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Marine spatial planning to solve increasing conflicts at sea: A framework for prioritizing offshore windfarms and marine protected areas

Boussarie Germain [1,*], Kopp Dorothee [2], Lavialle Gaël [1], Mouchet Maud [1], Morfin Marie [2]

[1] UMR MNHN-SU-CNRS 7204 CESCO, 43 rue Buffon, CP 135, 75005 Paris, France
[2] UMR IFREMER-INRAE-Institut Agro DECOD, 8 rue François Toullec, CS60012, 56325 Lorient Cedex, France

* Corresponding author : Germain Boussarie, email address : germain.boussarie@gmail.com

Abstract :

Direct and indirect anthropogenic pressures on biodiversity and ecosystems are expected to lower the provided ecosystem services (ES) in the near future. To limit these impacts, protected areas will be implemented as part of the Post-2020 Global Biodiversity Framework. Simultaneously, as an answer to climate change, renewable energies are being rapidly developed on a worldwide scale, leading to a significant increase in space use in the coming decades. Sharing space is an increasingly complex task, especially because of the high rate of emergence of such competitors for space. In fisheries-dominated socio-ecosystems, acceptability of offshore windfarms (OWFs) and marine protected areas (MPAs) is usually very low, partly due to an underrepresentation of fisheries in spatial plans and poor attention to equity in the spatial distribution of restrictive areas. Here we developed a framework with a marine spatial planning case study in the Bay of Biscay represented by the socio-ecosystem of the Grande Vasière, a mid-shelf mud belt spanning over 21,000 km2. We collected biological, environmental, and anthropogenic data to model the distribution of 62 bentho-demersal species, 7 regulating ES layers related to nutrient cycling, life cycle maintenance and food web functioning, as well as provisioning ES of 18 commercial species and 82 fisheries subdivisions. We used these spatial layers and a prioritization algorithm to explore siting scenarios of OWFs and two types of MPAs (benthic and total protection), aimed at conserving species, regulating and provisioning ES, while also ensuring that fisheries are equitably impacted. We demonstrate that equitable scenarios are not necessarily costlier and provide alternative spatial prioritizations. We emphasize the importance of exploring multiple targets with a Shiny app to visualize results and stimulate dialogue among stakeholders and policymakers. Overall, we show how our flexible, inclusive framework with particular attention to equity could be an ideal discussion tool to improve management practices.

Highlights

► We present a spatial planning approach to prioritize protected areas and windfarms ► We provide a methodological framework and a shiny app with attention to flexibility ► We include biodiversity, ecosystem services, fisheries, and offshore windfarms ► A case study is discussed, the Grande Vasière socioecosystem in the Bay of Biscay ► Accounting for equity for historical stakeholders, here fisheries, is not costlier

Keywords : Marine spatial planning, Biodiversity, Ecosystem services, Offshore windfarms, Marine protected areas, Fisheries

1. Introduction

Under current global management scenarios, the competition for space is expected to surge in the near future. Spatial planning is becoming more and more essential because sharing the once-considered-free space is now necessary between traditional and emerging activities.

On one hand, with contemporary stakes of global warming and the necessity of energy self-sufficiency, renewable energy is expected to skyrocket in the coming decades (United Nations, 2015; European Commission, 2019). As a response, the scale of global development strategies is important, with for instance 180 GW to be developed before 2050 in France, with 100 GW in solar panels, 40 GW in terrestrial windfarms and 40 GW in offshore windfarms (OWFs) (Ministère de la Transition Énergétique, 2022). Although these technologies will surely evolve, at present this roughly corresponds to 8,000 km² for offshore windfarms. It therefore arrives as a major actor and competitor for space use. Governments are now pushing for expeditious renewable energy development, sometimes with little concern for the repercussions on biodiversity, ecosystem services (ES), or potential drawbacks on the activity of historical stakeholders. Rapid implementation of renewable energy parks (*e.g.* solar panels, windfarms) could lead to non-optimal scenarios where stakeholders find the projects unacceptable, and key areas for biodiversity and ES are neglected. The main problem for stakeholders is that these renewable energy parks are not always compatible with other activities, notably at sea where extractive activities are limited inside the delimited perimeter of windfarms. This is especially the case for floating offshore windfarms that consist in a network of subsurface chains and cables, rendering ship cruising in the perimeter hazardous. As a consequence, the regulatory framework is very strict, consisting in spatial restrictions for a majority of activities.

