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Cost-effective restoration and conservation planning in Green and Blue Infrastructure designs. A case study on the Intercontinental Biosphere Reserve of the Mediterranean: Andalusia (Spain) – Morocco

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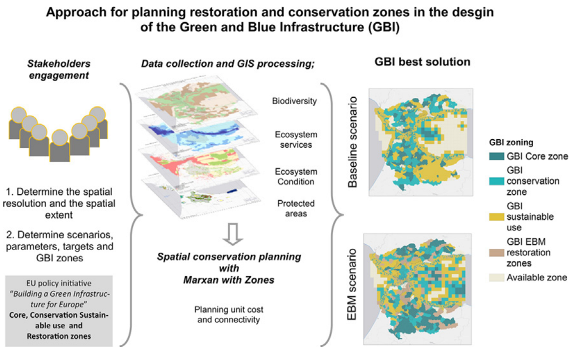
HIGHLIGHTS

- Existing GBI designs lack a systematic method to allocate restoration zones.
- Restoration was included in a cost-effective spatial plan of a multi-zone GBI.
- We jointly prioritized the allocation of ES, biodiversity and restoration features.
- We ensure an efficient and connected GBI design across three aquatic ecosystems.
- The results may guide the EU Strategy on Green Infrastructure and other policies.

GRAPHICAL ABSTRACT



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ABSTRACT

Green and Blue Infrastructure (GBI) is a network designed and planned to deliver a wide range of ecosystem services and to protect biodiversity. Existing GBI designs lacked a systematic method to allocate restoration zones. This study proposes a novel approach for systematically selecting cost-effective areas for restoration on the basis of biodiversity, ecosystem services, and ecosystem condition to give an optimal spatial design of GBI. The approach was tested at a regional scale, in a transboundary setting encompassing the Intercontinental Biosphere Reserve of the Mediterranean in Andalusia (Spain) – Morocco (IBRM), across three aquatic ecosystems: freshwater, coastal and marine. We applied Marxan with Zones to stakeholder-defined scenarios of GBI in the IBRM. Specifically, we aimed to identify management zones within the GBI that addressed different conservation,

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restoration and exploitation objectives. Although almost all conservation targets were achieved, our results highlighted that the proportion of conservation features (i.e., biodiversity, ecosystem services) that would be compromised in the GBI, and the proportion of provisioning services that would be lost due to conservation (i.e., incidental representation) are potentially large, indicating that the probability of conflicts between conservation and exploitation goals in the area is high. The implementation of restoration zones improved connectivity across the GBI, and also achieved European and global policy targets. Our approach may help guide future applications of GBI to implement the flexible conservation management that aquatic environments require, considering many areas at different spatial scales, across multiple ecosystems, and in transboundary contexts.

1. Introduction

Human development has contributed to human well-being and economic growth, but these gains have been achieved at rising environmental costs, as shown by habitat loss and climate change. Although human well-being has increased over the last fifty years, human activities are resulting in a rapid decline of the direct and indirect contributions of ecosystems to human well-being (i.e., ecosystem services, ES; Duraiappah, 2011; MA, 2005; Oliver et al., 2015). Specifically, aquatic ecosystems are among the most threatened ecosystems worldwide (MA, 2005). These ecosystems are particularly relevant in moderating water-vectored services, many of which, such as regulatory and cultural services, do not have an easily-recognised economic value, and thus are at risk of degradation when the focus is on monetising ES (Everard et al., 2016). Water flows through a landscape across not only aquatic, but terrestrial systems, provide a wide range of ES such as drinking water, food or climate regulation (Brauman et al., 2007). Since aquatic ecosystems are interconnected one with each other through water flows (i.e., linkages between upstream-downstream, surface-subsurface, lake-stream, river-floodplain, marine-freshwater; Lamberti et al., 2010), it is of particular importance that spatial planning approaches for these ecosystems take into consideration both structural and functional connectivity.

The ongoing degradation of ecosystem services highlights the need to invest in natural capital and to explicitly include its value in the decision-making process of economic (Bateman et al., 2013) and spatial planning analysis (Snäll et al., 2016). Since resources available for conservation are limited, the investment in natural capital must be strategically allocated in order to achieve cost-effective spatial planning solutions (Margules and Pressey, 2000). Among the increasing number of responses to cope with biodiversity and ecosystem services decline, the EU Commission promotes policy to implement Green and Blue Infrastructures (GBI). As an approach to land conservation, GBI is an interconnected network of natural and designed landscape elements, including water bodies and green and open spaces, which supply a wide range of provisioning, regulatory, cultural and supporting services (Benedict and McMahon, 2006; European Commission, 2013a; Ghofrani et al., 2017). Although projects implementing this specific approach worldwide are still scarce (Ghofrani et al., 2017), many different GBI programmes and projects have been or are under development in almost all European Union Member States (European Commission, 2016) and this approach is increasingly common in planning theory and policy, particularly in US and Europe (Lennon, 2015; Tzoulas et al., 2007). The GBI concept emphasizes the importance of ensuring the provision of valuable ES for human well-being (Kopperoinen et al., 2014; Lanzas et al., 2019; Maes et al., 2015; Snäll et al., 2016; Vallecillo et al., 2018) and is also about increasing the resilience of ecosystems by improving their connectivity (Karhu, 2011). Therefore, GBI is considered an ecosystem-based solution, since it may favour landscape permeability, climate change adaptation and may reduce vulnerability to weather and climate extreme events, while maintaining and preserving biodiversity and ES (European Commission, 2013b). Most recent approaches to set spatial priorities for GBI designation opt to apply cost-effective spatially explicit approaches in order to identify multifunctional GBI (Lanzas et al., 2019) based on ecosystem services (Lanzas et al., 2019; Snäll et al., 2016; Vallecillo et al., 2018) and biodiversity (Lanzas et al., 2019; Snäll et al., 2016). However, all the previous approaches fail to incorporate the allocation of multiple restoration actions (or they only address it partially, see Vallecillo et al., 2018). Restoration, however, is a major strategy for halting biodiversity loss and enhancing multiple ES supply in the long-term (Benayas et al., 2009; Bullock et al., 2011; Frélichová and Fanta, 2015), and it is one of the GBI components in itself (European Commission, 2016). However, there is a large uncertainty on what and where to act when enhancing ES and recovering threatened and endangered species (Thorne et al., 2015). Restoration of ecosystems is costly, and resources available are limited, thus investing in one restoration measure instead of another involves trade-offs and can be controversial. Traditional ex-post analysis of restoration areas (i.e. after the implementation of the protected site network) also leads to inefficient allocation of the areas to be restored (Adame et al., 2014). Therefore, prioritization of restoration areas should be systematic and cost-effective, and should be conducted during the network design stage (Adame et al., 2014). However, at present there is no standard approach to set priorities for restoration (Hagen et al., 2016) that can be implemented in international, regional and national initiatives for enhancing and maintaining biodiversity and ecosystem services such as GBI.

