



Fostering marine resilience through the reduction of anthropogenic pressures in temperate rocky reefs

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ABSTRACT

Resilience is vital for maintaining the health of temperate coastal systems, especially in the Anthropocene era, where anthropogenic pressures such as pollution, physical impacts, and overfishing pose significant threats. However, the scarcity of studies addressing marine resilience hampers its effective management. To address this issue, we evaluated the resilience of 300 temperate rocky reefs situated in Southern Europe, considering biological, environmental, and anthropogenic factors. We identified 43 top resilient areas recommended for conservation and 39 bottom resilient areas that could benefit from reducing anthropogenic pressures. Given that our findings suggest that anthropogenic pressures unequally influence the resilience of bottom resilient areas, we followed their decreasing order of influence to simulate five management scenarios based on the cumulative reduction of these pressures. While different percentages of reduction in anthropogenic pressures were necessary to significantly enhance resilience in each scenario, we found that, regardless of the approach taken, a comparable percentage of bottom resilient areas—ranging from 17 % to 23 %—could be reclassified as moderate resilient areas. By advancing resilience knowledge in temperate rocky reefs, this research underscores the important role that reducing anthropogenic pressures plays in enhancing resilience but also provides valuable insights for their strategic management.

1. Introduction

In an ever-changing world, resilience emerges as the crucial property that safeguards the integrity of natural ecosystems (Walker and Salt, 2012). Resilience buffers sudden or unexpected shifts, ensuring that ecosystems can recover from external perturbations—such as changing environmental, anthropogenic, and biological conditions—while maintaining their functions, thus decreasing the risk of catastrophic ecosystem collapse (Holling, 1973; Walker et al., 2004; Folke et al., 2010; Walker and Salt, 2012). As resilience plays a vital role in upholding the functions of natural ecosystems and their associated contributions to people (Cardinale et al., 2012; Reyers et al., 2022), its loss would involve significant and negative consequences for ecosystems, livelihoods, and human well-being (Folke et al., 2004; Agardy et al., 2005).

Unfortunately, the resilience of natural ecosystems is decreasing at an alarming rate in all ecosystems, from terrestrial (Bruno et al., 2019; Boulton et al., 2022) to marine (Ma et al., 2021; Rocha, 2022). Specifically in marine ecosystems, a range of environmental and

anthropogenic factors can negatively influence their resilience (Maynard et al., 2010; Ladd and Collado-Vides, 2013; Gibbs and West, 2019; Korpinen et al., 2019). From an environmental standpoint, storms and hurricanes can trigger loss of resilience by physically damaging the biological community, while rising sea surface temperatures, can lead to cascade effects such as sea-level rise, heatwaves, or ocean acidification (Hoegh-Guldberg et al., 2007; Doney et al., 2012). Meanwhile, anthropogenic factors such as overfishing, pollution, or physical damage, stand as the main drivers of resilience loss (Ling et al., 2009; Piola and Johnston, 2008; Maynard et al., 2015). For instance, overfishing of marine resources leads to important changes in food webs and ecosystem configuration (Estes et al., 1998); pesticides and chemical contaminants dumped in coastal areas impact the health of marine biological communities by increasing the likelihood of diseases (Folke et al., 2004; Piola and Johnston, 2008); and sea-related activities, such as diving or anchoring, physically impact the seafloor and benthic life by dismantling the benthic structure (Gladstone et al., 2013; Siciliano et al., 2016). While both environmental and anthropogenic factors can lead to a loss of resilience, we can only influence anthropogenic pressures in the

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short and medium term. Therefore, it is essential to develop management strategies aimed at eliminating or minimizing the impact of these anthropogenic pressures on marine resilience (Mumby and Steneck, 2008; Morecroft et al., 2012).

To date, little progress has been made in guiding management interventions in coastal systems to improve resilience (Steneck et al., 2019). In Nyström et al. (2008), provided the first attempt of merging the resilience theory with practice by providing empirical indicators of key attributes affecting resilience in coral reefs (i.e., biodiversity, spatial heterogeneity, and connectivity). More recently, Mcleod et al. (2019) argued that resilience-based management, an approach focused on prioritizing actions that influence ecosystems functioning, can support natural processes that sustain tropical marine social-ecological resilience, and Steneck et al. (2019) demonstrated that long-term management interventions focused on reducing algal abundances in coral reefs increases the resilience of juvenile and adult corals. However, while each of these examples shares a common objective, which is to enhance the resilience of tropical marine communities, the lack of resilience studies in temperate coastal systems can lead to biased management. This bias may favor actions that are clearly beneficial for improving resilience in tropical systems but may not be effective for their temperate counterparts. Although some studies in temperate coastal systems conclude that minimizing environmental and anthropogenic disturbances can enhance the resilience of certain algal species (Perkol-Finkel and Airoldi, 2010; Strain et al., 2015), the number of studies investigating ways to operationalize resilience management in temperate coastal systems remains scarce (Sanabria-Fernandez et al., 2019).

