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Research article

The challenge of setting restoration targets for macroalgal forests under climate changes

Erika Fabbrizzi[a,b,*], Sylvaine Giakoumi[b], Francesco De Leo[a], Laura Tamburello[b], Antonia Chiarore[b], Alberto Colletti[a], Marianna Coppola[a], Marco Munari[b], Luigi Musco[b,c], Fabio Rindi[d], Lucia Rizzo[b,e], Beatrice Savinelli[a], Giulio Franzitta[b], Daniele Grech[f], Emma Cebrian[g,h], Jana Verdura[i], Silvia Bianchelli[d], Luisa Mangialajo[i], Ina Nasto[j], Denada Sota[j], Sotiris Orfanidis[k], Nadia K. Papadopoulou[l], Roberto Danovaro[b,d], Simonetta Fraschetti[a,m]

[a] University of Naples Federico II, Naples, Italy
[b] Stazione Zoologica Anton Dohrn, Naples, Italy
[c] University of Salento, Lecce, Italy
[d] Università Politecnica delle Marche, Ancona, Italy
[e] Institute of Sciences of Food Production, National Research Council, Lecce, Italy
[f] IMC International Marine Centre, Oristano, Italy
[g] Centre d'Estudios Avançats de Blanes, Consejo Superior de Investigaciones Cientìficas (CEAB-CSIC), Blanes, Spain
[h] University of Girona, Girona, Spain
[i] Université Côte d'Azur, CNRS, UMR 7035 ECOSEAS, Nice, France
[j] University of Vlora "Ismail Qemali", Sheshi Pavaresia, Vlore, Albania
[k] Fisheries Research Institute, Hellenic Agricultural Organization-Demeter, Kavala, Greece
[l] Hellenic Centre for Marine Research (HCMR), IMBRIW, Crete, Greece
[m] NBFC, National Biodiversity Future Center, Palermo 90133, Italy

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ABSTRACT

The process of site selection and spatial planning has received scarce attention in the scientific literature dealing with marine restoration, suggesting the need to better address how spatial planning tools could guide restoration interventions.

In this study, for the first time, the consequences of adopting different restoration targets and criteria on spatial restoration prioritization have been assessed at a regional scale, including the consideration of climate changes. We applied the decision-support tool Marxan, widely used in systematic conservation planning on Mediterranean macroalgal forests. The loss of this habitat has been largely documented, with limited evidences of natural recovery. Spatial priorities were identified under six planning scenarios, considering three main restoration targets to reflect the objectives of the EU Biodiversity Strategy for 2030.

Results show that the number of suitable sites for restoration is very limited at basin scale, and targets are only achieved when the recovery of 10% of regressing and extinct macroalgal forests is planned. Increasing targets translates into including unsuitable areas for restoration in Marxan solutions, amplifying the risk of ineffective interventions.

Our analysis supports macroalgal forests restoration and provides guiding principles and criteria to strengthen the effectiveness of restoration actions across habitats. The constraints in finding suitable areas for restoration are discussed, and recommendations to guide planning to support future restoration interventions are also included.

* Corresponding author. University of Naples Federico II, Naples, Italy.
E-mail address: erika.fabbrizzi@unina.it (E. Fabbrizzi).

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1. Introduction

In marine and coastal areas, species populations, habitats and ecosystems are constantly modified under multiple anthropogenic stressors with severe consequences on marine biodiversity and ecosystem services (Chefaoui et al., 2017; Colletti et al., 2020; Gissi et al., 2021; Bevilacqua et al., 2021, Tamburello et al., 2022). The rate of changes that these ecosystems are experiencing calls for adopting new strategies to complement the traditional approaches of ecosystem conservation (Lester et al., 2020). Among these, marine ecosystem restoration, by the implementation of intentional activities (e.g., environmental remediation, ecological engineering, reconstruction, creation/re-creation or ecological rehabilitation), is increasingly considered as a prominent tool to promote and assist the recovery of degraded ecosystems (Society for Ecological Restoration International Science Policy Working Group, 2004). Restoring ecosystems means bringing back biodiversity and ecosystem services, representing thus a key motivation for funding and implementing restoration projects (Matzek, 2018; CBD, 2020). As a part of the EU Biodiversity Strategy for 2030, specific and binding restoration targets have been proposed in 2021 (EC, 2020). However, while criteria for reaching conservation targets have been largely discussed (Zhao et al., 2020), setting targets for restoration still needs a framework to guide the process of restoration prioritization.

One way to foster restoration targets is adopting Marine/Maritime Spatial Planning (MSP) principles, i.e., planning the spatial allocation of restoration efforts based on ecological knowledge and socio-economic constraints (Lester et al., 2020). MSP represents an effective approach in the challenge of balancing conflicting human demands of the maritime space, protecting the environment in a spatially explicit way and implementing ecosystem-based management to simultaneously fulfil environmental, biological and economic requirements (Leslie et al., 2003; Klein et al., 2008; Ehler and Douvere, 2009; Tuda et al., 2014; Stelzenmüller et al., 2021). MSP can be critical to achieve the targets of the current development and environmental policies, such as the United Nations Sustainable Development Goal 14 (UN SDG 14) (UN, 2015; Böhnke-Henrichs et al., 2013; Frazão Santos et al., 2020; Kirkfeldt and Frazão Santos, 2021) and the EU Biodiversity Strategy for 2030 (Katsanevakis et al., 2020), increasing the effectiveness of restoration practices. Considering the high costs required for restoring marine habitats at large spatial scales (Bekkby et al., 2020), the selection of sites where restoration is more likely to be effective can largely contribute to the achievement of restoration objectives with a high return on investment (Bayraktarov et al., 2016). However, in the marine environment, the process of spatial planning is still scarcely considered for the attainment of environmental goals mostly focusing on economic demands (Katsanevakis et al., 2020; Trouillet, 2020). Yet, considering where restoration activities are undertaken can result more important than how they are carried out (Fraschetti et al., 2021).