The Intercontinental Biosphere Reserve of the Mediterranean (IBRM), between Europe (Spain) and Africa (Morocco), contains several remarkable protected sites, high biodiversity richness and an important cultural heritage. Although pressures from human activities in the area threaten these values, the IBRM presents high potential for sustainable economic development (Malak et al., 2017; Molina and Villa, 2008).

This study presents a cost-effective and comprehensive spatially explicit approach in order to identify a multifunctional GBI based on ecosystem services, biodiversity (species and habitat types) and ecosystem condition across aquatic ecosystems (i.e., freshwater, coastal and marine), using the IBRM as a case study area. Specifically, we aim to devise a methodological approach for an optimal GBI design where the spatial allocation of multiple restoration measures is explicitly included during the systematic planning process. To our knowledge, this is the first time that the cost-effective allocation (in terms of financial costs, connectivity and loss of biodiversity and ES) of sites to be restored according to multiple different restoration actions has been attempted at the planning network design stage (but see Vallecillo et al., 2018 for a simplified approach based on only one restoration measure). For this purpose, we defined different GBI management zones previously identified by local stakeholders that addressed specific conservation and exploitation objectives, and achieved particular conservation targets, in terms of biodiversity (species and habitat types), ES and ecosystem condition. Finally, by comparing one GBI planning scenario that did not include restoration zones with one which did, we assessed how the implementation of restoration areas would affect the GBI spatial design.

2. Methods

2.1. Study area

The study area encompassed the IBRM in Andalusia (Spain) – Morocco and an area of influence (Fig. 1). The linkages across aquatic

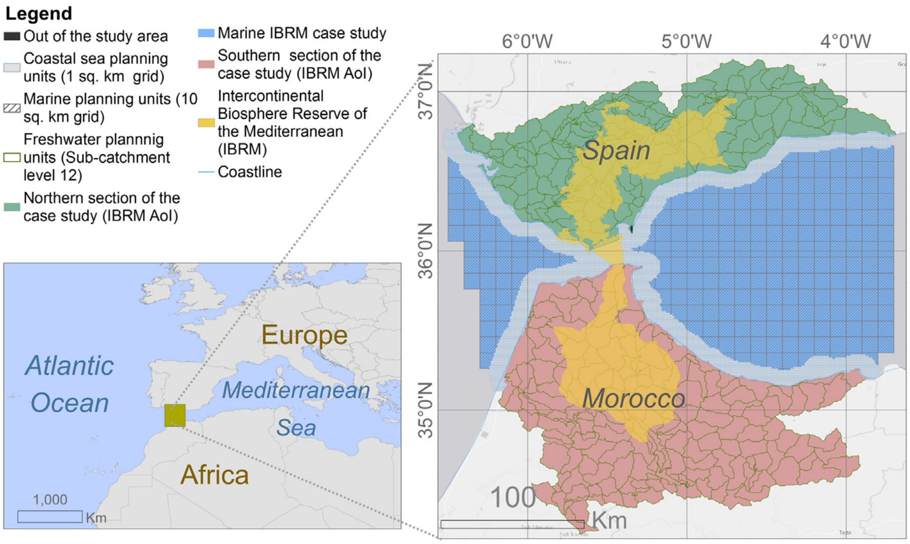

Fig. 1. Study area: Intercontinental Biosphere Reserve of the Mediterranean – Andalusia (Spain) – Morocco (IBRM) and its area of influence. IBRM: yellow colour; Moroccan area of influence of the IBRM: red colour; Spanish area of influence of the IBRM: green colour. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

ecosystems, and specifically the lineal structure of freshwater ecosystems (i.e., river network), implies that we must consider the propagation of threats along these networks to achieve effective conservation planning in these ecosystems. A frequent solution to cope with the upstream threats is to include all (or at least a large part) of the upstream catchment (Hermoso et al., 2015) in the conservation plan. For this reason, the area of influence coincides with the river catchments that overlap the IBRM as well as the marine area that washes the shores of these catchments. The study area spans over two continents, Europe and Africa, and the marine area of the Strait of Gibraltar, covering one million hectares that includes river basins, coastal, and marine areas (UNESCO-MAB, 2011).

The study area comprises various Western Mediterranean ecosystem types, which provide a diverse range of ES and high species richness. The biodiversity in the study area has global importance for conservation due to its endemicity. Even though northern and southern sections share similar ecological characteristics, human activities have shaped the landscape differently (e.g., almost 70% of the northern section of the IBRM is protected, while in the southern section only 30% of the Reserve is protected). Overall, this region has experienced a rapid population change due to socio-economic development and to the significant expansion of different economic activities over the last decades (Molina and Villa, 2008).

2.2. Spatial extent and resolution

The selection of areas for investment in GBI in the study area was based on planning units (PUs) that differed in size across the different aquatic ecosystems. According to the linear dependency along the river network (Hermoso et al., 2012), for freshwater ecosystems we used river sub-catchments (i.e., the river reach and its contributing area) derived from HydroSHEDS level 12 as PUs (Lehner and Grill, 2013). Coastal PUs (i.e. 10 km buffer from the shoreline; EEA, 2015) and marine PUs were derived from two regular grids. The PU size in the coastal and the marine realm was a compromise between the resolution of the available data and the extent of the study area (Lagabrielle et al., 2018). PUs of the marine ecosystems were represented through a grid of 10 km × 10 km, whereas the coastal PU grid was 1 km × 1 km (Fig. 1, Table 1). Higher resolution of the planning units in the coastal areas was due to the resolution of the data available and to the high number of human activities in these areas, which required more accurate data for their analysis.

2.3. GBI spatial planning approach

We propose a methodology to design a GBI network, based on stakeholder consultation, scenario development, management zones, related policies and EBM restoration measures (Fig. 2). We used Marxan with Zones software to identify a multifunctional GBI based on different prioritization features (i.e., ES, biodiversity -species and habitat types-, ecosystem condition, protected sites and restoration measures). Marxan with Zones is an extension of Marxan software (Watts et al., 2009) which applies a systematic conservation planning approach to optimize the allocation of different management zones. Marxan (Ball et al., 2009) was originally developed for designing protected site networks, but it has also used for establishing priority areas for restoration (Adame et al., 2014). Marxan balances costs and benefits, allowing the inclusion of connectivity and compactness criteria when selecting the priority areas (Watts et al., 2009).

Goals of the management zones and conservation targets for the different prioritization features were based on the choices and preferences of local stakeholders, including farmers, livestock producers, manufacturers, as well as, local non-profit organizations (Table 2; Faber et al., 2006).

Table 1
Statistical summary of the freshwater, coastal and marine planning units of the IBRM and its area of influence.

