non-urban MPAs and red boxplots represent distributions of urban MPAs. The central line inside each box represents the median, while the individual points represent the outliers. Given the relatively small size of the sample, the confidence intervals may not be relevant. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

accessible by car or bus, with parking or bus stops located less than 1 km apart: the coastline of an urban MPA is urbanised. Notably, an urban MPA does not have to be near the associated city; it can be located over 5 km away and still be considered urban based on other urban characteristics (Fig. 5). Urban MPAs that are touristic, consistently show the maximum score of 5 for three out of the four accessibility variables. Specifically, transport and footpath accessibility are invariably rated as 5 in this context. This observation underscores the characteristic that urban MPAs situated near touristic cities are equipped with well-developed facilities designed to facilitate connectivity between the city and the MPA. In the opposite, a non-urban MPA is typically located near a smaller town than an urban MPA (median is score of 1, i.e., less than 10,000 inhabitants), although population density can still be high. Non-urban MPAs are generally more difficult to access, with less than 20 % of the coastline accessible. The land-sea interface is predominantly composed of cliffs, rocks, or steep terrain, reducing the percentage of accessible coastline, as seen in MPAs such as Bonifacio. The distance between parking/bus stops or footpaths is also greater in non-urban MPAs, making access more challenging. The land adjacent to non-urban MPAs is typically undeveloped or sparsely populated, often part of a national park (e.g., Cap de Creus), agricultural areas (e.g., Banyuls), or small towns or villages (e.g., Plemmirio, Bonifacio). However, a non-urban MPA is not necessarily far from a city; for instance, the Bonifacio MPA is only 145 m from the city of Bonifacio.

Forty-three percent of the non-urban MPAs are in regions with high tourism activity (blue dots in Fig. 5). They are situated near towns where the number of tourists exceeds the local population by more than eightfold, corresponding to a tourism score of 5. This intense tourism activity in a wild, largely inaccessible area, may have an impact on the management of the protection area. These non-urban touristic MPAs, are located less than 1 km away to their reference cities – Banyuls, Bonifacio, and Cala Ratjada. The most touristic MPA in our study is Bonifacio, where the local population is 3200 inhabitants and the number of tourists is 2 million, meaning 625 times more people are there during the summertime. The impact of tourism is not only considerable on the land, in term of water, food production, wastes, pollution and car traffic, but also on the sea, with boat traffic, anchoring issues and recreational activities (Hynes et al., 2024). The management tools implemented to deal with tourist activities will not be the same as for the non-urban and non-touristic MPAs. Notably, 70 % of the selected MPAs have a tourism score greater than 3, indicating that the number of tourists in the nearby city is at least four times the local population annually. The Mediterranean region is heavily associated with coastal tourism, making it one of the world's most prominent tourist destinations, attracting over 400 million visitors in 2019 (Plan Bleu, 2022; Weston et al., 2019). Tourism in marine and coastal areas, including both land based and water-based activities, are part of the "blue economy" (Hynes et al., 2024). Tourism activity is controversial, with good practices such as "Pescatourism" in the Mediterranean Sea (Guedri et al., 2025) and conflictual situations with no sustainable tourism development (D'Anna et al., 2016). All MPAs with high tourism scores are located within a one-kilometre radius of a port. The Mediterranean Sea is also a popular destination for cruise tourism, particularly among European travellers, and recreational boating is widespread. Ports, being key entry points to cities, facilitate tourism (Herbert and Gibout, 2018). Touristic MPAs are not a Mediterranean-specific phenomenon. For example, the Nha Trang Bay MPA in Vietnam attracts more than 720 000 tourists annually, despite the fact than only 5000 people reside on the island within the protected area. Consequently, this MPA is regarded as a tourist destination where local communities are encountering difficulties in adapting to this pressure (Pham, 2020). In another context, the island of Cozumel in Mexico has an annual average of four million visitors. However, the Arrecifes de Cozumel National Park covers a significant area of 12,000 ha. Its presence in this touristic area has been shown to generate 762 million dollars of local economic activity per year (Lara-Pulido et al., 2021). In Vietnam, the Nha Trang Bay MPA is located around islands. The juxtaposition of nature conservation with tourist activities can potentially compromise the integrity of coral reefs. However, it can also serve as a catalyst for the allocation of conservation funding. The development of ecotourism has been demonstrated to support conservation initiatives (e.g., eco-friendly dive operators).