To facilitate the resilience management in temperate coastal systems, the first challenge to overcome is gaining a comprehensive understanding of the existing resilience in the area. Knowing the resilience of temperate rocky reefs may help prioritize geographic areas that require urgent intervention. For example, areas with high resilience may benefit from conservation actions to avoid the future impacts of anthropogenic pressures, whereas programs to alleviate anthropogenic pressures may be more adequate in areas with low resilience. The second challenge to overcome is revealing the anthropogenic pressures that contribute to the gain and loss of resilience in temperate rocky reefs. For instance, Sanabria-Fernandez et al. (2019) found that anthropogenic physical pressures and pollution obtained minimum scores in areas with high resilience. By identifying these factors and understanding their impact on resilience, it becomes possible to effectively manage them and maintain or increase resilience. In this study we aim to overcome those challenges and provide a novel approach to operationalize resilience management in temperate rocky reefs. Specifically, we (i) assessed marine resilience in temperate rocky reefs based on seventeen factors across three fundamental dimensions influencing resilience: biological, environmental, and anthropogenic, (ii) investigated the extent to which reductions in anthropogenic pressures can translate into significant improvements in resilience, and (iii) provided specific management interventions tailored to each of the studied anthropogenic pressures. Our findings identified 43 top and 39 bottom resilient areas. Specifically, in bottom resilient areas, anthropogenic pressures exert unequal contributions, indicating a priority order of influence. Following this order, a simulated reduction of the pressures could significantly enhance resilience, leading to five management scenarios where up to 23 % of the bottom resilient areas could rise to moderate resilient areas. This study highlights a range of management strategies that can be adopted to enhance the resilience of temperate rocky reefs, providing a promising pathway toward their sustainability.

2. Material and methods

2.1. Study area

We carried out this study in 300 temperate rocky reefs of the Iberian

Peninsula, North Africa, the Balearic Islands, and the Canary Islands (Fig. 1). We focused on these temperate rocky reefs because despite their rich biodiversity, they face multiple anthropogenic threats (Coll et al., 2010; Alcorlo et al., 2023) and their resilience has been insufficiently unexplored (Sanabria-Fernandez et al., 2019). Moreover, these systems hold significant historical and cultural importance for local communities and represent important fishing grounds and diving spots for national and international tourists while also providing a host of contributions to human well-being (Pascual et al., 2017).

2.2. Factors influencing resilience

Based on previous studies, we defined and quantified seventeen variables as the main factors affecting resilience in temperate rocky reefs (Table 1). Factors were classified into biological (nine factors), environmental (three factors), and anthropogenic (five factors) dimensions following Sanabria-Fernandez et al. (2019) and computed at each of the 300 surveyed locations.

2.2.1. Biological factors

We calculated nine biological factors affecting resilience: macroalgal cover, community richness, abundance of invertebrate herbivores, abundance of sea urchin fish predators, abundance of top predators, fish functional diversity, trophic redundancy, vulnerability of the fish community, and abundance of sea urchin invertebrate predators. (Table 1). In doing so, we collected fish, invertebrate and macroalgal information from 300 temperate rocky reefs located in Southern Europe, following the standard Reef Life Survey underwater visual census protocol (hereafter, RLS; Edgar et al., 2020). The surveys, conducted from 2015 to 2022, included sampling sites located at depths ranging from five to twelve meters, typically consisting of two or more transects parallel to the coastline. Using RLS, we estimated the abundance of each fish species sighted along a 50 m long and 10 m wide belt transect, the abundance of each mobile invertebrate species sighted along a 50 m long and 2 m wide belt transect, and the macroalgal cover from 20 seabed photoquadrats taken every 2.5 m along a 50 m belt transect (Edgar et al., 2020). Then, we used the biological information collected through RLS to compute the nine biological factors specified in Table 1. These indicators may be influenced by threats or stressors present in temperate coastal ecosystems. For further information regarding the computation of the biological factors, please refer to Table 1.

2.2.2. Environmental factors

We used the latitude and longitude of the RLS sampling locations to gather information about the three environmental factors affecting the resilience of temperate coastal systems. We collected the mean Sea Surface Temperature ($^{\circ}\text{C}$), nitrate concentration ($\text{mmol}\cdot\text{m}^{-3}$), and phosphate concentration ($\text{mmol}\cdot\text{m}^{-3}$), from the Bio-Oracle database (Assis et al., 2018) using the extract function of the raster R package. All variables were gathered within a 5 arc-minute spatial resolution (Table 1). We computed the deviation of each environmental factor from the ecoregion's average. To do so, we calculated the difference between the environmental factor value at a sampling location and the average value of that factor within the ecoregion (Sanabria-Fernandez et al., 2019).

2.2.3. Anthropogenic factors

Concurrently, we gathered information about five anthropogenic factors affecting the resilience of temperate rocky reefs: fishing pressure, anthropogenic pollution, anthropogenic physical pressures, human population, and proximity to the nearest city. Fishing pressure was estimated by quantifying the total yearly gross tons of fish caught in each Spanish coastal province per kilometer of coastline (Lazzari et al., 2021). We collected information about the number of marine outfalls within 5 km of our sampling locations from the European Environment Agency database to estimate the anthropogenic pollution factor