Case study sub-region	Realm	Resolution	Count	Total area (km^2)	Mean area	Std. Deviation
Northern section	Freshwater	Sub-catchment level 12	150	14,160	112,5	62
Southern section			186	20,597	114	58
Northern section	Coastal	1 km^2 regular grid	–	3.531	–	–
Southern section			–	3393	–	–
Ocean	Marine	10 km^2 grid	–	25,828	–	–

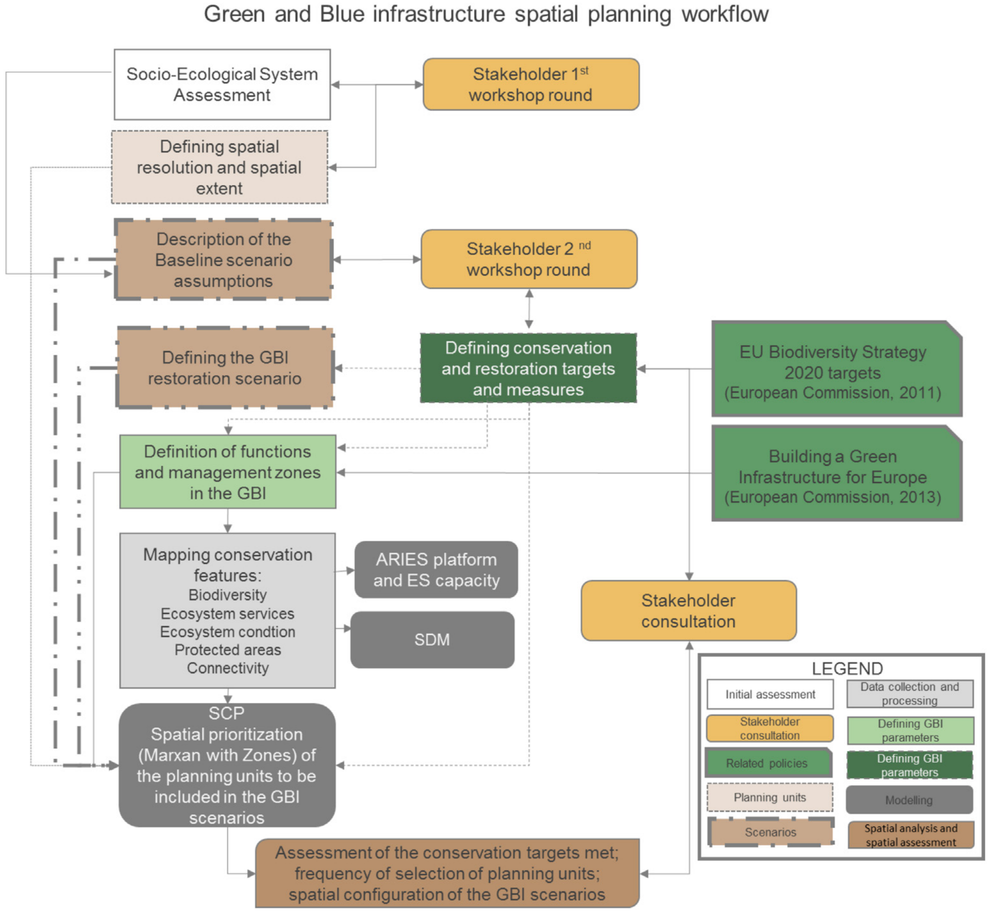

Fig. 2. GBI spatial planning workflow diagram.

2.3.1. GBI scenarios

We tested two different scenarios: (1) Scenario 1, the baseline scenario, considering the optimal spatial allocation of the different prioritization features in the study area; (2) Scenario 2, the EBM scenario, where, together with the prioritization features included in the baseline scenario, ecosystem-based management (EBM) restoration measures for habitats at poor ecosystem condition were implemented and contributed to the design of the GBI (UNEP, IUCN, TNC, 2014). The comparison between both scenarios allowed an assessment of how the inclusion of restoration areas would affect the GBI spatial design.

2.3.2. GBI management zones

We considered four different GBI management zones including two with conservation aims (the core zone and conservation zone), one to manage trade-offs between biodiversity conservation, maintenance of compatible ES and incompatible ES (the sustainable use zone) (Hermoso et al., 2018), and a fourth one to implement the restoration objectives considered in the EBM scenario (the EBM restoration zone).

The spatial arrangement of the zones was done by means of the boundary zone file in Marxan with Zones (Watts et al., 2009). To spatially distribute the zones, we buffered the core zone with the conservation zone in all realms (i.e., freshwater, coastal and marine). Therefore, we identified core zones that are connected through another core zone or through a conservation zone. Additionally, in the freshwater realm, we used a special spatial arrangement of PUs inspired by Abell et al. (2007), where core zones were mainly buffered upstream by conservation zones (Hermoso et al., 2015). Therefore, conservation zones played two different roles: as connectors of core zones and upstream buffers of these core zones. Restoration zones in scenario 2, containing

Table 2
Targets for the prioritization features to be achieved in the different management zones and scenarios. B = baseline scenario; R = restoration scenario. Targets are provided as a percentage of the total amount of each conservation feature in the study area.

	Scenarios quantitative targets (in percentage)									
Zone	Core		Conservation		Sustainable use		Restoration		Total	
GBI features	B	R	B	R	B	R	B	R	B	R
Biodiversity	9	9	5.25	5.25	0.75	0.75	–	0.79	15	15.79
Endangered species	12	12	7	7	1	1	–	1.05	20	21.05
Protected areas covering aquatic ecosystems	100	100	0	0	0	0	–	0	100	100
ES regulation and maintenance	9	9	5.25	5.25	0.75	0.75	–	0.79	15	15.79
ES cultural	0	0	9	9	6.00	6	–	1.35	15	16.35
ES provisioning	0	0	0	0	75	75	–	0	75	75
Habitats at unfavourable conservation status	0	0	0	0	0	0	–	15	–	15
Habitats at favourable conservation status	9	9	5.25	5.25	0.75	0.75	–	0.79	15	15.79

the restoration prioritization features, were spatially arranged following the same criteria as conservation zones.

2.3.3. Prioritization features

For planning the GBI design we obtained accurate spatial data on the distribution of ecosystem services and the occurrence of biodiversity features (i.e. species and habitat types) over the study area. Ecosystem condition across the habitats guided the selection of restoration areas and was used as an additional criterion to prioritize habitat types among planning units. Existing protected areas and potential restoration sites were also considered as priority features to be included in the GBI design (restoration sites only included in the EBM scenario).