On the other hand, climate change (Gattuso et al., 2015; Lotze et al., 2019), overexploitation (Jackson, 2001) and destruction of vulnerable habitats are putting tremendous pressure on the natural environment, leading to an urgent need for protection (Lotze and Worm, 2009; McCauley et al., 2015). Efficient protection can be attained, among other measures, via spatio-temporal restrictions of impacting activities *i.e.* by implementing and enforcing protected areas (PAs) (Davidson and Dulvy, 2017; Jacquemont et al., 2022). At sea, the United Nations, the European Union, and France in particular (our case study), have adopted this strategy that has proven efficient in many ecosystems, notably for the protection of vulnerable habitats and species not under quota management, when restrictions are added to the marine protected area (MPA) status (Edgar et al., 2014). While the restriction of activities even inside strict MPAs is still debated and a subject of conflict, historical stakeholders must prepare for future restrictions, especially in coastal seas. Indeed, MPAs are at the center of environmental objectives with targets of 30% of sea surface under protection by 2030, and 10% of the surface under strict protection ('Bringing nature back into our lives', EU Biodiversity Strategy for 2030, European Commission, 2020).

In marine environments, these two rising stakes are gradually adding to the already complex maritime space management, cumulating both unique and common issues from professional fishing, aquaculture, natural resources extraction, recreative activities and strategic zoning for transport and military purposes. Spatial protection of the environment and marine renewable energies are fiercely opposed by fishermen, especially because management plans can be unilaterally implemented, without accounting for activities already in place, either incompletely or sporadically (Chollett et al., 2022; Psuty et al., 2020). Although many efforts are deployed to account for these oppositions and minimize the impacts of emerging activities on fishing and on biodiversity, the risk of ocean grabbing is looming (Bennett et al., 2015; Queffelec et al., 2021) and the plurality of human, political, biological, and environmental stakes render the complexity of decision-making unprecedented.

For this, decision-support tools (DSTs) for marine spatial planning (MSP) (Frazão Santos et al., 2018; Pınarbaşı et al., 2017) are widely used by science and conservation communities for prioritization and optimization of space. These software-based tools, which have usually been developed for simulative and analytical purposes, are not yet systematically used in the decision process by MSP practitioners (Janßen et al., 2019). According to Janßen et al. (2019), stakeholders perceive DSTs as overly complex or untrustworthy. One of the reasons of this scepticism could be that often, professional fishing activities are only accounted for by a single metric of total cost, neglecting the plurality of fishing fleets (Box 1) and their territoriality (Chollett et al., 2022). Moreover, to extend the use of DSTs in MSP processes by authorities and stakeholders, it must be inclusive, socially fair, and flexible:

- Inclusive, by involving stakeholders as early as the data collection step, verify the pertinence of the chosen indicators, and to provide useful information on their activities (*i.e.* segmentation, coherence of data) to improve the planning process (Kockel et al., 2020; Pomeroy and Douvere, 2008).
- Equitable, by considering not only the most lucrative activities but also the diversity of actors (Trouillet, 2020). Also by focusing on a proportion of activity decrease and not a loss in value (Flannery et al., 2018; Frazão Santos et al., 2021; Kockel et al., 2020).
- Flexible, because MSP is an iterative process, constantly evolving with the flow of discussions, and because objectives and targets can be subject to different interpretations. For instance, environmental protection objectives are defined at the global scale of nations (10% surface). The repartition of protection could however be balanced between habitats or ecosystems based on given criteria (*e.g.* biodiversity representation, Jetz et al., 2022). Also, studying the variability of MSP results depending on the degree of equity of scenarios or on targets' values would lead to interesting questions, to understand the possible consequences of future management plans. Flexibility is therefore key in MSP, but is often a neglected aspect, mainly because of the complexity of scenarios and the number of possibilities offered if too many parameters are variable.