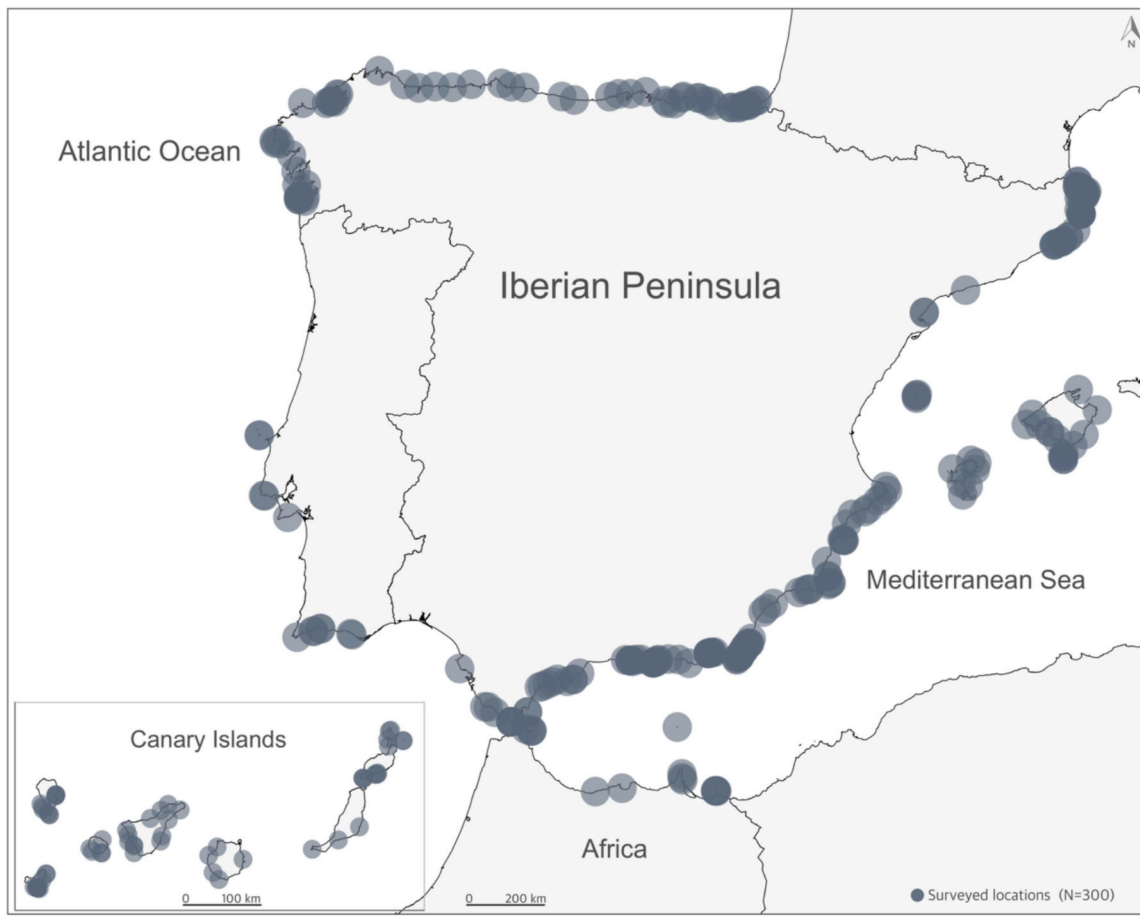


Fig. 1. Study area with 300 sampling sites (grey dots; the darkness of shading increases with site overlap).

(Wernberg et al., 2009; Urban Waste Water Treatment Directive, 2022). Anthropogenic physical pressures were estimated by tallying the number of dive centers within 10 km of each sampling location (Siciliano et al., 2016; Database of Spanish Underwater Activities, 2022). We used the total number of residents in the municipality nearest to the sampling location to estimate the human population factor (Spanish Statistics Institute, Portuguese Statistics Institute, Government of Morocco, and UK Government). Finally, we estimated the proximity to the nearest city factor by measuring the straight-line distance from our sampling locations to the center of the nearest city, using the raster R package (Hijmans et al., 2023). Additional information and justification for the use of these factors are provided in Table 1.

2.3. Quantifying real resilience and identifying top and bottom resilient areas

We used the Inclusive Resilience Indicator of a Site (IRIS) (Sanabria-Fernández et al., 2019) to first estimate the real resilience – referred to as $IRIS_{Real}$ – of each sampling location. We estimated the real resilience of the locations surveyed using the collected biological, environmental, and anthropogenic factors. To do this, we normalized by min-max (between 0 and 1) the 17 factors, computing their original factor intensity. It is important to note that we used one minus the normalized value of those factors that showed a negative link with resilience, for example the fishing pressure (Table 1). Then, we quantified the resilience following the IRIS formula developed by Sanabria-Fernández et al. (2019), as:

$$IRIS = \frac{\sum_{k=1}^N FI_k}{N}$$

Where k refers to each contributing factor, FI is factor intensity, and N is the total number of factors (17 in our study). Finally, we renamed it as $IRIS_{Real}$.

We used the ranked $IRIS_{Real}$ in ascending order to identify the top and bottom resilient areas. For this, we fitted a dose-response model using a Weibull distribution, which is a non-linear distribution, applying the *drc* R package (Ritz et al., 2015). After that, we detected the lower and upper inflection points (i.e., the thresholds of the distribution) by applying the Unit Invariant Knee point estimation approach, using the *inflection* R package (Christopoulos, 2019). Once we identified the inflection points of the $IRIS_{Real}$, we classified its scores into bottom, moderate, and top resilient areas. Whereas bottom resilient areas were those with resilience scores between 0 and the lower inflection point, the top resilient areas were those with resilience scores between the upper inflection point and 1. Finally, we classified as moderate resilience areas those areas with resilience scores between lower and upper inflection points (Fig. 2).

2.4. Definition of management scenarios and quantification of simulated resilience

To improve bottom-resilient areas, we developed five management scenarios based on the additive and simultaneous reduction of anthropogenic pressures. We first identified the order of influence of these pressures in the bottom-resilient areas, which informed the creation of our management scenarios. In the first scenario, we gradually reduced the original values of the most influential pressure from 1 % to 100 %, leading to a complete elimination of that pressure. In the second scenario, we gradually reduced the two most influential pressures. We

Table 1

Presents the factors used to estimate the resilience of temperate coastal systems, their relationship with resilience when these factors reach high values, the rationale for their influence, the explanation of the method followed for their quantification, and the source of the data along with the literature supporting their use.