2.3.3.1. Biodiversity. According to the data availability, we considered endangered species at the national level in Morocco and at the regional level in Spain (Andalusia region). Specifically, species occurrences of freshwater fishes, aquatic birds, amphibians, invertebrate species and characteristic plant species of aquatic and associated transitional ecotone habitats (dunes, sand and coastal cliffs) were included (Table S1 and S2 in the Supplementary Material). All of the species data were scarce and mostly based on presence-only data (lacking reliable information on true absences). Therefore, to obtain the complete information on spatial distribution required by Marxan with Zones, we developed models predicting the probability of presence of these species across the study area. Species occurrences were first aggregated to the planning units (sub-catchments and grids). We then used species distribution models (SDM) to map the range-wide potential distribution of each species within its realm (i.e., freshwater, coastal and marine). These models related species occurrences to the environmental conditions at those locations (Domisch et al., 2015). For each realm, we used a specific set of predictors that were not highly correlated (Spearman correlation coefficient < /0.7/; see supplementary methods in the Supplementary Material) and selected species that occurred in at least five sub-catchments or grids (as a minimum pre-requisite for building the model). We then used the “biomod2” R-package (R Development Core Team, 2018) and three machine-learning algorithms (Random Forest, Boosted Regression Trees and Maximum Entropy), where 70% of the species data were used to train the model, and the remaining 30% were used to validate the model. After a 10-fold cross-validation, we combined all single projections per species into a consensus prediction, where predictions yielding a higher model evaluation score (as given by the True Skill Statistic; Allouche et al., 2006) received a higher weight in the final consensus prediction using the default weighting factor of 1.6 (Thuiller et al., 2013). The mapped probability of occurrence of each species per PU was then used as a “conservation feature” in the subsequent spatial prioritization analyses.

2.3.3.2. Ecosystem services (ES). In agreement with previous studies, ES were classified as “incompatible” or “compatible” ES, depending on whether they do or do not represent conflicts with conservation goals (Chan et al., 2006; Hermoso et al., 2018). We mapped a total of fifteen ES following the Common International Classification of Ecosystem services (Table S3 in the Supplementary Material): (1) provisioning services, (2) regulation and maintenance and (3) cultural services (Haines-Young and Postchin, 2017). Provision ES (such as water and biomass provision) were considered as conservation-incompatible due to material extraction necessary to make use of the ES, whereas all other ES (maintenance and regulation ES and cultural ES) were included as conservation-compatible (Schröter and Remme, 2016). ES on flood regulation, carbon sequestration, pollination, soil retention and potential recreational opportunities were produced using the ARtificial Intelligence for Ecosystem Services modelling platform (Villa et al., 2014; Willcock et al., 2018). Those ES that we were not able to map using ARIES due to data availability constraints were derived from direct assignation of the ES capacity to each habitat type based on expert judgement (Burkhard et al., 2012; Burkhard and Maes, 2017). All ES were mapped at the 100 m resolution, re-scaled to range between 0 and 1 and aggregated to the respective PU expressing the average of the data.

2.3.3.3. Habitat types and ecosystem condition. Habitat types were spatially defined at EUNIS level 2 (Moss, 2008). According to the strong causal relationship existing between human pressures and ecosystem condition, we used spatial information on human footprint as a proxy of ecosystem condition (Maes et al., 2018). Human footprint was quantified from SEDAC (2009) for the freshwater realm, and from the spatial distribution of human activities in the study area for the coastal-marine realms. By means of quantiles of the human footprint values, we defined three different ecosystem condition levels. Habitats in the lowest human footprint category were considered at a favourable condition, whereas habitats in the two higher human footprint categories were considered at unfavourable-inadequate and unfavourable-bad condition, respectively. In order to achieve the representation of healthy ecosystems in the GBl, only habitat types at favourable ecosystem condition were included as prioritization features, but degraded ecosystems were used to identify the prioritization restoration areas (see below EBM restoration measures) where EBM measures should be implemented within the GBl (only included in the EBM scenario).

2.3.3.4. Protected areas. In the northern section of the study area we considered Natura 2000 sites, namely the Special Conservation Areas (SCA), Sites of Community Interest (SCI) and Special Protection Areas (SPA), as well as the Coastal Areas of Special Protection as protected areas. In the southern section, we used the World Database on Protected Areas (UNEP-WCMC and IUCN, 2018), including the following sites: biological and ecological interest sites; marine protected areas (OSPAR); national parks; natural monuments, natural parks, nature places, nature reserves, peri-urban protected areas, permanent hunting reserves, Ramsar sites, wetlands of international importance; and specially protected areas of Mediterranean importance (Barcelona Convention).

2.3.3.5. EBM restoration measures. We defined restoration features as those areas where EBM measures can potentially be implemented to improve the current ecosystem condition (i.e., areas with habitats at unfavourable condition). Specifically, we focused on these EBM measures: (1) the restoration and regeneration of riparian buffer strips in farmland habitats, (2) the restoration of wetlands and (3) the restoration of marine habitats (i.e. cold-water corals and seagrass) (see supplementary methods in the Supplementary Material). Restoration features were included as one more prioritization feature (together with biodiversity, ecosystem services, habitat types and protected sites) to be prioritized during the spatial planning analysis in Marxan with Zones (only included in the EBM scenario).

2.4. Spatial analysis

The aggregated probability of occurrence of each species derived from the SDM, the area covered by protected areas and by different habitat types at different ecosystem condition, the averaged value of ES, and the area covered by the restoration features within each PU were included as prioritization features to be targeted in Marxan with Zones. Marxan with Zones uses a simulated annealing optimization algorithm to minimize an objective function. The objective function includes two main components; (1) a measure of the ‘cost’ of the reserve (configuration of PUs) and (2) a penalty when not achieving various criteria (Watts et al., 2009). These criteria included penalties for not achieving targets for the prioritization features and connectivity penalties for missing connections between PUs in the marine and coastal realms, and along the river network in the freshwater realm (Hermoso et al., 2015). Marxan with Zones optimises the spatial allocation of different management zones, and then the design of the GBI, by minimizing the above-mentioned objective function.

Number of runs and iterations per run, feature penalty factor parameter, and bound cost parameters (zone bound cost file in Marxan with Zones) were calibrated in order to determine the most suitable values for our study in terms of target achievement and spatial configuration of the zones (Watts et al., 2009). After calibration, we ran Marxan with Zones 100 times for the different scenarios (10 million iterations each). We set a high species penalty factor (SPF = 100) to ensure the full achievement of targets. Out of the 100 runs we kept the best solution, which was the solution with the lowest score for the objective function, as well as the frequency of a PU to be selected. Due to the differences in connectivity (see below) and PU size, we ran separate models for freshwater and marine-coastal realms that were then combined.

2.4.1. Connectivity across the GBI

Regarding connectivity, in marine and coastal realms, connections between PUs were based on the Euclidean distances among the centroids of pairs of units. In the freshwater realm, connectivity was based on the longitudinal connections between PUs along the river network, by assigning weighted penalties according to this longitudinal distance (Hermoso et al., 2018).

2.4.2. Targets for the prioritization features

The zone target file in Marxan with Zones was used for specifying the contribution of each zone to achieve the biodiversity and ES targets. According to these specifications, the achievement of conservation targets for compatible ES and biodiversity are mainly covered in the core and conservation zones, whereas sustainable use zones will mainly contribute to the achievement of targets for the provisioning ES (Table 2). Target achievement for the restoration features in the EBM scenario was based on Aichi target 15 of the CBD, and target 2 of the EU biodiversity strategy (i.e., restoration of at least of 15% of degraded ecosystems).