Here, we developed an MSP approach meeting these conditions of inclusivity, equity, and flexibility. The first step consisted in defining a set of indicators related to human activities, ecosystem services, and biodiversity in consultation with at least one stakeholder from each category of activity (Supplementary Table S1). Then, we collected and mapped the related data. We used these numerous spatial layers with a systematic conservation prioritization DST with multiple types of zones to both account for incompatibilities between activities and their varying impacts on the ecosystem. Finally, we present a Shiny app to visualize, study and discuss results associated with multiple varying targets. We present this framework with the extensive case study of the Grande Vasière (GV), a major socioecosystem with marine renewable energy development (MRED), biodiversity, ES and fisheries stakes, encompassing 21,000 km^2 in the Bay of Biscay. We collected biological, environmental, and anthropogenic data to model the distribution of 62 bentho-demersal species, 7 regulating ES layers related to nutrient cycling, life cycle maintenance, and food web functioning, as well as provisioning ES of 18 commercial species and 82 fisheries subdivisions. We used these spatial layers to explore different siting scenarios: (i) two scenarios with the development of OWFs only, with and without accounting for equity, and (ii) a scenario with OWFs alongside two types of MPAs (benthic and total protection) aimed at conserving species, regulating and provisioning ES, while also ensuring that fisheries are equitably impacted.

2. Methods

2.1. General overview of the prioritization framework and scenarios

The framework presented here can be applied to any spatial planning study relying on a DST (Fig. 1). Box 1 encapsulates the definitions of the concepts used. Features belong to one of three categories: human activities, ecosystem services, and biodiversity (each taxon represented by one feature). Each unique combination of targets constitutes a set of targets. One of the novelties in this study's framework comes from the ability to test multiple sets of targets in a prioritization scheme, corresponding to different scenarios and tuning of parameters and targets. After choosing the types of zones (*e.g.* renewable energy, economic, multi-use, recreational, partial or total protection) and features that one wants to include in the prioritization process, we propose to organize multiple sets of targets and batch-compute solutions using an optimization algorithm (*prioritizr*, Hanson et al., 2019). After obtaining multiple sets of solutions, one can directly visualize and present the results in a Shiny app.

In the following sections, we develop how we chose and obtained the spatial layers included in our case study (*i.e.* the features). Then, we expose the technical aspects of the prioritization itself, and present the visualization tool.

To highlight the different possibilities offered by this framework, we developed two prioritization cases, one with only MRED objectives (two types of zones) and one with MRED, ES, and biodiversity conservation objectives (four types of zones). To understand the cost and consequences of accounting for equity in spatial planning, we declined the first case in two scenarios, with and without setting targets for features related to fisheries.

Box 1

Important definitions of concepts used throughout this study

Decision-Support Tools (DSTs): '*software-based intermediaries that provide support in an evidence-based, decision making process*' (Rose et al., 2016; Pınarbaşı et al., 2017).

Ecosystem services (ES): '*benefits provided by ecosystems that contribute to making human life both possible and worth living*' (Díaz et al., 2006).

Fishing fleet: a homogenous group of vessels defined by criteria specific to each study. Here, fishing fleets are defined by various parameters: common management systems and stakes, types of gear used, fishing periods and target areas, as well as catch composition and regional attachment.

Feature: here generalized from biodiversity feature or conservation feature to also match with ES and human activities. Corresponds to a spatial layer that we use as input in the DST, usually to set targets to protect this feature (Ardron et al., 2010).

Feature's score: the amount or percentage of feature that is protected in a given solution (*i.e.* prioritization output). This score can be higher than the associated target.

GPFs (gear-port-fleets): subdivisions we used to represent fisheries activities, corresponding to groups of vessels delineated by their belonging to a given fishing fleet, port, and the type of gear used.

Marine Spatial Planning (MSP): '*an integrated planning framework that informs the spatial distribution of activities in and on the ocean in order to support current and future uses of ocean ecosystems and maintain the delivery of valuable ecosystem services for future generations in a way that meets ecological, economic and social objectives'* (Foley et al. 2010).

Ocean grabbing: '*dispossession or appropriation of use, control or access to ocean space or resources from prior resource users, rights holders or inhabitants*' (Bennett et al., 2015).

Planning Units (PU): space units resulting from the subdivision of the study area. They can be of diverse shapes and sizes. Here for instance, we used 3,372 pixel-like PUs (squares) of 2.5 by 2.5 km.

Scenarios: groups of prioritization runs based on hypotheses. For instance, two distinct scenarios constitute the MRED-only prioritizations: accounting for or ignoring equity.