	Factor	Link with resilience	Rationale	Factor quantification	Sources
Biological factors	1. Macroalgal cover	↑	It plays a crucial role in littoral rocky reefs in temperate oceans, serving as primary producers that provide oxygen and three-dimensional habitat for invertebrates and fish.	We analyzed 20 high-quality photographs taken along 50 m-long transects in each locality. Using CPCs software, we randomly selected 5 points within a centered digital square of 400 cm ² in each photograph. Percent cover was calculated as the ratio of algal points to total points for each transect.	Reef Life Survey; Dayton, 1985; Strain et al., 2015; Sanabria-Fernández et al., 2023
	2. Community richness	↑	Species richness is intrinsically linked to community stability.	We quantified the number of fish and invertebrate species present in our sampling locations.	Reef Life Survey; Barnhardt and Leslie, 2013; Borja et al., 2013
	3. Invertebrate herbivory	↓	Increased abundance of invertebrate herbivores, i.e., sea urchins, is shifting macroalgae dominated communities to barren grounds.	We used the total abundance of the next six species of sea urchins: <i>Arbacia lixula</i> , <i>Centrostephanus longispinus</i> , <i>Diadema africanum</i> , <i>Echinus esculentus</i> , <i>Paracentrotus lividus</i> , and <i>Psammechinus miliansi</i> .	Reef Life Survey; Ling et al., 2014; Kraußvein, 2017
	4. Sea urchin fish predators	↑	The abundance of fish species that feed on juvenile or adult sea urchins, controls sea urchin populations and contributes to enhancing macroalgal cover.	We employed the total abundance of 14 fish species known to feed on sea urchins as an estimate of the intensity of fish top-down control on sea urchins.	Reef Life Survey; Fishbase; Guitelli and Dulcis, 2007; Clemente et al., 2010
	5. Sea urchin invertebrate predators	↑	The abundance of invertebrate species that feed on juvenile or adult sea urchins regulates sea urchin density and contributes to enhancing macroalgal cover.	We utilized the total abundance of 10 invertebrate species known to feed on sea urchins as an estimate of the intensity of invertebrate top-down control on sea urchins.	Reef Life Survey; Shears and Batcock, 2002; Clemente et al., 2007
	6. Abundance of top predators	↑	The abundance of top predator fishes is a proxy of ocean health. Their presence and abundance point to more resilient, fully functional communities.	We estimated the total abundance of 31 fish species categorized as higher carnivores quantified at the sampling sites.	Reef Life Survey; Fishbase; Crowder and Norse, 2008; López et al., 2011
	7. Fish functional diversity	↑	High values of functional diversity provide marine communities a better response to disturbance since the system is likely to have traits that enhance recovery.	We used the FD package to calculate the RaoQ metric, considering functional diversity using thermal physiology, life history strategy, feeding ecology, behavior, habitat use, and geographic range breadth traits.	Reef Life Survey; Fishbase; Laitinen et al., 2014; Nash et al., 2017
	8. Trophic redundancy	↑	Redundancy of fish species in trophic levels confers robustness because trophic groups remain functional despite the loss of a species.	We categorized each fish species quantified according to its trophic group: planktivore, benthic invertivore, browsing herbivore, higher carnivore, and scraper.	Reef Life Survey; Fishbase; Michell and Halpern, 2005; Rice et al., 2012
	9. Vulnerability of the fish community	↓	Fish constitute major components of most marine communities. The vulnerability of fish depends on intrinsic traits and is inherently linked to resilience.	We estimated it as the average vulnerability for each of the sampling locations, considering the vulnerability of each fish specimen using the community-weighted mean approach.	Reef Life Survey; Fishbase; Cheung et al., 2007; Berkes et al., 2008
Anthropogenic factors	10. Fishing pressure	↓	Fishing activities are causing degradation, fragmentation, and consequent loss of resilience in marine communities.	We quantified it as the total number of gross tons fished yearly in each province divided per km of coastline. This gross tonnage is considered one of the most important predictors of fishing effort.	FAO; Parente, 2004; Ling et al., 2009; Lazzari et al., 2021
	11. Anthropogenic pollution	↓	Pesticides, chemical, metal, and liquid pollutants increase the likelihood of disease in macroalgae, invertebrates, and fishes.	We calculated the number of sewage emissions in the vicinity of our sampling sites (< 5km).	Urban Waste Water Treatment Directive, 2022; Pico and Johnson, 2008; Wernberg et al., 2009
	12. Anthropogenic physical pressures	↓	Impacts from divers, snorkelers, or anchors increase the susceptibility of disease in macroalgae and invertebrates.	We estimated the total number of dive centers within a distance of 10 km from each sampling locations.	Database of Underwater Activities, 2020; Riera et al., 2016; Scialano et al., 2018
	13. Human population	↓	Ocean sprawl, recreational fishing activities, or water pollutants are directly related with the size of human population and have strong impacts on resilience.	We collected the total number of inhabitants of the municipality of the sampling location.	Spanish Statistics Institute, Portuguese, Morocco, and UK Governments
	14. Proximity to the nearest city	↓	Reefs near urban centers experience more disturbances than distant ones, which affects the resilience of the marine community inhabiting them.	We quantified the straight-line distance between our sampling sites and the nearest city center.	Stuart-Smith et al., 2008; Cinner et al., 2018; Hilmans et al., 2021
Environmental factors	15. SSTmax deviation	↓	Deviation from the average maximum sea surface temperature is a major cause of stress in marine organisms, increasing their susceptibility to disease.	We calculated it as the difference between the SSTmax value of each sampling location and the average of the SSTmax values of each marine ecoregion.	Bio-Oracle Database (Assis et al., 2018); Hilmans et al., 2021
	16. Nitrate deviation	↓	Nitrates play a major role in marine productivity. Anthropogenic activities are increasing the nitrate concentration in marine systems.	We estimated it as the difference between the nitrate concentration value of each sampling location and the average of the nitrate concentration values of each marine ecoregion.	Bio-Oracle Database (Assis et al., 2018); Wernberg et al., 2009; Strain et al., 2015
	17. Phosphate deviation	↓	Phosphates also play a major role in marine productivity. Anthropogenic activities are increasing the phosphate concentration of marine systems.	We calculated it as the difference between the phosphate concentration value of each sampling location and the average of the phosphate concentration values of each marine ecoregion.	Bio-Oracle Database (Assis et al., 2018); Wernberg et al., 2009