2.4.3. Cost-effective allocation of the prioritization features

We considered costs of each PU to be the area covered by the respective PU, assuming that the larger the GBI is the more "expensive" its implementation and management gets. This avoided the overrepresentation of large PUs providing larger contributions towards the achievement of targets just because of a matter of size (Ardron et al., 2010). Area-based PU costs were used in the core zone, conservation zone, and in the sustainable use zone. However, the prioritization of the spatial location of the EBM restoration zone took into consideration the relative restoration costs associated with the different measures in relation to the total area within the PU to be restored. Relative restoration costs have been derived from restoration action costs reported for previous projects and studies collected from the available literature (Table 3). Costs reported in Table 3 were then weighted according to the ecosystem condition of the habitats in the area to be restored, assuming habitats in unfavourable-bad ecosystem condition required larger restoration investments than habitats in unfavourable-inadequate condition.

Table 3
Monetary costs for restoring riparian habitats (based on Natural Water Retention Measures) and for restoring all other habitats Bayraktarov et al. (2016). Annual rates are based on the mean duration of the restoration projects reported by Bayraktarov et al. (2016).

Key habitats	Annual costs/ha (dollars; 2010)
Riparian	187.37
Coral	1,826,651.00
Seagrass	82,140.00
Saltmarshes	31,965.71
Coastal wetlands	35,438.18

2.4.4. Trade-offs between conservation and exploitation goals

The proportion of prioritization features (biodiversity, compatible ES and protected sites) represented within the core and conservation zones was considered an indicator of potential co-benefits between biodiversity conservation and met ES provided by the GBI. Contrastingly, the proportion of prioritization features in the sustainable use zone or outside the GBI (i.e., "available zone" in Marxan with Zones), and the inclusion of provisioning ES in the core and conservation zones were considered as incidental representation. This incidental representation was interpreted as the proportion of prioritization features that would be compromised in the GBI and the proportion of provisioning ES that would be lost due to conservation, respectively (Hermoso et al., 2018).

2.5. Assessment of the conservation and restoration targets met

We checked for differences between scenarios using Kendall's rank correlation coefficient, comparing the selection frequency of PUs (Vallecillo et al., 2018). Since PUs included in the best solution was a binary variable, the degree of consistency between the best solution obtained for each scenario and the selection frequency of PUs (i.e., degree of overlapping between PUs with high frequency of selection and PUs in the best solution) was quantified using Generalized Linear Models (GLM) with binomial distribution and logit link function. The best solution was included as the dependent variable in the GLM models, while frequency of selection was the explanatory variable. In order to quantify differences in consistency among realms, we also included an interaction term between the frequency of selection and the realm (marine or freshwater) as an additional factor in the GLM. All statistical analyses were performed using R (R Development Core Team, 2018).

3. Results

3.1. Targets achieved

For the best solution in the baseline scenario, almost all targets for biodiversity and ES were achieved (the ratio between the amount of the conservation feature held in each management zone and the particular zone target was larger than 1, see Fig. 3). Only protected areas were underrepresented in the core zone according to the targets specified. However, >56% of the study area's aquatic habitats in protected sites were covered under the core zone (26%) and conservation zone (30%) of the best solution, although coastal-marine PUs included <1% of the total marine protected sites. Achievement of targets in the EBM scenario (scenario 2) was very similar to that of the baseline scenario (scenario 1; Fig. 3). According to the baseline scenario, the probability of conflicts between conservation and exploitation goals in the GBI was relatively high, particularly in the freshwater realm, as shown by the high incidental representation of incompatible ES (i.e., provisioning ES) within core and conservation zones (Fig. 4). Similarly, the proportion of prioritization features included in the sustainable use zone was also high. However, the multi-zoning design of the GBI allowed to meet the specified conservation targets within the conservation zones (core and conservation), minimizing the trade-offs between conservation and exploitation goals. Restoration targets specified in scenario 2 were achieved for all the prioritization features in all realms, except for the representation of habitats at poor ecosystem condition in coastal and marine realms, where only about 90% of the 15% target was reached (Fig. 5). The restoration zone of the GBI contained about 15–20% (for marine-coastal and freshwater realms) of the potential biodiversity and compatible ES assets in the study area.

3.2. Spatial configuration of the GBI

According to the best solution of the baseline scenario (Fig. 6), the GBI network in the marine and coastal realms was more spatially

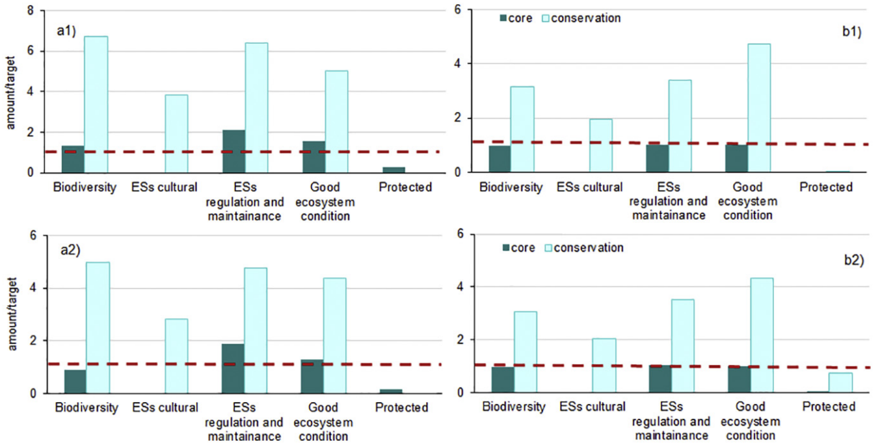

Fig. 3. Targets met for prioritization features as a ratio between the amount of the prioritization features held in the core and conservation zone and the targets specified for the prioritization features (see Table 2). (a1) Scenario 1 (i.e., baseline), freshwater realm; (b1) Scenario 1, coastal and marine realms. (a2) Scenario 2 (i.e., EBM scenario), freshwater realm; (b2) Scenario 2, coastal and marine realms.

aggregated compared to the freshwater realm. For freshwater ecosystems, the optimized GBI successfully connected the study area along the river network of different sub-catchments. The main core area in the marine realm was identified in the Alboran Sea. Regarding the coastal realm, overall the GBI design was patchier along the Spanish shoreline, with larger numbers of core-conservation patches but of smaller size, compared to Morocco. The restoration zone in scenario 2 (i.e., the EBM restoration scenario) contributed to enlarging the initial GBI designed with the baseline scenario, by reducing connectivity costs between core and conservation areas (Fig. 7). Patchiness of the core-conservation zones is therefore reduced in the EBM scenario both in freshwater and in coastal-marine realms. In the baseline scenario, for the freshwater and coastal realms, the best solution of PUs to be contained in the core and conservation zones was relatively consistent with the frequency of selection (Table 4). Consistency between best solution and frequency of selection of PUs was larger in the baseline scenario compared to the EBM scenario. Consistency was also higher for the sustainable zone in both scenarios compared to core and conservation zones (Fig. 8). The most consistent best solution according to the frequency of selection was that for the restoration zone in the EBM scenario. Correlation between scenarios was statistically significant for all zones (Table 5). The highest correlation between scenarios was found in the conservation zone (rank coefficient, tau = 0.40), whereas correlation was very similar for the conservation zone and core zone (Table 5). According to the results for the interaction term between frequency of selection of PUs and the realm, the coincidence of best solution PUs and frequently selected PUs was usually higher in the marine realm, although differences in consistency between realms were not statistically significant in the baseline scenario. In the EBM scenario, however, consistency was significantly higher in both conservation and sustainable zones, but not in the restoration zone. Frequency of selection of the core zone in the freshwater realm was higher in the southern section of the study area compared to the northern section. The sustainable use zone was selected more consistently (i.e., higher frequency of selection) in the coastal realm, than in the marine and freshwater. The restoration zones are dispersed across the whole study area. Nevertheless, they prioritized more PUs with ecosystems in unfavourable status.