Marxan software (Ball et al., 2009) is the most widely used open-source decision-support tool (Watts et al., 2017) in conservation. Initially conceived for the design of protected areas network meeting several ecological, social and economic criteria at once (Ball et al., 2009, Christensen et al., 2009), Marxan integrates cutting-edge conservation science alongside human uses shaping dialogue between scientists and decision-makers. The application of Marxan in a restoration perspective is still very limited and has mainly been implemented in terrestrial and freshwater realms (see Adame et al., 2015; Renwick et al., 2014; Yoshioka et al., 2014; Jellinek, 2017; Hermoso et al., 2021). Nolan et al. (2021) recently introduced the predictions of coral cover in a spatial prioritization analysis with Marxan to distinguish between protection and restoration areas, targeting the most degraded areas for restoration, and avoiding low-quality areas for protection.

In this study, for the first time (to the best of our knowledge), the consequences of adopting different restoration targets and criteria on spatial restoration prioritization have been assessed at a regional scale. We focused on Mediterranean macroalgal forests since, in the last 20 years, forests loss has been largely documented across the whole basin for local and global cumulative impacts (Sales and Ballesteros, 2009, Fulton et al., 2019, de Caralt et al., 2020, Verdura et al., 2021, Tamburello et al., 2022), with limited evidences of natural recovery (Riquet et al., 2021), even within protected conditions (Sala et al., 2012, Tamburello et al., 2022).

Spatial priorities were identified by Marxan under six planning scenarios considering three main restoration targets, conceived to reflect the objectives of the EU Biodiversity Strategy for 2030. We combined fine-scale data about their present and past distribution across the Mediterranean Sea with data about their environmental requirements gathered using the Habitat Suitability Model (HSM) outputs provided by Fabbrizzi et al. (2020). The use of HSMs in supporting environmental management is critical, since they provide relevant insights about potential drivers of habitat loss (Catucci et al., 2022). In addition, since the distribution of fucalean forests is strongly constrained by warming temperatures (Verdura et al., 2021), we included in the spatial planning the distribution of Sea Surface Thermal Anomalies (SSTA) hotspots across the Mediterranean Sea. Finally, the aim of this study is also to provide recommendations to guide the spatial planning of future marine restoration actions.

2. Materials and methods

2.1. Study area and Planning Units

Considering the whole Mediterranean coastline as our Planning Region (i.e., our study area), we defined Planning Units (PUs) as the set of potential sites from which to select restoration areas. We used square PUs, superimposing a regular grid with a resolution of 0.004166 decimal degrees (i.e., about 400 m^2) to the entire coastline, obtaining 112,539 PUs. The adopted resolution matches the ones of the HSM developed in Fabbrizzi et al. (2020), as the outcomes of that model, expressing the suitability of each area for fucalean forests occurrence (with values ranging in the [0,1] interval), were used to identify areas suitable for restoration.

In our analysis, in fact, we locked out from the potential restoration areas to be selected PUs corresponding to the distribution of cells classified as unsuitable by the HSM, i.e., cells with HSM values less than 0.61. This value corresponds to the cut-off which allowed to optimize the accuracy of the HSM predictions by reaching the best compromise between the sensitivity and the specificity of the model (Fabbrizzi et al., 2020). This exclusion ensured that the analysis only retained those sites in which restoration efforts are more likely to be effective, indicating the presence of suitable conditions.

Areas with high frequency of Sea Surface Temperature Anomalies (SSTA) were locked out from the analysis as well. Considering the distribution of SSTA hotspots into the spatial planning was crucial to exclude areas where the high frequency of extreme climatic events can compromise the effectiveness of restoration actions. SSTA data were retrieved from the NOAA's Environmental Modeling Center database (https://www.emc.ncep.noaa.gov/emc_new.php): monthly values over the past five years (2015–2020) were taken into account, only including spring and summer seasons (months between March and August), since temperatures of these periods are considered the most critical for recruitment and survival of Mediterranean fucaleans (Sauvageau, 1912; Orfanidis et al., 2021). Thus, areas where temperatures exceed the long-term average from 1981 to 2010 by at least 1 °C (Chollett et al., 2022) above the 75° percentile were considered as unsuitable for restoration actions (hereafter referred to as "thermal anomalies hot spots").

Finally, areas where forests are already present (i.e., existing forests that are in good state and do not need restoration) and those for which no occurrence data were available were locked out too. More specifically, we locked out from the Marxan analysis 112,219 PUs, out of which 70,410 were classified as unsuitable according to the HSM and the SSTA layer (Fig. 1a), 36,814 corresponded to areas where forests occurrence is documented, while for the remaining 4995 no occurrence data are available (Fig. 1b).

2.2. Restoration features

Restoration features are intended to represent the entities (e.g., species, habitats, ecosystems) to be restored. In this study, we determined restoration features in three steps. Firstly, we considered the following types of fucalean forests: i) Regressing forests (Rf), i.e., areas where a pattern of regression from a previous healthy status of the canopy was documented by literature analyses and expert knowledge; ii) Extinct forests (Ef), i.e., areas where fucalean forests were historically documented but are currently absent.

To map these forests, we used an existing dataset that assembled data about the current and historical distribution of fucalean forests across the Mediterranean Sea (Fabbrizzi et al., 2020), refined by conducting a literature review and data collection. For the literature review, which involved both peer-reviewed and grey literature, different databases were used: ISI Web of Science (WOS), Scopus, AlgaeBase (https://www.algaebase.org/) and GBIF (https://www.gbif.org/). The search of pertinent articles was conducted for the whole Mediterranean Sea, setting 2020 as the only temporal cut-off. A total of 1236 studies including the keywords "*Cystoseira*" and "Mediterranean" were evaluated, retaining only those reporting geographical information about the distribution (presence/absence) and, when available, the status (coverage, trend, and present-past conditions) of any *Cystoseira* species. The screening of the literature was completed before the recent split of the genus *Cystoseira* in the three separate genera *Cystoseira, Ericaria* and *Gongolaria* (Molinari-Novoa and Guiry, 2020). All studies without georeferenced data were no further examined and were excluded from the review. The information obtained from the literature was also combined with new data collected in the field within the framework of the AFRIMED project (http://afrimed-project.eu/) (see Orfanidis et al., 2021). Additional data were provided by AFRIMED partners as personal information.