Note: We used 1 minus the normalized value of the factors that show a negative link with resilience (↓), so that higher factor values were always associated with increased resilience.

repeated this process by simultaneously and progressively reducing all the anthropogenic pressures until we developed all five scenarios. For each management scenario, we estimated 100 IRIS Simulated values, corresponding to one IRIS Simulated value for each 1 % reduction in pressure (Fig. 2). The calculation of each IRIS Simulated value was carried out using the formula described in the previous section (2.3), adjusting the anthropogenic pressures while keeping the biological and environmental factors without modification.

2.5. Statistical analyses

We followed a two-steps approach to significantly increase resilience. Firstly, we explored whether the anthropogenic pressures in bottom resilient areas exhibit different contributions, which could indicate a priority order for their reduction. To this end, we fitted a linear model using the values of the pressures as the dependent variable and the pressures themselves as fixed effects. Secondly, we focused on determining the necessary percentage of reduction in anthropogenic pressures, considering both their individual contributions and their cumulative effects, to achieve a significant increase in resilience. For this purpose, we fitted a linear model for each of the 100 IRIS Simulated in each management scenario, where the IRIS Simulated served as the explanatory variable and the IRIS Real as the response variable. Subsequently, we selected the first model that exhibited significant differences between the IRIS Real and the IRIS Simulated, thereby identifying the precise percentage reduction required in the anthropogenic pressures to achieve a significant increase in the resilience of bottom resilient areas. We performed the computation of the IRIS (Real and Simulated), along with statistical analyses and graphical representations, using R software (R Core Team, 2024).

3. Results

3.1. Unveiling top and bottom resilient areas

We identified 43 top resilient areas, 39 bottom resilient areas, and 218 moderate resilient areas scattered across the study area (Fig. 3a & b). Top resilient areas were classified as those with scores ranging from 0.62 to 1.0, while bottom resilient areas were defined as those with scores between 0 and 0.52 (Fig. 3a & b). The remaining areas, with scores ranging from 0.53 to 0.61, were classified as moderate resilient areas (Fig. 3a & b).

3.2. Enhancing resilience of bottom resilient areas through the reduction of anthropogenic pressures

Anthropogenic pressures showed a significant and varying contribution to the resilience of bottom resilient areas. The human population factor was the most influential, followed by anthropogenic pollution, anthropogenic physical pressures, proximity to the nearest city, and fishing pressure (LM, AIC = -70.03, F-value = 11.574, p < 0.001, Fig. 4a). To significantly enhance resilience, the first management scenario called for a 57 % reduction in human population pressure (Fig. 4b). The second scenario required a 30 % reduction in both human population and anthropogenic pollution pressures (Fig. 4b). The third scenario needed a 22 % reduction in human population, anthropogenic pollution, and anthropogenic physical pressures. The fourth scenario aimed for a 20 % reduction in all previously mentioned pressures, including proximity to the nearest city. Finally, the fifth scenario demanded a 19 % reduction across all anthropogenic pressures addressed in this study (Fig. 4b). These reductions enabled between 17 % and 23 % of bottom resilient areas to be reclassified as moderate