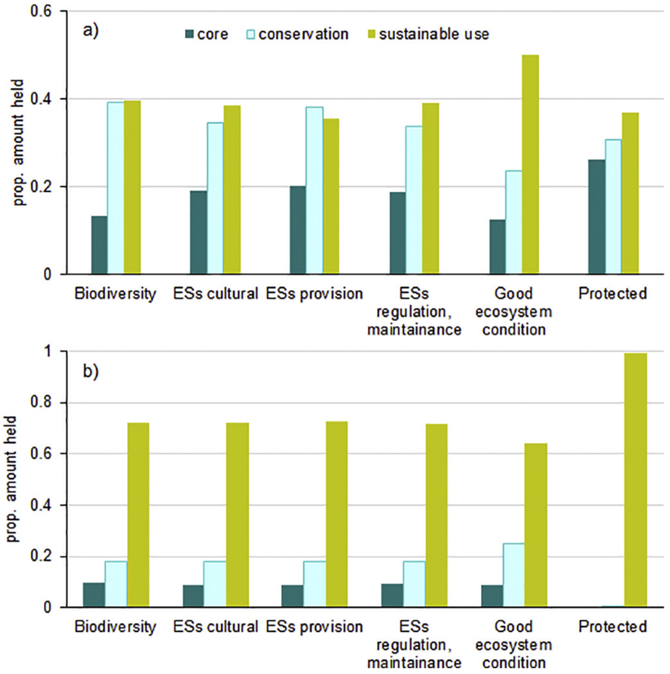

Fig. 4. Proportion of the total amount of prioritization features in the study area contained in the best solution for GBI in scenario 1 (baseline). (a) Freshwater realm; (b) Coast-marine realms.

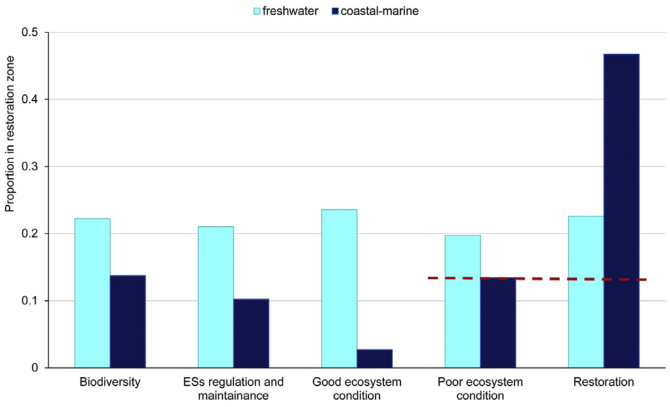

Fig. 5. Proportion of the prioritization features in the restoration zone (freshwater and coastal-marine realms) in relation to the total amount of the features in the study area. Results from the best solution for GBI in scenario 2 (i.e., EBM restoration). Dashed red line: specified targets for restoration prioritization features (i.e., habitats at poor ecosystem condition and sites to be restored). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

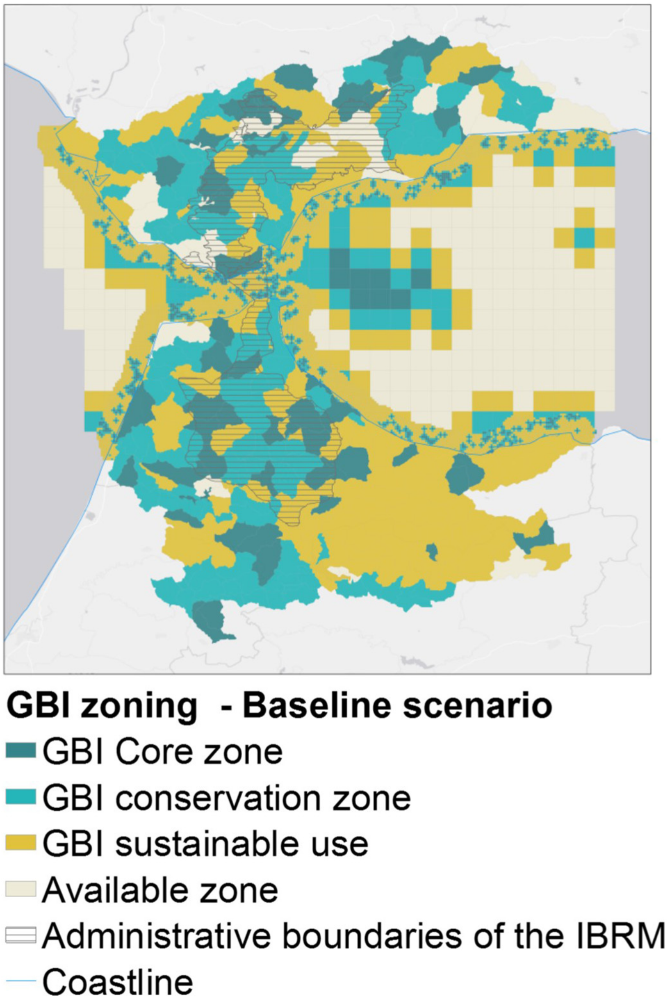

Fig. 6. Spatial configuration of GBI for the baseline scenario.