Variables defining urban MPAs

The developed urban indicator effectively distinguished 'more' and 'less' urban MPAs in the Mediterranean. Analysing each variable separately revealed which of them contributed the most to the urban indicator in categorising MPAs. The three directions shown in the PCA (Fig. 6) represent how the variables influence variance in the indicator. First, "Population" variables play a major role: population density in Mediterranean countries is well above the global average, with many coastal cities. Barcelona, Marseille, Naples, Athens are port cities with populations exceeding one million (Doignon et al., 2023). The Mediterranean coastline is among the world's most densely populated due to its historical and cultural prominence. For instance, in 2006, artificial land cover accounted for 49.6 % of the area between Marseille and the Italian border (Robert et al., 2019). The similar scores of urban and non-urban MPAs (Fig. 7) for population size and density variables reflect the high coastal population adjacent to MPAs anywhere in the Mediterranean basin (Salvati et al., 2014). Next, "Access" variables strongly influence the MPA's urban character. The significant differences between urban and non-urban MPAs (Fig. 7) in coastline, transport, footpath accessibility and land cover variables highlight the importance of these factors. Land cover is shaped by urban sprawl and illustrate the competition for space between human activities and nature (Kachelriess et al., 2014). Measuring land cover is key to evaluating an MPA's urban character and protection quality. High land cover affect coastal access by construction of roads, boosting development and mobility in dense urban areas (Rodrigue, 2017). Urban MPAs are typically located in more accessible regions that benefit from these facilities. Good physical connectivity — roads, parking — increases visits, tourism, and popularity (Li et al., 2023) while lack of public transport and parking facilities restricts access, resulting in a lower level of urbanism for MPAs. Access variables cover all ways to reach an MPA: pedestrian access via footpaths, motorized access through car parks and bus stops, and maritime access via boats, considering the entire coastline accessible. These modes complement each other and are all relevant (Mouillot et al., 2024). Finally, "Attractiveness" variables – infrastructure, tourism and distance, also shape urbanisation. Surprisingly, distance is not a predominant factor in determining the level of urbanisation of MPAs. An MPA near a small city with a limited population and only a single road may still be considered non-urban. Conversely, an MPA far from a densely populated city can still be considered as urban if it has large, well-developed and accessible beaches served by public transport, car, foot, or boats. Literature suggests that remote or elevated protected areas are less accessible, easier to manage and less prone to damage (Joppa and Pfaff, 2009; Mouillot et al., 2024). Infrastructure variables like sewage treatment plants, aquaculture, ports, airports, and factories did not strongly differentiate urbanisation level of MPAs. It is possible that the Mediterranean context is not well-suited to serve as a typical example. Major coastal cities with large ports and airports are rare. Instead, medium-sized cities with marinas near MPAs are common, fitting a more tourism-oriented city profile. Airports tend to be located further inland, and aquaculture farms are rarely found in these areas.

The overlap and proximity of vectors on the PCA suggest correlations between variables, detailed in Supplementary Material 2 (Text SM1, Figure SM1). For example, "Footpath accessibility" is strongly correlated with the variable "Transport accessibility" and "Land Cover" (coefficients 0.77 and 0.75 respectively, and highly significant p-values ***). This correlation is to be expected: high access scores imply many footpaths, bus stop or car parks. The development of this kind of infrastructure is linked to the presence of buildings, houses or builds areas next to the coast, raising "Land Cover" scores. We decided to retain these correlated variables, as it is precisely the balance of all variables that reflects the significant differences between urban and non-urban MPAs. Removing them would distort the graphical representation of the PCA and NMDS, rendering interpretation no longer feasible. Ultimately, it is the full, complementary set of variables – even those like population and distance that alone show no significant differences – that define the urban indicator for each MPA.

Evolution of the urban indicator

The urban indicator can be adapted globally but was developed here for the Mediterranean's unique geographic, socio-demographic, and cultural context. This pioneering study on this topic highlights the need to consider urban pressures on MPAs and offers a method that can inform other regions outside the Mediterranean Sea. The method developed is applicable worldwide. However, applying it elsewhere requires adjusting the scoring system and thresholds to local conditions to reflect the characteristics of each different context. The geomorphological situation of the MPA also shapes urbanisation. The Mediterranean ecosystem is distinguished by a temperate climate, characterised by rocky, sandy-muddy seabeds and Posidonia meadows. Protected areas in an urban context may also be proximate to estuaries or bays, such as the Marapendi municipal nature park near Rio de Janeiro (Poian, 2017) and da Barra Do Rio Grande in Brazil, where the pressures and pollution are different from those in the Mediterranean. It is evident that reef ecosystems, mangroves, expansive sandy beaches, dunes and lagoon ecosystems can support substantial biodiversity; however, these environments are also characterised by significant anthropogenic activities, including the presence of industrial ports in proximity to coastal cities and substantial maritime traffic. Another example of a protected area in an urban context is the Cape d'Aguilar marine reserve in Hong Kong. Recent data indicate that the number of ships registered within Hong Kong Harbour has doubled over the past two decades (Xu et al., 2015). Whatever the type of vessel, marine transport can exert significant pressure through activities such as channel dredging, ballast water discharge, and oil spills. This particular port is not comparable to our case study in the Mediterranean, due to the large number and the different types of vessels. A similar argument can be made for the demographic context of Hong Kong, with its population of 7 million. The urban indicator developed in our study must be adapted so that the thresholds and scores are appropriate for the geographical location of the protected area.