Targets (quantitative): their value corresponds to the minimum amount of the associated feature to protect. In this study, if not all targets can be reached, no solution is provided by the algorithm. Additionally, a **set of targets** is the combination of all targets' values associated to one run of DST, therefore to one best solution.

Zone contribution to reaching the targets: proportion of the features' values considered protected inside a given PU if this PU is attributed to a given type of zone. This value depends on both the type of zone and the feature.

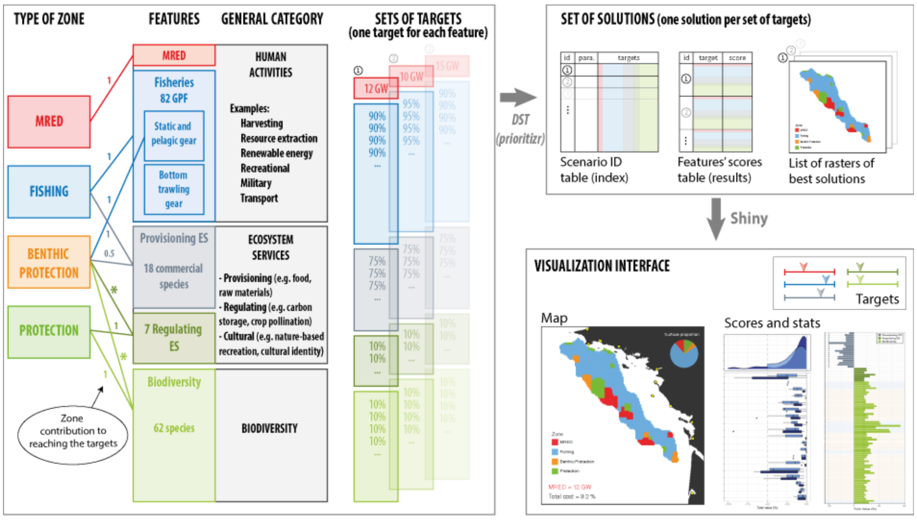

Fig. 1. Overview of the prioritization framework. After defining the different types of zones and spatial layers constituting the features, sets of targets are chosen and used as input in *prioritizr* to obtain a set of solutions. This set of solutions, constituted of an index table, a results table and a list of rasters containing the best solution for each set of targets, is then used in a Shiny app to modify on-demand the sliders corresponding to targets and visualize the results (map and associated scores and statistics). Stars indicate that the zone contributions to reaching the targets are variable depending on the feature.

2.2. Spatial prioritization analysis

2.2.1 Study area

The Grande Vasière (GV) is a mid-shelf mud belt spanning over more than 21,000 km^2, located in French waters of the Bay of Biscay (northeastern Atlantic). This area is renowned for its bentho-demersal ecosystem, providing key regulating and provisioning ES. The mean total yearly landings associated with bentho-demersal species in the GV is equal to 68.6 M€ during the studied time frame (2013-2020). Important spatial planning stakes are also emerging in this area, designated as a priority area for offshore windfarms development (French Ministry of Ecological Transition, 2019).

For spatial prioritization purpose, we split the GV in 3,372 planning units (PUs), measuring 2.5 by 2.5 km (*i.e.* 6.25 km^2), based on the spatial resolution of environmental data. All the following datasets have been processed at this spatial extent and resolution, therefore obtaining spatial layers that contain one value of the given dataset for each PU.

2.2.2. Type of zones and associated costs

We defined four types of exclusive zones, meaning that each planning unit can only be attributed to one type of zone by the prioritization algorithm. The 'MRED zone' is a theoretical zone in which priority is given at floating offshore windfarms development. The 'fishing zone' does not restrict any fishing activity. The 'benthic protection zone' only permits the use of static and pelagic gear, as opposed to bottom trawling gear, whereas the 'protection zone' restricts all extractive activities, comparable to a no-take MPA.