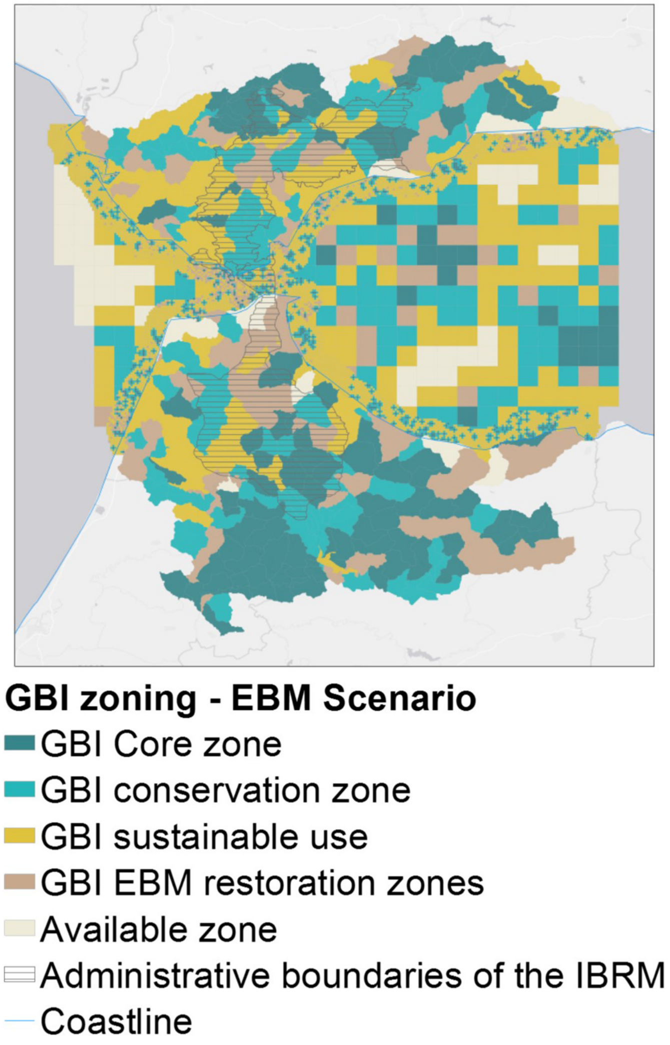

Fig. 7. Spatial configuration of GBI for the EBM scenario.

4. Discussion

Our study showed how restoration measures can be explicitly included in the systematic spatial planning of a multi-zoning GBI by considering restoration measures as additional management features to be represented in the optimal GBI solution (as biodiversity and/or ES do in usual conservation planning designs). Since Marxan with Zones may cope with many different prioritization features, our approach can be implemented in other areas where other biodiversity features, ES and restoration measures are of interest. As far as we know, this is the first study showing a systematic multi-zone approach that combines both conservation and restoration management plans while designing GBI. Although restoration is a key element in GBI designs (European Commission, 2016), existing spatial planning approaches of GBI (e.g. Lanzas et al., 2019; Snäll et al., 2016; Vallecillo et al., 2018) lack an objective and systematic method to allocate different restoration zones, thus the spatial identification of restoration areas have to be based on ex post analyses that did not ensure the cost-effectiveness of the results. As we demonstrated here, restoration zones should be prioritized during GBI design, in order to identify the most efficient spatial configuration of all GBI zones, including restoration zones. In this way, the allocation of any GBI zone (and also restoration areas) depends on the constraints imposed to the other, and the costs of maintaining connectivity are minimized (Hermoso et al., 2018). According to our results, the inclusion of restoration areas affects the cost-effectiveness and connectivity of the GBI solution, supporting our conclusion that the areas to be restored should always be considered during the GBI design process. We also show that systematic planning of restoration areas, in combination with other multiple management zones, may help decision-making towards a GBI design that simultaneously addresses trade-offs and co-benefits emerging between conservation and exploitation goals (Hermoso et al., 2018). The multi-zoning approach ensures the supply of provisioning ES, together with the maintenance of biodiversity (species and habitats) and other regulating and cultural ES. Finally, by including the optimal spatial allocation of restoration measures as an additional zone to be prioritized, we considered not only the current environmental, economic and social conditions in the area, but also the future role of areas to be restored and the prospective improvement of the degraded ecosystems that would take occur following implementation of the restoration measures.

4.1. Connectivity across aquatic ecosystems

Linkages between aquatic and terrestrial ecosystems, or between freshwater and marine ecosystems, involve bidirectional exchanges of water, sediments, nutrients, organic matter, and organisms (Chauvet and Decamps, 1989), thus these ecosystems should not be managed in isolation from each other. In the present study, we address a combined systematic spatial planning of different ecosystem types in an aquatic context. Our approach provides a cost-effective and well-connected spatial GBI design across freshwater, coastal, and marine realms. The resulting design offers a connected network across the aquatic ecosystems in the study area by considering the linear nature of the river

Table 4
Consistency between PUs included in the best solution and frequency of selection of the PUs. GLM results (binomial distribution, logit link), response variable: best solution. Factor levels of realm: marine; freshwater. Nagelkerke R^2 values are provided for each model.

	Estimate	Std. error	z value	p-Value
Baseline scenario				
Core; $R^2 = 0.10$				
(Intercept)	−3.315	0.078	−42.500	<0.0001
freq.core	0.085	0.006	14.012	<0.0001
freq.core:realmmarine	0.012	0.007	1.787	0.0739
Consevation; $R^2 = 0.12$				
(Intercept)	−2.699	0.074	−36.529	<0.0001
freq.cons	0.056	0.003	16.550	<0.0001
freq.cons:realmmarine	0.007	0.004	1.868	0.0618
Sustainable; $R^2 = 0.18$				
(Intercept)	−2.844	0.137	−20.695	<0.0001
freq.sustain	0.053	0.003	15.574	<0.0001
freq.sustain:realmmarine	0.000	0.003	−0.098	0.922
EBM scenario				
Core; $R^2 = 0.08$				
(Intercept)	−3.139	0.078	−40.497	<0.0001
freq.core	0.092	0.006	15.597	<0.0001
freq.core:realmmarine	−0.006	0.007	−0.966	0.334
Conservation; $R^2 = 0.09$				
(Intercept)	−2.690	0.073	−37.048	<0.0001
freq.cons	0.043	0.003	12.661	<0.0001
freq.cons:realmmarine	0.020	0.004	5.125	<0.0001
Sustainable; R2 = 0.22				
(Intercept)	−2.287	0.089	−25.717	<0.0001
freq.sustain	0.031	0.004	8.833	<0.0001
freq.sustain:realmmarine	0.014	0.003	4.517	<0.0001
Restoration; $R^2 = 0.47$				
(Intercept)	−3.861	0.080	−48.420	<0.0001
freq.restor	0.084	0.005	15.366	<0.0001
freq.restor:realmmarine	−0.007	0.005	−1.252	0.211

Table 5
Kendall rank correlation coefficient (tau) between frequency of selection in baseline and EBM scenarios for each zone in the GBI.

	Tau	p-Value
Core	0.29	<0.001
Conservation	0.41	<0.001
Sustainable	0.32	<0.001

network (i.e. the riverine longitudinal connectivity), which is critical to maintain ecological processes in the freshwater realm, as well as between freshwater and coastal-marine realms (Hermoso et al., 2018). The connectivity that ensures the fluxes of nutrients, energy, and materials (including physical, chemical, and biological fluxes) between aquatic ecosystems, are of main importance to maintain the dynamics of these systems and the ecosystem services that they provide (Lamberti et al., 2010). Our comprehensive approach, both in terms of administrative and ecological boundaries, may help to guide the spatial management of aquatic ecosystems as a whole, taking into account the complex interdependencies that exist among different aquatic realms. The results presented here are of particular relevance given the limited number of studies addressing the integration of ecosystem services and landscape planning in aquatic ecosystems (Boulton et al., 2016; Martinez-Harms et al., 2015, but see Hermoso et al., 2018, 2015). This is especially true given the importance of these ecosystems for human well-being (MA, 2005) and according to the increasing global threats to aquatic ecosystems, which risk the future persistence and access to the services that these ecosystems provide (MA, 2005; Vörösmarty et al., 2010).