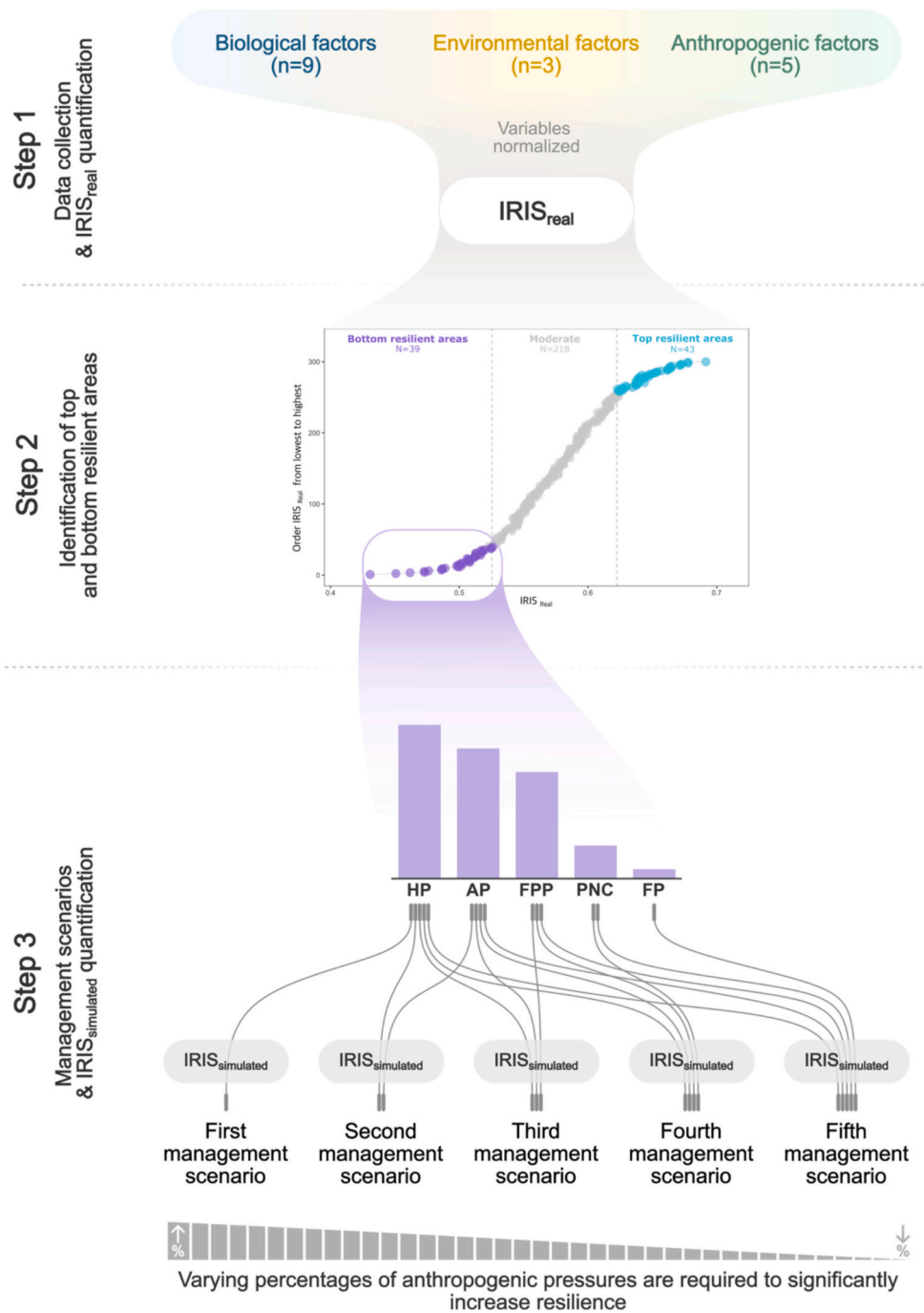


Fig. 2. Workflow detailing the three essential steps developed.

resilient areas. Notably, the percentages of reclassification did not vary significantly across the different management scenarios (LM, AIC = 26.92, $p > 0.05$, Fig. 4c).

4. Discussion

Coastal systems are dealing with the cumulative effect of unsustainable practices such as overfishing, pollution, and physical impacts, among others, leading to an alarming loss of marine resilience (Lotze et al., 2006; Halpern et al., 2008; Maynard et al., 2015). The combined impact of these unsustainable practices, coupled with a lack of studies on resilience in temperate rocky reefs, hampers their effective management toward more resilient systems. To address this challenge, the present study advances our understanding of resilience in temperate

rocky reefs by identifying 43 top resilient areas, which are characterized by high resilience scores, and 39 bottom resilient areas, which have low resilience scores. Focusing on bottom resilient areas, we showed that anthropogenic pressures contribute unequally in these areas, indicating a priority order of influence. Based on this order, we defined five management scenarios in which a simultaneous and additive reduction of these factors could significantly enhance resilience, allowing up to 23 % of bottom resilient areas to be reclassified as moderate resilient areas. Hence, our study provides novel insights into not only the resilience of temperate rocky reefs but also strategies to improve their management.

By definition, top resilient areas presented the highest resilience scores of the studied area. Although these areas were unevenly distributed along the coastline, we found that the western part of the Canary Islands and certain areas in the southern Mediterranean Sea exhibited a

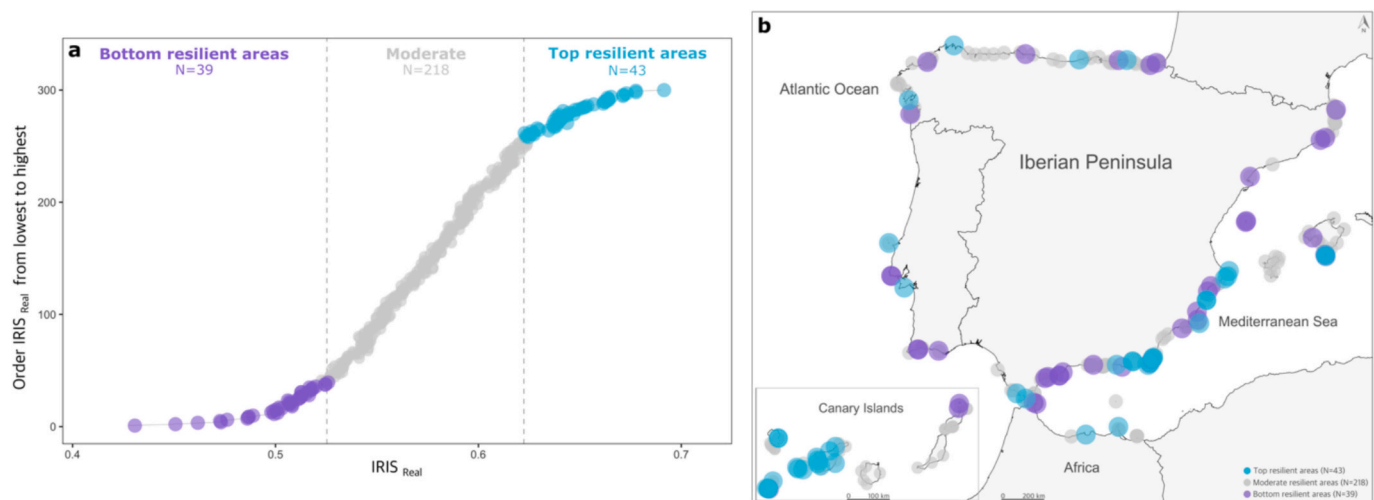


Fig. 3. (a) Relationship between the IRIS_{Real} (x-axis) and their position in the ordered distribution from lowest to highest (y-axis) showing the Weibull distribution (solid line) and the thresholds for bottom and top resilient areas (dashed lines). (b) Geographical distribution of the bottom, moderate, and top resilient areas.