The cost in prioritization algorithms like Marxan (Ball et al., 2009), Marxan with Zones (Watts et al., 2009), Zonation (Moilanen et al., 2005), or here *prioritizr* (Hanson et al., 2019a) is a spatial layer representing either the actual cost of implementing for instance protected areas (*e.g.* costs of functioning and enforcement), or a surrogate if the actual cost is not known (Ban and Klein, 2009). This cost layer can also represent the loss of revenue ('opportunity cost') associated to the restriction of activities in the newly created zones for a certain group of actors, usually historical users and farmers in land spatial planning (Strassburg et al., 2019), or fisheries in marine environments (Chollett et al., 2022; Mazor et al., 2014; Yates et al., 2015). When using Marxan with Zones or *prioritizr* with multiple zone types, one spatial layer of cost per type of zone is to be defined. In our case, we defined the cost layers for the MRED zone and the protection zone as the total yearly landings value, all fisheries taken together. On the contrary, attributing a PU to the fishing zone has no cost because all activities are allowed. The cost layer corresponding to the benthic protection zone is equal to the sum of all yearly landings value of fisheries using bottom trawling gear, as the latter is theoretically prohibited in this type of zone.

2.2.3. Features, targets, and zones contributions to reaching the targets

In this case study, we chose to vary the target values inside each feature's category uniformly, for the sake of equity, and because the number of different combinations is considerable. However, selecting different values for each target is technically possible but only discussed in this study.

Some of the models and spatial layers presented here were computed for both this study and another article. A more detailed description is thus available in Lavialle et al. (submitted).

2.2.3.1. Biodiversity

We defined five categories of features (Fig. 1). First, the biodiversity category corresponds to the conservation of bentho-demersal species, each target being a percentage of the total number of individuals on the GV.

We used biological data from two yearly scientific surveys (LANGOLF-TV from 2014 to 2018 and EVHOE from 2013 to 2019, Supplementary Fig. S2) along with environmental data to model the number of individuals per PUs for these bentho-demersal species. LANGOLF-TV is an underwater video survey conducted by towing a sledge equipped with a camera along transects. Videos of 7 minutes were analyzed to count individuals of various taxa. EVHOE is part of the International Bottom Trawl Survey (ICES 2015) and consists in 30 minutes hauls at 3.5 knots with a '*Grande Ouverture Verticale*' demersal trawl. The two sampling methods give different snapshots of relative abundance, duplicated for some taxa but not all, the two surveys having different taxon-specific capturabilities. Among the detected fauna, we selected 62 taxa that were observed on at least 30 stations and at least half of the sampling years (Supplementary Table S3). Such thresholds were chosen to feed enough data points to the model fitting procedure and to filter species subject to false zeros (species often present but observed only one year due to specific conditions). When both surveys were selected for a taxon, we chose the more appropriate in terms of capturability by expert knowledge (*e.g.* LANGOLF-TV for *Nephrops norvegicus*). For each taxon, we then fitted Generalized Linear Models with spatial covariance structure (GLMMs), and ordinary kriging with external drift on years.

Predictors for GLMMs were the following: depth, current speed, temperature, sediment type, and roughness for environmental variables, and gillnet and bottom trawl fishing time for anthropogenic predictors (Lavialle et al. submitted). We then chose for each taxon the modelling method with the best predictive performance, measured by a Monte Carlo cross-validation procedure, complemented by a visual examination of the results (Supplementary Table S4). More details on models are available in Lavialle et al. (submitted). Biodiversity features were thus represented by 62 individual spatial layers of relative abundance with a number of individuals modelled for each PU (Supplementary Fig. S5). These biodiversity layers also served as base layers to obtain some of the regulating ES layers, for which the number of individuals per PU has been converted in total biomass by using mean wet weights for each species available from the EVHOE dataset, except for two taxa from LANGOLF-TV for which this value was not in the EVHOE dataset. We considered the mean net weights available for these species from the literature: 20g for *Pennatulacea* (Murillo et al., 2018) and 18g for *Spirographis* spp (Currie et al., 2000).

Only the benthic protection and protection zone contribute to reaching the conservation targets: we set the zone contribution to 1 for the protection zone, and to either 0.95 for species mainly impacted by bottom trawling, or 0.5 for the others (expert knowledge). There can be debate regarding the MRED zone which could have a potential positive reserve effect or a negative effect due to chains dragging on the seafloor, but little is known on the impacts of floating offshore windfarms on the different species. Being conservative in our approach, we chose to set to 0 the contribution of the MRED zone to the conservation of all species.