The assembled dataset comprises a total of 39,293 occurrence records (25,145 digitized as a vector shapefile of points and 14,148 as a vector shapefile of polylines) covering a large span of time from 1789 to 2020. Table S1 shows the literature used for data collection, composed of 335 articles, including both peer-reviewed and grey literature. Each article is labelled with an ID number which corresponds to the ID of the related records in the georeferenced dataset. The contribution to the dataset by AFRIMED partners through personal data is also listed in Table S2.

The dataset expresses the number of Regressing forests and Extinct forests occurring in each PU. The species considered for the identification of the restoration features were: *C. compressa* (Esper) Gerloff & Nizamuddin, *C. foeniculacea* (Linnaeus) Greville, *C. humilis* Schousboe ex Kützing, *E. amentacea* (C. Agardh) Molinari & Guiry, *E. brachycarpa* (J. Agardh) Molinari & Guiry, *E. crinita* (Duby) Molinari & Guiry, *E. mediterranea* (Sauvageau) Molinari & Guiry, *G. barbata* (Stackhouse) Kuntze and *G. elegans* (Sauvageau) Molinari & Guiry. These species were assumed as a rather uniform ecological entity pertaining all to the shallow rocky shores (see Fabbrizzi et al., 2020).

In the second step, each type of forest was split in two restoration features according to the level of Habitat Richness (HR) surrounding the forest. The HR data layer was assembled using the model data on the distribution of the following Mediterranean species/habitat: *Posidonia oceanica* meadows, bioconstructions (coralligenous formations and maërl beds), essential fish habitats (nursery and spawning grounds), and deep-sea habitats (Martin et al., 2014; Boero et al., 2016). We preferred data derived from models to the raw ones since spatial information on marine species and habitats are largely incomplete. HR data were combined in a polygon shapefile which displayed the number of different habitats for each PU across the Mediterranean Sea. Given the distribution of HR values across PUs, we considered the value corresponding to the third quartile as a threshold discriminating between low and high HR.

HR was used to incorporate into the planning process the evidence that positive species interactions can enhance restoration success (Eger et al., 2020). Facilitation between primary producers and indirect trophic effects have the potential to mitigate the effects of warming on the distribution of species, expanding the range of physical conditions under which species can persist (Silliman et al., 2015; Bulleri et al., 2018; Eger et al., 2020). Under these criteria, we defined 4 restoration features: 1) Rf in high HR; 2) Rf in low HR; 3) Ef in high HR; 4) Ef in low HR (Fig. 1). Finally, a further class of restoration features were assessed using the distribution of the Habitat Suitability Model false positive cases (hereafter referred to as "HSMf"). These features correspond to the areas where fucalean forests have never been documents but are suitable for their growth according to the HSM provided by Fabbrizzi et al. (2020), and hence are also suitable for restoration. In this study, HSMf were treated as equivalent to Ef in low HR under the assumption that they had macroalgal forests, now extinct due to environmental or human pressures, leading to a great uncertainty in restoration outcomes, since in these areas the presence of forests was only predicted.

2.3. Restoration targets and scenarios

Restoration targets express the minimum proportion of the restoration features to be included in the planning solutions. We set six

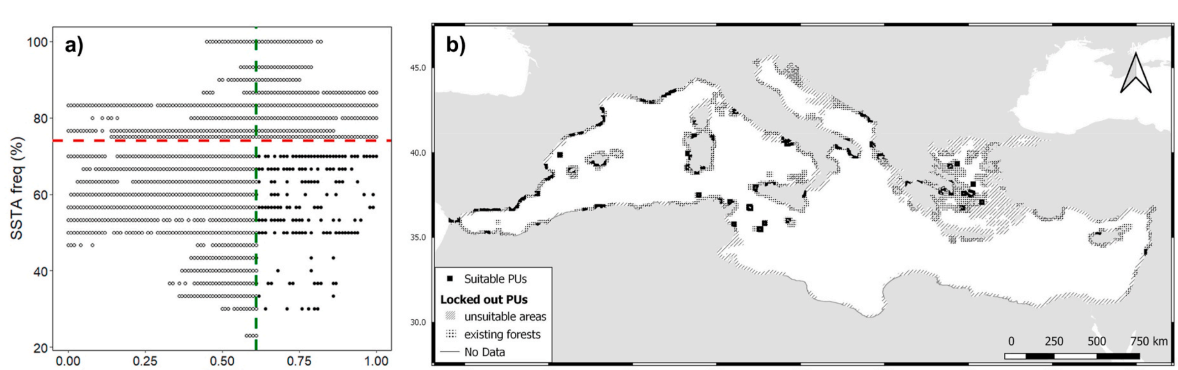

Fig. 1. Planning region and identification of PUs. (a). The scatterplot with the distribution of suitable (black points) and unsuitable (white points) areas according to the HSM outputs and the SSTA frequency. The vertical green dotted line represents the threshold assessing suitability according to the HSM (values > 0.61). The horizontal red dotted line represents the threshold assessing suitability according to the SSTA (values < 75%). Areas where forests occurrence is documented and those for which no occurrence data are available are not represented in the scatterplot. (b). Map of the distribution of suitable and locked out PUs.

restoration scenarios with two sets of targets each: a) restoring 10% of fucalean forests in high HR and 5% of those in low HR, without considering HSMf; b) restoring 10% of fucalean forests in high HR and 5% of those in low HR, including HSMf; c) restoring 20% of fucalean forests in high HR and 10% of those in low HR, without considering HSMf; d) restoring 20% of fucalean forests in high HR and 10% of those in low HR, including HSMf; e) restoring 30% of fucalean forests in high HR and 20% of those in low HR, without HSMf; f) restoring 30% of fucalean forests in high HR and 20% of those in low HR, including HSMf (Fig. 1).