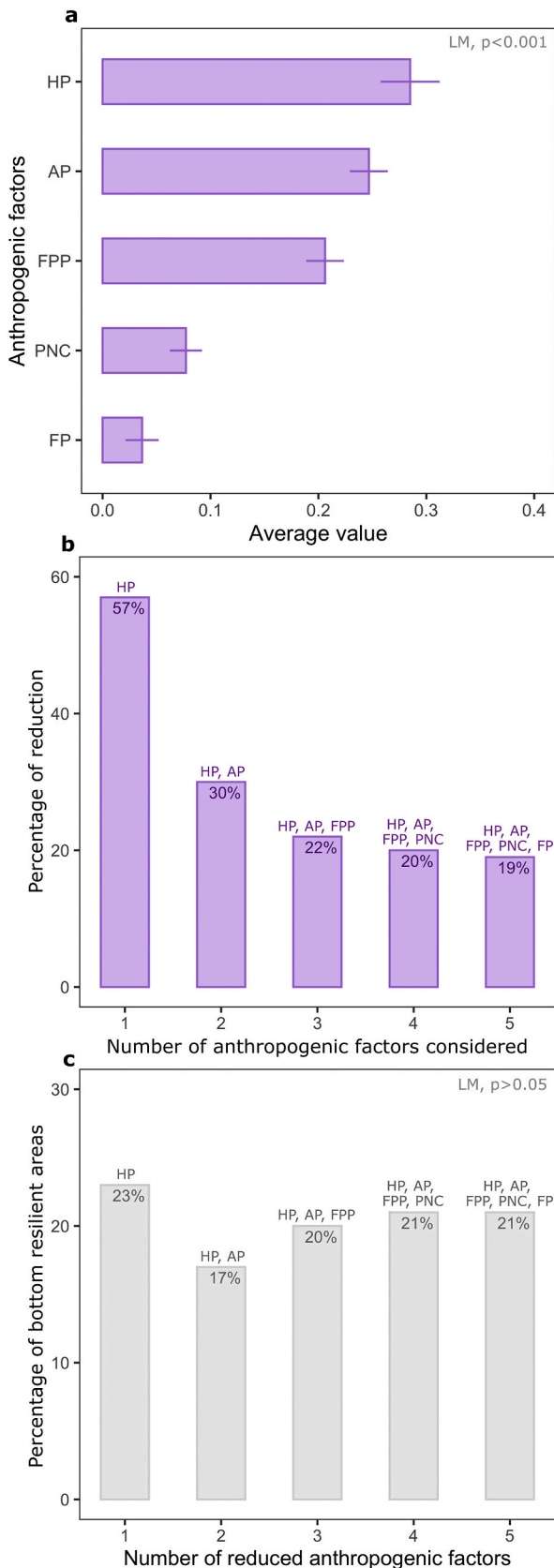
higher concentration of top-resilient areas. To ensure these areas remain in good condition, management interventions should prioritize increasing their protection status through national, regional, or local institutions. This approach has already been implemented by Davies et al. (2016) and Green et al. (2009) in tropical systems, where they identified priority areas of high resilience in Western Australia and Papua New Guinea, respectively, and designated them as resilient protected areas. These studies serve as excellent examples of integrated research on resilience, as they account for biological, environmental and management factors to reveal resilience patterns and prioritize areas for preservation in the context of climate change.

While it is essential to preserve the remarkable resilience of top resilient areas, we must not overlook bottom resilient areas. Taking action to reduce anthropogenic pressures is extremely urgent if we are to prevent further loss of resilience in these areas (Maynard et al., 2015; Bruno et al., 2019). Below we propose examples of flexible management strategies useful to reduce anthropogenic pressures causing resilience loss, which are adaptable to multiple coastal scenarios.

Given that our findings indicate certain anthropogenic pressures exert a greater influence on the resilience of bottom resilient areas than others, we propose five management scenarios aimed at a consecutive and additive reduction of these pressures. Human population was positioned as the anthropogenic factor with the highest influence in the resilience of bottom resilient areas. First management scenario requires that a reduction of almost 60 % of this factor is needed to significantly improve the resilience and convert up to 23 % of the bottom resilient areas into moderate ones. This translates into the need for a strong regulation of the human population in coastal areas. Limiting or regulating human population across those activities that are most likely to impact marine resilience stands as the best way to reduce this anthropogenic factor (Di Franco et al., 2009; Flynn and Forrester, 2019; Giglio et al., 2020). Indeed, the establishment of no-take zones in marine protected areas, zones where anthropogenic activities are completely prohibited, has proven to not just conserve but also enhance marine resilience (Edgar et al., 2014; Perkins et al., 2020). The second management scenario, where an equal reduction of both human population and anthropogenic pollution to at least 30 % is needed to increase resilience, would require a more diverse set of actions. Together with reducing human population through limiting people's access to natural areas, reducing the concentration of nutrients, pesticides, and contaminants discharged into coastal areas would also alleviate the loss of resilience (Piola and Johnston, 2008; Wernberg et al., 2009). This is particularly relevant considering the negative impact that outfalls have on the richness and biodiversity of the affected area, as they can lead to a

decline in quality from good to poor in just 16 months (Borja et al., 2003). A combination of various chemical, physical, and biological techniques can be taken to reduce anthropogenic pollution depending on the local conditions, including advanced oxidation processes, adsorption, activated sludge, membrane bioreactors, and membrane technologies (Rhind, 2009; Saleh et al., 2020).