2.2.3.2. Regulating ecosystem services

Another category of features is the regulating ES category. The associated targets correspond to maintaining a percentage of the total value for each spatial layer. We considered seven regulating ecosystem services provided by the GV socioecosystem, subdivided into three main categories: food web functioning, nutrient cycling and storage, and life cycle maintenance.

- *Food web functioning:* Prey-predator overlap is an important regulating ES as a proxy of energy transfer through predation. We approached it with Pianka's index (Carroll et al. 2019) corresponding to a measure of the biomass-weighted encounter rate between each trophic group of prey and predator. To do so, the Ecopath trophic boxes from Corrales et al. (2022) were used to assign taxa's biomass to trophic groups. We then weighted each Pianka's index by the proportion of a given prey in the diet of a given predator, before averaging it over all preys and predators. The second ES related to food web functioning that we considered is the trophic links diversity ES. A high trophic links diversity in the food web sustains its stability (Rooney and McCann, 2012). To estimate this ES, we computed a Shannon's index of predator-prey trophic links, replacing the relative proportion of species by values of Pianka's encounter rate.
- *Nutrient cycling and storage:* We considered three regulating ES related to nutrient cycling and storage: bioturbation, filter feeding and carbon storage. For bioturbation, we computed the BPc index defined by Solan et al. in 2004 in each PU by summing the BPc value from each taxon occurring. Associated parameters for each taxon were defined from the literature (Queirós et al., 2013) or by expert knowledge for *Cancer pagurus*, *Cepola macrophthalma* and *Gastropteron rubrum*. We

approached the filter feeding ES by summing the modelled abundance of filter feeding taxa: Actiniaria, Alcyonacea, Crinoidea, Hydrozoa, Pennatulacea and *Spirographis*. Finally, we estimated the carbon storage potential by attributing scores to different sediment types, based on granulometry: from 0 with rocky substrates to 7 with mud composed of silt and clay (Garlan et al., 2018).

- *Life cycle maintenance:* We identified two regulating ES related to life cycle maintenance provided by the GV: hake nurseries and sale spawning grounds. For the first, we modelled juvenile hake (*Merluccius merluccius*) abundance using the same method employed for other taxa (described in section 2.3). However, instead of using all individuals, we used only the abundance of individuals smaller than 42.85 cm (L50 in ICES, 2016). For the second, we used monthly sole (*Solea solea*) biomass rasters computed with Bayesian models in Alglave et al. (2022, 2023), combining scientific survey and commercial catch, only between February and March, period identified in the literature as the spawning period in the area (Koutsikopoulos and Lacroix, 1992; Mahe et al., 2006; Petitgas, 1997). We then applied the Net Persistence Index (NPI) adapted from Colloca et al. (2009) and Milisenda et al. (2021) to identify hake nursery and sole spawning grounds that are consistent over multiple years. We kept only positive values of both NPI layers to only focus on hotspots.

The protection zone contributes to reaching all of these regulating ES targets, but the contribution of the benthic protection zone has been set to 0.5 for 6 of the 7 regulating ES (Fig. 1). For carbon storage though, we considered that bottom trawling being restricted in this type of zone, attributing a PU to the benthic protection zone contributes at 100% to reaching its target. More information would be needed to assess the impact of stationary gear on carbon storage.

2.2.3.3. Provisioning ecosystem services

The third category is the provisioning ES category, each feature corresponding to provisioning of a commercial species. Maintaining such food provisioning is crucial for people and industries relying on it (*e.g.* markets, canning factories, restaurants, and food industry). It is important to note that we aimed at maintaining the provisioning ES through the maintenance of the value extracted from it, regardless of the resource's stock and its sustainability. Resources' stocks are indirectly protected by conserving the biodiversity and regulating ES features in this study, as well as other management measures (*e.g.* total allowable catch). Each target therefore corresponds to the maintenance of a percentage of yearly landed value of a given species or group of species. Based on expert knowledge from fisheries committees, a representative of a producer's organization and two fisheries scientists that we interviewed, we selected 18 commercial species or groups of species, representing 96% of the French bentho-demersal turnover from the GV. The provisioning ES features therefore consisted in 18 individual spatial layers of turnover mean values over 2016-2020 from vessels of more than 12 meters in length (obtained through the Sacrois algorithm, 2022).