4.2. Uncertainty in costs and targets

Other authors applying Marxan with Zones for GBI design found that the input parameters used in the analysis, mainly the definition of management zones, costs for the spatial planning units, and targets for the prioritization features, can lead to significantly different spatial solutions in the allocation and extent of the management zones (Hermoso et al., 2015; Vallecillo et al., 2018). This is also a common constraint in other zonation exercises (e.g., Klein et al., 2009; Lanzas et al., 2019). To avoid a design representing an unrealistic management plan, we need well-informed targets, expressing the real conservation and exploitation needs and costs in the study area. To reduce this source of uncertainty in the obtained results, our zoning approach provides a GBI where the stakeholders can specifically define the contribution of each zone to achieve targets for particular prioritization features and objectives. The importance of explicitly considering the expertise and knowledge of stakeholders when planning the GBI (i.e. not arbitrarily fixing objectives and targets) has been previously highlighted by other authors (Lehtomäki and Moilanen, 2013). The focus on restoration presented in our study emphasizes the need of incorporating stakeholder values in the spatial planning process (Bullock et al., 2011). The engagement of stakeholders, such as farmers, livestock producers, manufacturers, as well as local non-profit organizations, may reduce the uncertainty related to planning decisions. Use of participatory processes may also promote the incorporation of other non-environmental planning aspects such as ethical considerations and social justice (Wilson and Howarth, 2002) in GBI design.

4.3. GBI at the Intercontinental Biosphere Reserve of the Mediterranean

According to our results, the possible conflicts between exploitation and conservation goals are potentially high in the study area. Our results

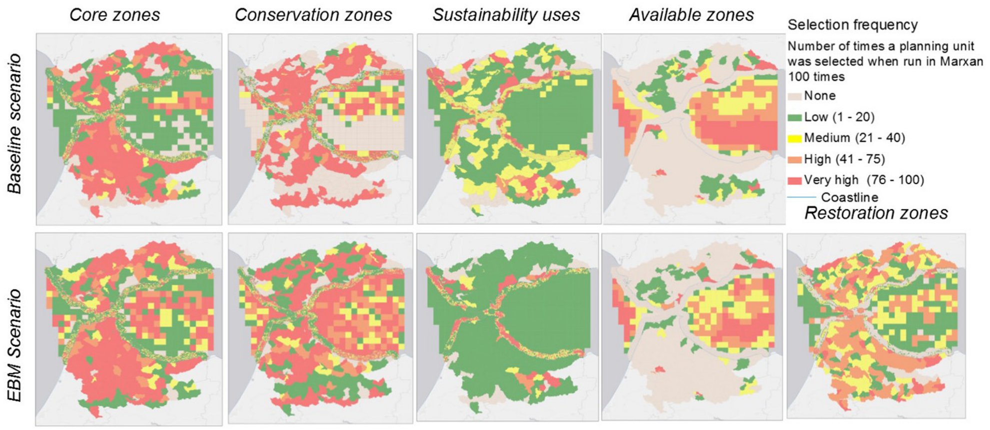

Fig. 8. Selection frequency of the different management zones. Red hues correspond to higher selection frequency. Each figure corresponds to a management zone for the baseline and the EBM scenario. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

also show that the IBRM presents a high potential for the enhancement of biodiversity and ES, according to the large number of areas where ES and biodiversity are high and ecosystem condition is unfavourable-inadequate. However, even if restoration targets were achieved in our GBl design, we should keep in mind that ecosystem restoration of areas that have unfavourable ecosystem condition are unlikely to reach an equal level of good ecosystem status as previously non-degraded ecosystems (Benayas et al., 2009; Schneiders et al., 2012). Therefore, a monitoring of the areas to be restored in the GBl would be highly recommended in order to ensure that the initial design of the GBl is still valid in the future or, if necessary, to modify the design by including new restoration areas or by reinforcing the restoration measures in those areas not completely recovered. However, according to Vallecillo et al. (2018), areas characterized by low human pressure, but with high biodiversity values, exhibit a high capacity to deliver ecosystem services, particularly regarding regulating and cultural services (Chan et al., 2006; Schneiders et al., 2012). Therefore, restoration of these areas is highly expected to enhance ecosystem services provided by the GBl (Vallecillo et al., 2018).

Our results are applicable to both marine and terrestrial conservation planning across three different realms - freshwater, coastal, and marine - allowing for a transboundary and comprehensive management of the study area. The consideration of social and policy requirements in the study area, in the form of objectives and targets guided by stakeholder consultation, increases the applicability of the results. The regional solution proposed here can be taken as a first stage of a nested spatial planning framework where results can be downscaled to a finer local spatial GBI design (Gilliland and Laffoley, 2008). In this study, the same policy objectives have been applied in both northern and southern sections. However, a further improvement would be to assign country and/or river basins specific targets to achieve different policy goals based on country-specific or region-specific policy agendas. Frequency of selection of the planning units highlights the relatively high degree of uncertainty in the GBl design at the IBRM. This uncertainty means that several GBl designs provide equally valid alternative solutions (i.e. with minimum costs). This is a consequence of the high level of incidental representation of compatible ecosystem services observed in the sustainable management zone. However, this is an advantage in terms of stakeholder involvement and management flexibility, since the final GBl design to be implemented in the field can be selected among different minimum cost alternatives, according to overall policy and stakeholder priorities in the study area.

5. Conclusion

We demonstrate that a cost-effective and systematic spatial GBI designation, where restoration efforts, together with biodiversity and ecosystem services, are simultaneously prioritized at the design stage is feasible. Our approach efficiently selected restoration areas that, at the lowest cost, maintain and enhance biodiversity and the provision of one or more ecosystem services. The spatial arrangement of the multiple management zones minimizes the potential conflicts among the conservation, restoration and exploitation goals within GBI, while ensuring connectivity across the network. The approach presented here also shows that different ecosystems can be prioritized simultaneously in an aquatic context, to ensure a cost-effective and well-connected spatial arrangement across freshwater, coastal and marine realms. The flexibility of this approach means the GBI network can be accommodated to the particular requirements of different study areas, since the definition of the management zones, costs, restoration measures and conservation targets can be modified to cope with specific management interests and needs.

The implementation of GBI is one of the most promising actions for adaptation to global change (Ghofrani et al., 2017). In spite of the clear advantages of systematic planning approaches such as the one here presented, analytical and computational methods for this purpose are not yet described within the wide variety of spatial analysis for green infrastructure reported by the European Environment Agency (EEA, 2014). Our approach could help guide future applications of the EU GBI Strategy to address the flexible conservation management that aquatic environments require (DiFrancesco and Tullos, 2014), and could be useful to design GBI in many other areas at different spatial scales and in transboundary ecosystem contexts.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://dataportal.aquacross.eu.

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