2.4. Costs of restoration

Costs data reflect the effort to be allocated in including a PU among priority areas for restoration. They pertain to the socio-economic implications of conducting restoration activities. We estimated costs of restoration of each PU from Verdura et al. (2018) where costs for restoring 25 m^2 of a forest has been assessed. These costs represent an average between 1092 €/25 m^2 (costs of in situ restoration) and 2665 €/25 m^2 (costs of ex situ restoration). The obtained value was then calibrated on the basis of facilities distribution which affects the costs linked to the transport for both the in situ and the ex situ techniques. Thus, we considered 0.40 €/km (see Verdura et al., 2018) to assess the cost of covering the distance between the restoration site and the nearest facility. The cost of a PU decreases in relation to its proximity to the following facilities: i) International, National and Regional MPAs. Information about their distribution across the Mediterranean Sea were retrieved from MAPAMED database (https://medpan.org/main_activities/mapamed/); ii) Ports (World Port Index, 2014 -https://maps.princeton.edu/catalog/sde-columbia-worldports2014: this dataset was derived from the 23rd Edition of the World Port Index prepared and published by the United States National Imagery and Mapping Agency); iii) Diving facilities (https://www.google.com/maps/d/viewer?hl=en&gl=US&ved=0CFMQjwU&ei=SOzqTIfnCJGQyQWB7KXcDg&ie=UTF8&oe=UTF8&msa=0&mid=1WLySIlMSbCBLJ0TtucPh43BOgcw&ll=36.648535204425414%2C13.872461034103644&z=5); iv) Marine Stations (MARS network, https://www.marinestations.org/members/mars-members-map/), Marine Institutes (CIESM, http://ciesm.org/online/institutes/CIESM_InstitutesFullIndex.php) and Specially Protected Areas Regional Activity Centres (SPA/RAC, https://www.rac-spa.org/map_structure); v) Locations of previous experiences on restoration activities, in terms of scientific background documented with published studies (data collected in the framework of MERCES project, http://www.merces-project.eu/). All data for these layers were processed and converted into the same raster format of the HSM to integrate the information in the PUs grid.

Hence, costs for each PU were defined as:

$$PUc = Rc + (\overline{PUf} \times 0.40)$$

where PUc is the cost estimated for a PU, Rc is the average between in situ and ex situ restoration costs for a surface area of 25 m^2, $\overline{PUf}$ is the distance between the PU and the nearest facility for restoration in km and 0.40 is the cost of transports per km (€/km).

2.5. Marxan parameters

The three above mentioned scenarios, with their respective restoration targets (see section 2.3), were adopted to run Marxan. Based on a heuristic algorithm, specifically the "simulated annealing", Marxan finds multiple near-optimal solutions to maximize conservation (here restoration) interests while minimizing costs with the constraint of meeting the set of conservation (here restoration) targets. For each scenario, Marxan was run 100 times using 1,000,000 iterations, resulting in two main outputs: the best planning solution and the selection frequency of PUs, i.e., the number of times a PU is selected over the 100 runs as a measure of its relative priority and irreplaceability (Fig. 2). The Boundary Length Modifier (BLM) value, used to improve the spatial compactness of individual solutions, was set to 0 since it was not critical in our analysis to have clumped solutions. The Feature Penalty Factor (FPF), a multiplier that determines the size of the penalty that will be added to the objective function if the target for a feature is not met, was calibrated to optimize Marxan performance in finding solutions. Too small FPF values mean achieving the "lowest cost" solution but, at the same time, missing several targets, since the cost of selecting additional PUs is greater than the small penalties for missing the targets. Conversely, too large FPF values reduce Marxan potential for exploring different options resulting in higher cost solutions (Fischer et al., 2010). We iteratively increased the FPF, starting from 1, until finding the value that allows minimizing both the amount of features by which the targets are not met (namely "shortfall") and the costs for solutions in each scenario. In this analysis, Marxan solutions, supporting the decisions which underpin the spatial prioritization process, were used to identify priority areas for fucalean forests restoration in the Mediterranean basin.

3. Results

3.1. Planning Units and restoration features

After comparing current and historical distribution of the selected species, 93 Rf and 762 Ef were identified. According to the level of HR surrounding the forests, restoration features were grouped in 88 Rf in low HR, 5 Rf in high HR, 735 Ef in low HR and 27 Ef in high HR. In addition, 232 areas were identified as the supplementary features HSMf (Fig. 3). Taken together, Rf and Ef were distributed over 310 PUs, of which only 88 were classified as suitable as potential restoration areas.

Other 232 suitable PUs corresponded to the HSMf, for a total of 320 PUs across the whole Mediterranean Sea actually suitable to be restored.

3.2. Restoration scenarios and costs

For each scenario, we explored the best planning solution and the selection frequency of PUs, i.e., the number of times a PU is selected over the 100 runs as a measure of its relative priority. Costs associated to PUs ranged between € 1178.5 to € 1261.7 (Fig. S1).

In the scenarios *a* and *b* (i.e., restoring 10% of restoration features in high HR and 5% of those in low HR, respectively excluding and including the HSMf), all targets were reached. The best solution included 18 PUs as priority areas corresponding to an estimated cost of about € 21,225 for a restored surface area of 450 m^2, not considering (Fig. 4a) and considering (Fig. 4b) the HSMf.

In the scenario *c* (i.e., restoring 20% of restoration features in high HR and 10% of those in low HR, excluding the HSMf), 49 PUs were indicated as priority areas for a total cost of about € 57,817 for a restored surface area of 1225 m^2, without reaching the target for the Ef in low HR (Fig. 4c). Conversely, in the scenario *d* (i.e., restoring 20% of restoration features in high HR and 10% of those in low HR, including the HSMf) all targets were met and 52 PUs were selected as priority areas in the best solution corresponding to an estimated cost of about € 61,408 for a restored surface area of 1300 m^2 (Fig. 4d).