The urban indicator developed in this study reflects the urban characteristics of an area at a given time, based on static data. Since urbanisation is dynamic and constantly evolving, the indicator should ideally be updated every five year, incorporating adjustments that may be evident through population measurements or satellite imagery tools. Collaboration with local authorities could be envisaged to directly integrate into the indicator changes in population or construction on the coastline of the protected area. If major changes occur, variables and thresholds should be revised to maintain relevance. To assess whether the urban indicator requires updating, managers could analyse the MPA's resilience using tools like the Resilience Self-Assessment Tools (R-SAT) developed by Resilience Partnership Institute, which appear to be a suitable measure for the present case. This instrument is used to facilitate the adaptation of MPA management in the face of rapid changes, such as climate change or urban sprawl.

5. Perspectives

This innovative classification of MPAs based on their degree of urbanisation helps to highlight the geographic and socio-demographic context of the area. We are not directly measuring the effects of urbanisation on the protected area here, but the more urban an MPA is, the more it is subjected to human threats and pressures. The next step will be to include ecological indicators in the comparison of urban and non-urban MPAs. One potential method for assessing ecological characteristics could be to measure the biomass inside and outside of urban MPAs to determine their ecological effectiveness. The objective would be to ascertain whether the effectiveness of urban MPAs in achieving their conservation goals is diminished by the presence of human activities and the associated threats. The subsequent step will be to examine whether management practices differ between urban areas, which face high human pressure, and non-urban areas, where there is less frequent human activity. Tourist areas may need to implement additional measures to handle seasonal tourist influxes each summer, whereas urban MPAs must maintain heightened surveillance and management efforts year-round to ensure protection against constant threats. Additionally, the local community in the city linked to the urban MPA can be made aware of the importance of the marine environment and engaged in the conservation of the protected area through participation in management activities (surveillance, beach cleaning, citizen science etc). To assess the management effectiveness of each MPA, it is necessary to develop a set of qualitative interviews which will allow the management strategies at different locations to be compared. This will be the subject of a future research study. This study will involve cross-referencing urban indicators with ecological variables, as well as with the measured management effectiveness, using quantitative and qualitative data.

Finally, this urban indicator could be added to the MPA Guide as a predominant factor for an effective MPA. Moreover, when the MPA is implemented or effectively managed with at least one fully protected zone in the area, following the MPA Guide, the urban indicator could be used to adapt the management depending on the urban context. This classification of MPAs as urban could assist managers to better understanding the specific challenges of their area and encourage collaboration with managers of MPAs in similar categories.

6. Conclusion

To classify the MPAs into urban and non-urban categories, we have created an innovative urban indicator based on 9 variables derived from population and satellite imaging measurements. Together, this specific set of complementary urban variables define the urban indicator for each MPA.

The indicator reveals that urban MPAs are associated with populated and dense cities that may be touristic. An urban MPA is accessible with the presence of parking, roads, and footpath to connect the land and the sea in an easy way. The land adjacent to urban MPAs is mainly built up, without wild area or land protection. But urban MPAs are not common: only 30 % of the selected MPAs are urban.

The non-urban MPAs have a lower urban indicator score and are in a wilder and less accessible areas, but may also be touristic. The impact of tourism is not negligible in the Mediterranean basin.

The typology of urban MPAs in this study is created with reference to the Mediterranean Sea, which is a specific geographic, socio-demographic and cultural context. It could be interesting to adapt and apply this approach to other contexts. The urban environment around MPAs near bigger cities such as in Mexico, Brazil or Gabon will have different threats and pressures for human activities.

CRediT authorship contribution statement

Julie Marty-Gastaldi: Writing – review & editing, Writing – original draft, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Cécile Sabourault:** Writing – review & editing, Validation, Funding acquisition. **Nathalie Lazaric:** Writing – review & editing, Validation, Supervision, Conceptualization. **Benoit Dérijard:** Writing – review & editing, Validation, Supervision.

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Declaration of competing interest

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

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecolind.2025.114013.

Data availability

Data will be made available on request.

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