Although the third, fourth, and fifth management scenarios involve a progressive increase in the number of anthropogenic pressures to be reduced (from three to five), they need similar reduction percentages to generate a significant increase in resilience (22 %, 20 %, and 19 %, respectively). Additionally to the management measures proposed for the first and second scenarios, regulating anthropogenic physical pressures in the third scenario would require, for example, limitations on the number of scuba divers allowed per dive site, or the establishment of anchoring-free areas. These actions have proven to be effective in reducing damage to iconic sessile species, such as *Posidonia oceanica* in the Mediterranean Sea (Balaguer et al., 2011). However, since these measures are primarily implemented in marine protected areas, which account for only 8 % of the total marine surface (WDPA, 2025), it is advisable to extend them beyond them. The fourth scenario would additionally require a reduction of the distance to the nearest city. This reduction can be done by artificially increasing this distance, for example, by limiting the use of infrastructure that provides access to coastal areas. Although with a different objective, this approach has been implemented in large cities such as London, Singapore, or Stockholm to reduce CO₂ emissions (OECD, 2002; Metz, 2018). Similarly, road closures during the American bison (*Bison bison*) migration season in Wood Buffalo National Park, Canada (<https://parks.canada.ca/>) and restrictions during sea turtle nesting periods at Mon Repos Beach, Australia (<https://parks.des.qld.gov.au/parks/mon-repos>), serve as measures to reduce anthropogenic pressures in specific periods. Coastal areas would benefit from this approach, especially during the peak summer season. Lastly, regulating fishing pressure, along with the other four anthropogenic pressures, leads to the fifth management scenario. Several management measures have historically been adopted to reduce this factor, ranging from catch and effort regulation to spatial access limitations (Anderson et al., 2018). Regardless of the approach taken, fisheries management should be tailored to each local context, consider the multidimensional contributions of small-scale fisheries, and integrate fishers' knowledge and perceptions (de Juan et al., 2024; Basurto et al., 2025). For example, co-management practices are a flexible management strategy in which stakeholders participate in decision-making, implementation, and enforcement processes. These practices have emerged as a promising approach to reducing the pressure of



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Fig. 4. (a) Average \pm standard error of the anthropogenic factors, namely: HP (human population); AP (anthropogenic pollution); FPP (anthropogenic physical pressures); PNC (proximity to the nearest city); and FP (fishing pressure) in the bottom resilient areas. The order of the management factors is determined by their scores. (b) Necessary percentage of simultaneous reduction of anthropogenic pressures to achieve significant differences between the IRIS_{Real} and the IRIS_{Simulated}. (c) Percentage of bottom resilient areas that could transition to moderate areas through the simultaneous reduction of anthropogenic pressures.

marine resource extraction on natural systems and enhancing the sustainability of small-scale fisheries (Gelcich et al., 2019). This approach, already implemented in some fisheries in northern Spain, enables not only self-regulation of fisheries but also quicker identification of new social-ecological challenges and solutions, leading to a more efficient reduction of this pressure (Nogué-Algueró et al., 2023; Druon et al., 2023).

Even though we propose different measures tailored to reduce each of the anthropogenic pressures, and we demonstrate that varying percentages of pressure reductions are required in each scenario, we found that the percentage of locations reclassified from bottom to moderate resilience was consistent across the different management scenarios, ranging from 17 % to 23 %. This means that managers and decision-makers would have a wide range of strategies to improve resilience. That said, there is one measure that could address all five management scenarios simultaneously: the establishment of marine protected areas. When well designed—such as having no-take zones, being large and isolated, properly enforced, and given sufficient time to flourish—marine protected areas have been proven critical for the optimal functioning of ecosystems (Edgar et al., 2014). However, focusing solely on restricting anthropogenic pressures through protected areas may raise two main drawbacks. First, it hinders the increase of resilience in areas lacking protection that are already highly affected by anthropogenic pressures. Second, properly designing and implementing marine protected areas over large areas may present financial and equity challenges that are difficult to overcome. For example, substantial investments in surveillance are necessary, and dedicated participatory processes must be adopted to avoid increasing social vulnerabilities (Gill et al., 2017; Claudet et al., 2024). Consequently, our findings open up a range of opportunities to improve marine resilience by reducing anthropogenic pressures and promoting conservation. They also suggest that measures taken should be tailored to the nuances of the local social-ecological context in order to strengthen the long-term resilience of temperate rocky reefs.

5. Conclusion

By empirically investigating the marine resilience of temperate rocky reefs in Southern Europe, we uncovered a range of management strategies that can be implemented to significantly enhance resilience. We emphasized the urgent need to preserve top resilient areas, as they are invaluable resources that must be conserved to prevent degradation. Furthermore, we identified five management scenarios aimed at increasing resilience in bottom resilient areas through the reduction of anthropogenic pressures. Our results reveal that, regardless of the management scenario followed, the percentage of bottom resilient areas that can be reclassified as moderate resilient areas remains unchanged, thereby opening up a wider range of management opportunities. We encourage future studies on the resilience of temperate coastal systems to explore the influence of alternative anthropogenic factors and examine different climate change scenarios. Given that resilience plays a vital role in the health of natural ecosystems and their contributions to human well-being, we anticipate that this study will advance knowledge related to the preservation and enhancement of resilience in temperate coastal systems globally.

CRedit authorship contribution statement

José A. Sanabria-Fernández: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Formal analysis, Data curation, Conceptualization. **Natali Lazzari:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation.

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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Data availability

All the data used in this research are open access and are available in the GitHub repository of the corresponding author (<https://github.com/Sanabria-Fernandez/Fostering-marine-resilience-in-temperate-rocky-reefs.git>).

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