Finally, in both the scenario *e* and the scenario *f* (i.e., restoring 30% of restoration features in high HR and 20% of those in low HR, respectively excluding and including the HSMf), targets were not completely reached (Fig. 4e and f). The best solutions included 58 PUs as priority areas, corresponding to an estimated cost of about € 68,424 to restore 1450 m^2 in the scenario *e* and 136 PUs corresponding to an estimated cost of about € 160,505 to restore 3400 m^2 in the scenario *f*.

Table 1 summarizes the results obtained from the best planning solution in each scenario.

Taking into account the selection frequency for each PU in each scenario we identified the priority level of the selected areas: "low

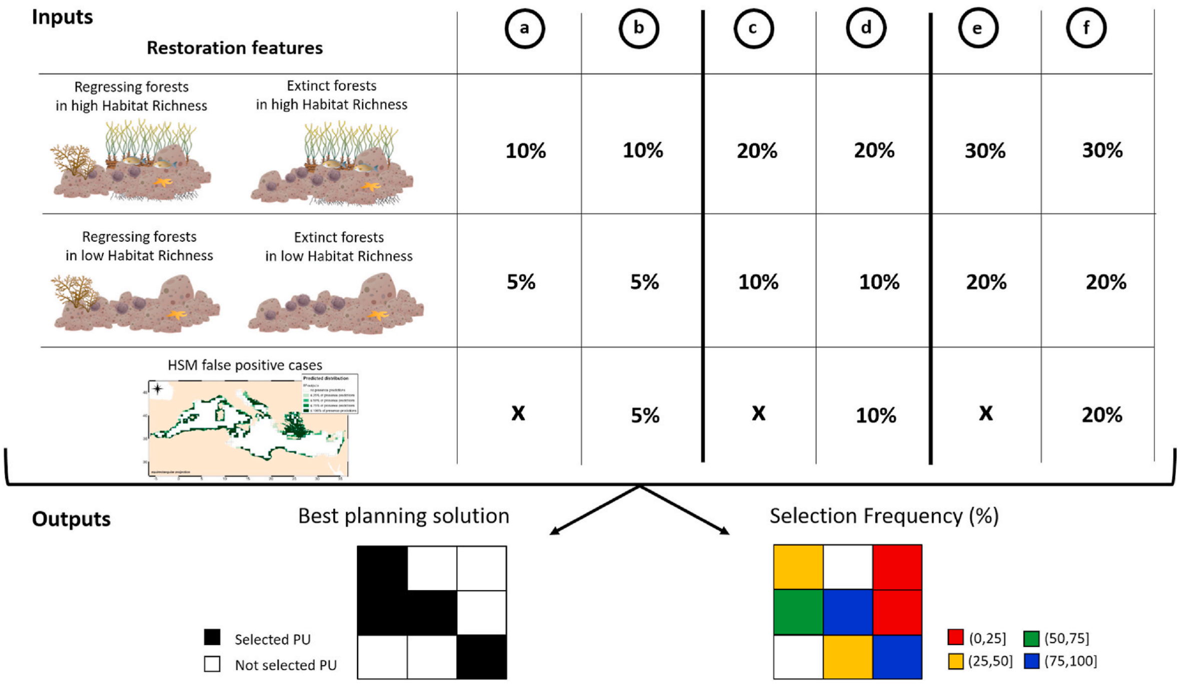

Fig. 2. Graphical representation of Marxan inputs and outputs. Letters *a*, *b*, *c*, *d*, *e* and *f* correspond to the six scenarios while percentage numbers represent the targets set for each restoration feature in each scenario. In the scenarios *b*, *d*, and *f*, letter "x" means that the HSMf (i.e., the HSM false positive cases) were not taken into account.

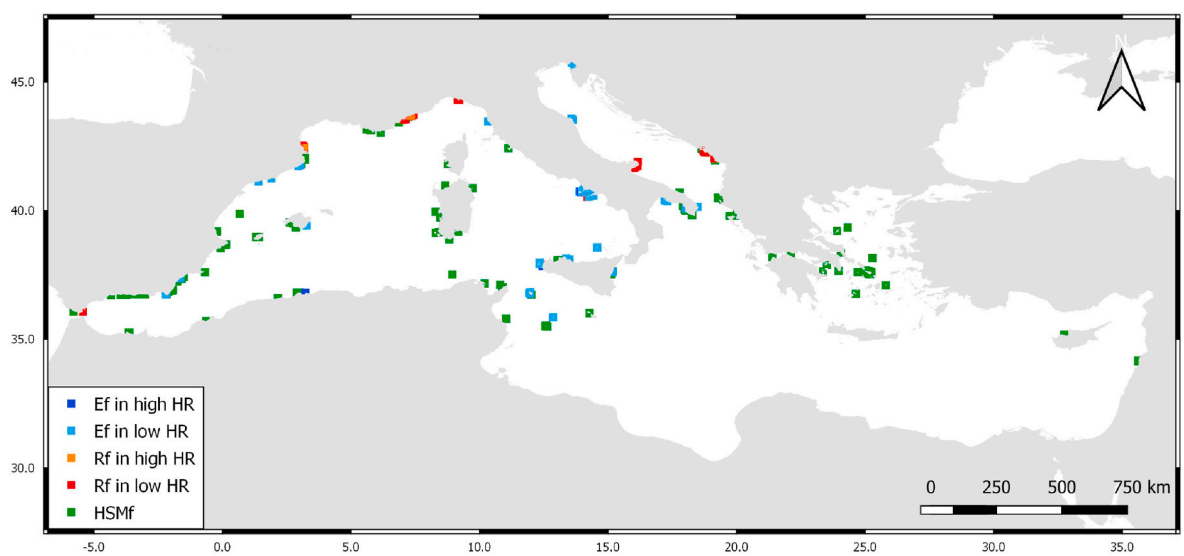

Fig. 3. Map of the distribution of Regressing forests (Rf) and Extinct forests (Ef) in high and low Habitat Richness (HR) and of the Habitat Suitability Model false positive cases (HSMf) across the Mediterranean Sea.

priority" for the areas selected between the 1% and 25% of the solutions; "moderate priority" for those selected between the 26% and 50%; "high priority" for those selected between the 51% and 75%; "top priority" for those selected between the 76% and 100%. The overlaps found comparing in pairs the PU selection frequency among the scenarios without HSMf and those with the HSMf (i.e., scenario *a* vs scenario *b*, scenario *c* vs scenario *d*, scenario *e* vs scenario *f*) represent the consensus among solutions (i.e., consensus areas) and was considered as a validation of the classification obtained from each single scenario. Fig. 5 shows the distribution of the consensus areas found in the first pair of scenarios, i.e., those for which targets were completely reached. Across all the Mediterranean basin, consensus areas were found to be only 54 and spread out across France, Italy, Montenegro and Spain. Top priority areas corresponded to 5 PUs distributed as follows: 3 in Italy, 1 in France and 1 in Spain.

4. Discussion

Our results from literature analyses and data collection documented the occurrence of wide areas of regression and extinction in macroalgal forests across the Mediterranean Sea needing conservation and/or restoration. Most of the regressing and extinct forests occur in areas where the level of habitat richness is low, i.e., areas where ecosystem integrity is already compromised. The consequences of habitat loss on

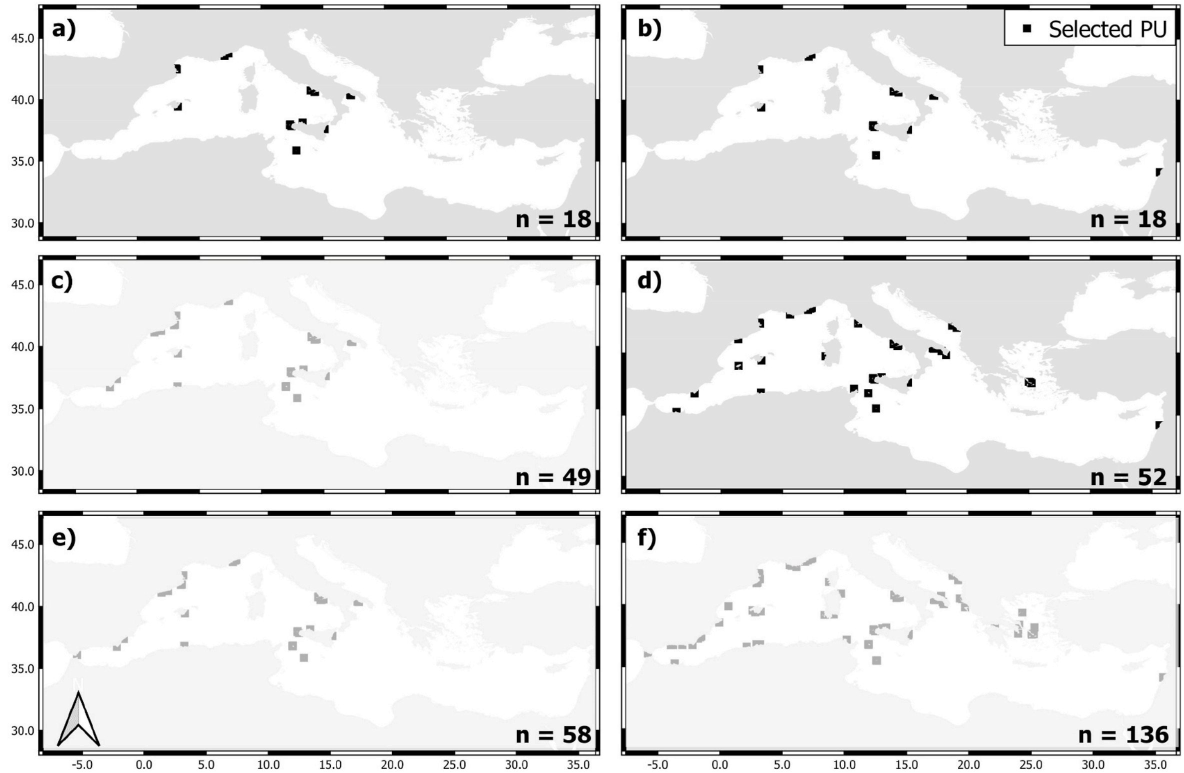

Fig. 4. Maps of the best solution under each scenario. (a) Restoring 10% of fucalean forests in high HR and 5% of those in low HR, excluding HSMf; (b) Restoring 10% of fucalean forests in high HR and 5% of those in low HR, including HSMf; (c) Restoring 20% of fucalean forests in high HR and 10% of those in low HR, excluding HSMf; (d) Restoring 20% of fucalean forests in high HR and 10% of those in low HR, including HSMf; (e) Restoring 30% of fucalean forests in high HR and 20% of those in low HR, excluding HSMf; (f) Restoring 30% of fucalean forests in high HR and 20% of those in low HR, including HSMf. For each scenario, the number of PUs included in the solution is specified at the bottom right of the maps. Maps in transparency indicate the solutions for which targets were not met.

Table 1
Results obtained from the best planning solution in each scenario. Last column on the right specifies if targets of the corresponding scenario are met ("Y") or not met ("N"). Therestored surface area is calculated considering the condition under which 25 m^2 of regressing/extinct forests are restored in each PU.

Restoration scenario	N° of PUs	Costs	Restored surface area (m^2)	Targets met
A	18	€ 21,225	450	Y
B	18	€ 21,225	450	Y
C	49	€ 57,817	1225	N
D	52	€ 61,408	1300	Y
E	58	€ 68,424	1450	N
F	136	€ 160,505	3400	N

between-habitat diversity have been little explored. Airoldi et al. (2008) suggested that habitat loss causes a major reduction of spatial diversity in species distribution, a process also described as "biotic homogenization" (Bulleri et al., 2002; Thrush et al., 2006; Balata et al., 2007). In other words, restoration success should be higher in areas featured by high habitat diversity. This conclusion has critical consequences in terms of restoration since the successful recovery of one habitat might trigger the recovery of others present in the same area through positive species interactions and facilitation cascades effects (Eger et al., 2020), given that causes of extinctions are removed. The knowledge about drivers and consequences of habitat loss is key to improve the identification of criteria to be adopted in a restoration framework to properly select locations, methodologies and tools for increasing the potential of successful interventions.

While protection criteria have been widely discussed and commonly recognized by many international initiatives and organizations (i.e., UN SDG, EU Biodiversity Strategy for 2030, CBD post-2020) (Grorud-Colvert et al., 2021), restoration criteria are still scarcely investigated, resulting in a lack of shared guidelines to be pursued when implementing restoration. In the marine environment, the process of selecting priority areas for conservation is mainly focused on the *ecological coherence* of MPA networks, formally assessed through the following criteria: *representativity* – the MPA network should represent the range of marine habitats and species by protecting all major habitat types and associated biological communities present in the network boundaries, *replication* – all major habitats should be replicated and distributed throughout the network, *connectivity* – the MPA network should seek to maximize and enhance linkages amongst individual MPAs and *adequacy* – the MPA network should be of adequate size to deliver its ecological objectives and ensure ecological viability and integrity of species populations, communities and ecosystems (Gabrié et al., 2012; Giakoumi et al., 2012; UNEP/MAP RAC/SPA, 2014; Boero et al., 2016; Agnesi et al., 2017; COHENET, 2017; Fraschetti et al., 2018). In a restoration framework, criteria should be based on a cost-effective identification of the most suitable locations considering environmental and socio-economic constraints (McGowan et al., 2020), adopting as eligibility criteria the following principles: the historical presence of the habitat/species focus of restoration, the suitability of the current and the future environmental conditions together with the feasibility of the restoration intervention in terms of costs and availability of facilities (Cebrian et al., 2021). However, as far as *connectivity*, a stepping-stone approach can be adopted to enhance habitat connectivity so that restoration success can be further strengthen and upscaled. Our analysis showed that the number of potential sites from which selecting the priority areas was drastically reduced after the exclusion of unsuitable areas. These unsuitable areas derived from the HSM outputs and from the inclusion of the layer on the thermal anomalies hotspots,

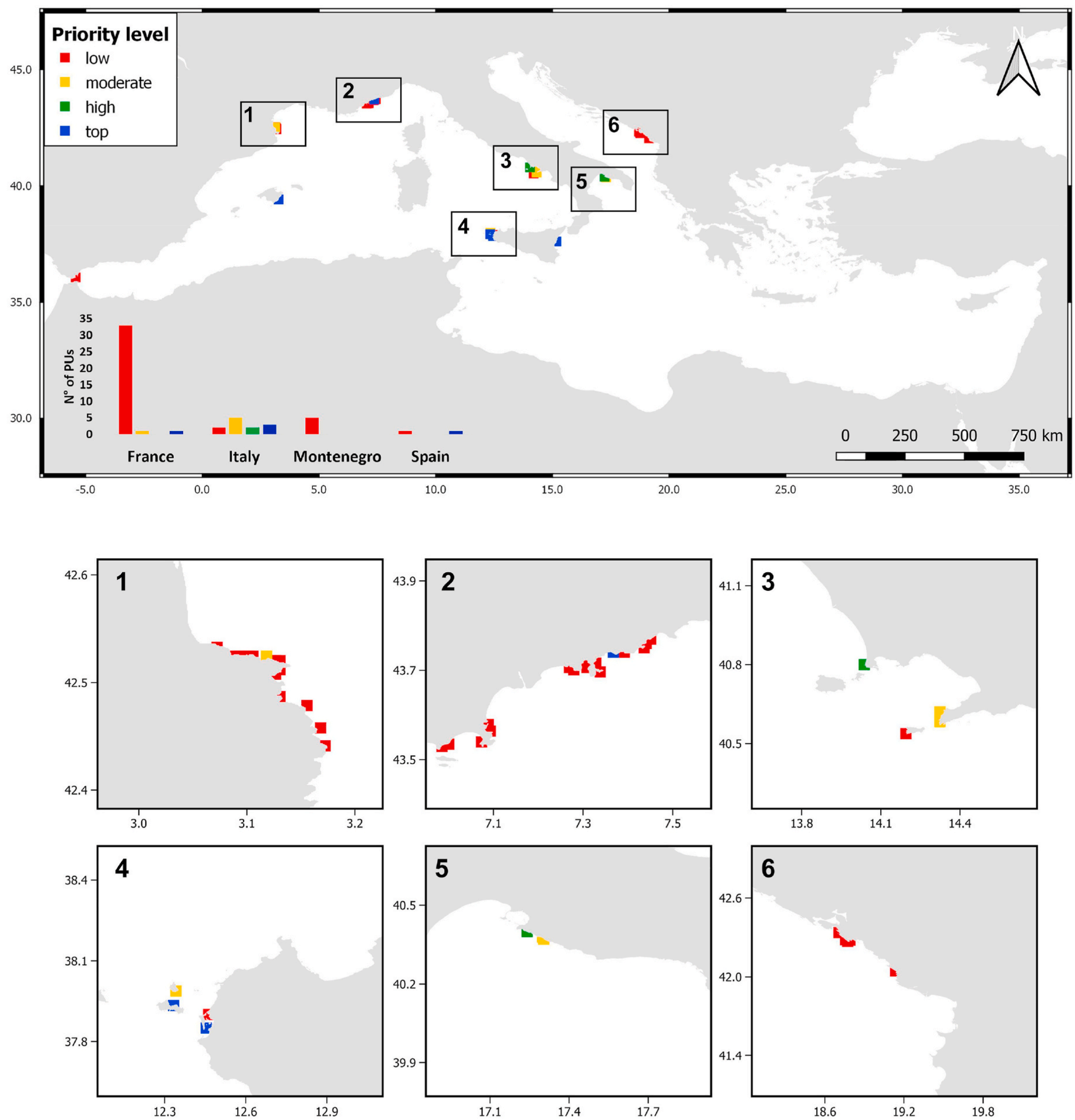

Fig. 5. Distribution of the consensus areas grouped by priority level found comparing the scenario a to the scenario b. The bar chart expresses the distribution of consensus areas per country. Rectangles numbered from 1 to 6 in the overall map on the top of the figure correspond to the zoomed maps on the bottom. These latter allow to better represent individual PUs in areas where the large-scale of the study limits a detailed visualization of the features.

determining the lack of environmental requirements for restoration success. The data used for the analyses, together with the cost assessment to show the actual feasibility of restoration actions, are critical elements to inform the process of prioritization, providing guidance for the identification of suitable restoration targets. Clearly, the quality of data feeding the HSM is of paramount importance, and planning large-scale restoration interventions in absence of fine-scale information can seriously compromise outputs accuracy. In this regard, it is worthwhile to stress the urgency of collecting new field data filling gaps about the distribution of fucalean forests, especially along the southern and eastern Mediterranean coasts. Similarly, restoring in the present without considering the effects of climate changes and ocean warming increases the potential of failures (Gann et al., 2019; Wood et al., 2019; Verdura et al., 2021).

Setting different restoration scenarios allowed us to explore the consequences of adopting different targets developed a priori at a Mediterranean scale. In our analysis, only the first set of targets was completely fulfilled, meaning that, in the Mediterranean Sea, restoring 10% of the forests in high HR contexts and 5% of those in low HR is an achievable goal, even when the additional HSMf features (i.e., the areas potentially suitable for fucalean forests growth but where neither restoration features nor fucalean forests occur) were not considered. Increasing targets gradually raises the number of areas to be restored, amplifying the risk of including areas less suitable for restoration and for which a greater economic investment is required. For this reason, targets for scenarios *e* and *f* could not be met, even if the supplementary HSMf features were considered. In other words, restoring 30% of the forests in high HR contexts and 20% of those in low HR turned out to be unfeasible in the Mediterranean Sea, demonstrating that environmental constraints cannot be disregarded when setting restoration priorities and confirming the crucial role of the context of where the restoration activity is undertaken in determining restoration success (Fraschetti et al., 2021). The inclusion of the supplementary HSMf features, in the scenario *d*, had the effect of increasing the possibility to reach higher targets compared to the scenario *c*, but also increasing restoration costs and uncertainty in the restoration outcome. Thus, creating new forests in areas where the presence of a forest has never been documented and it is only suggested by the HSM predictions, would allow meeting more challenging restoration targets bearing the higher risk associated to these areas. In fact, this would represent the creation of a new habitat, a practice that has been considered as controversial (Boudouresque et al., 2021).

The selection frequency outcomes suggested instead that only few areas can be addressed as “top priority”, meeting all the adopted restoration criteria. The consensus across scenarios (Micheli et al., 2013) about these areas can inform decision makers indicating the best candidate locations for macroalgal forests restoration. Restoration initiatives carried out in these areas translate into supporting the establishment of forests in locations where environmental conditions are currently suitable. They could also be addressed as climatic refugia for the presence of fucalean forests, since they have experienced thermal anomalies with a very low frequency.

Even though restoration priorities could widely vary depending on the prioritization criteria used (Strassburg et al., 2020), our case study demonstrates that introducing systematic conservation planning principles and tools in restoration projects is crucial to understand and define how much and where an ecosystem or habitat can be recovered, effectively managing our efforts and assessing the possibility of setting region-specific targets. Indeed, adopting MSP leads to accounting environmental constraints and socio-economic implications affecting restoration activities and the use of Marxan allows to allocate restoration targets identified a priori, combining spatial information from different sources. Future efforts should try to integrate site prioritization into marine spatial plans where restoration is co-optimized with protection, accounting for ecological, social and economic objectives to enhance system resilience.

4.1. Final recommendations

Despite the focus of the study was on the identification of criteria for macroalgal forests restoration, our intention was also to improve the spatial planning of future restoration efforts across marine habitats. Setting binding targets should be science-based and data-driven to ensure the effectiveness of restoration actions, as their cost in the marine environment is usually very high. More specifically:

- The collection of new information about current and historical species distribution, especially in data-poor regions, is critical for better understanding the drivers of changes, optimizing the identification of restoration sites. Our dataset underrepresented the southern and eastern Mediterranean biasing the spatial prioritization analysis. In addition, suitable sites were identified pooling different fucalean species together. Effective restoration requires knowledge at species level supporting the development of species-specific restoration plans.
- Since the context of *where* restoration activities are undertaken can be of greater relevance to a successful outcome than *how* (method) the restoration is carried out (Fraschetti et al., 2021), high-quality information on environmental variables and on the distribution and intensity of human threats is urgently needed to support the development of context-dependent restoration plans.
- An effort to advance the knowledge about the distribution and status of habitats is critically needed, associated to an improved understanding and interpretation on how to assess degradation (and thresholds of changes) across habitats. Fine-scale habitat mapping is largely lacking in the marine systems (Halpern et al., 2008; Dailianis et al., 2018; Fraschetti et al., 2018), limiting the consideration of the effects of the between-habitat diversity potentially affecting restoration outcomes. Updated information about the distribution and the status of marine habitats through coordinated monitoring across the Mediterranean countries should be a research priority for supporting future conservation and restoration initiatives.
- Refinement of restoration costs assessment is also recommended, since still large uncertainty can be observed, depending on the disparate restoration techniques, the target species and the involved countries (see Verdura et al., 2018; Tamburello et al., 2019; Gianni et al., 2020; Medrano et al., 2020). Also, selection of areas for restoration should be based on cost-effectiveness analysis to attain the maximum benefit with a limited budget. The development of standardized socio-economic assessments can support decision-makers in selecting the most cost-effective areas to be restored.

Credit author statement

Erika Fabbrizzi, Simonetta Fraschetti, Sylvaine Giakoumi: Conceptualization, Formal analysis; Erika Fabbrizzi, Simonetta Fraschetti: Data curation, Writing – original draft; all authors: Investigation, Resources and Writing - review & editing; Simonetta Fraschetti: Project administration, 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.

Data availability

Data are available on Mendeley Data repository (https://data.mendeley.com/).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2022.116834.

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