While the fishing zone fully contributes to reaching such targets, we stated that attributing a PU to the benthic protection zone contributes at 50% of its value to reaching the target (Fig. 1).

2.2.3.4. Territoriality and diversity of fleets

The GV constitutes a fishing area for a diversity of métiers, landing in a dozen of ports in the Bay of Biscay. To explore the inclusion of territorial and socio-economic equity in the MSP process, we segmented the fishing activities into fishing fleets (Box 1), landing ports and gear used (bottom trawling gear *vs.* static and pelagic gear), resulting in gear-port-fleet subdivisions (hereafter GPF). Subdividing by fishing fleet allows to measure the consequences of planning scenarios at the scale of the whole economic activity of a group of fishing vessels, compared to métiers which consider only a fraction of their activity. Our definition of fishing fleets was inspired by Lavialle et al. (2014) and updated with the help of fishermen representatives and scientific experts (Supplementary Fig. S6). We excluded the fleets with low dependance on the GV (less than 5% turnover) and the ones constituted of less than three vessels. Purse seine has also been excluded because of known problems to spatialize fishing effort with VMS data. For each of the 19 fishing fleets identified, we selected the landing ports representing 95% of their turnover, resulting in the selection of 12 ports.

Each feature from the fisheries category thus corresponds, for a given GPF, to spatialized turnover mean values over 2016-2020 from vessels of more than 12 meters in length (obtained through the Sacrois algorithm, 2022).

Each associated target is defined as a percentage of maintained yearly landings value. The 82 GPFs fall into two categories with different restrictions in the benthic protection zone: static and pelagic gear (n = 46) *vs.* bottom trawling gear (n = 36). Allocating PUs to the fishing zone contributes to reaching all the GPF targets, while allocating them to the benthic protection zone only contributes to reaching the ones associated with static and pelagic gear (Fig. 1). We hypothesize that no fishing activity is compatible with floating OWFs comprised of a network of subsurface cables.

2.2.3.5. Marine renewable energy development (MRED)

The MRED feature corresponds to the implementation of OFW, the associated target being a number of GW to be deployed in the GV. This power in GW is directly approximated by a surface in km^2. According to current OWF projects, 1 GW corresponds to 200 km^2 in surface (32 PUs), but this can be subject to potential changes in the future. Most of the GV area has a high potential for OWFs development due to favorable wind conditions and suitable depths. Indeed, it has been defined by the French Ministry of Ecological Transition in 2019 as a priority zone for MRED and especially OWFs. Only the northwestern part of the GV is less suitable because of high swell potentially incompatible with the implantation of OWFs, but this area is already part of an exclusion zone due to military and shipping activities (Supplementary Fig. S4). In Europe, 300 GW are to be installed in 2050, and in France, the potential for OWFs has been estimated between 49 and 57 GW (European Commission, 2020). A target has been announced at 40 GW in 2050 by the French President in February 2022 in Belfort. A previous document has estimated that 60% (30 out of 50 GW) of the potential is located in the Bay of Biscay (FEE, 2021). If half of 60% of the 40 GW goal was to be developed in the GV, it would lead to the target of 12 GW of OWFs in the GV. Attributing PUs to the MRED zone contributes to reaching the MRED target.

2.2.4. Parametrization

We set *prioritizr* with the Gurobi solver (Gurobi Optimization, 2019; Hanson et al., 2019b) to reach all targets at a minimal cost, using the add_min_set_objective function, meaning that no solution is given by the algorithm if a single target cannot be reached. The best solution was retained for each set of targets, corresponding to the less costly solution. Moreover, as solutions with numerous small areas consisting in single or few PUs are not relevant for management, we arbitrarily set a penalty (equivalent to the boundary length modifier – hereafter BLM – in Marxan) using the add_boundary_penalties function, basically adding penalties to avoid the selection of fragmented biodiversity protection/MRED zones. As fragmentation of solutions depends on the number of zone types, BLM was set to 100,000 for the MRED only scenario, and to 150,000 for the MRED, ES and biodiversity scenario. The values were chosen as a tradeoff between overall cost and solutions' fragmentation, but this is among the parameters that are flexible (see Supplementary Fig. S7 for solutions for multiple BLM values). We accounted for the regulatory exclusion zones for MRED with the add_manual_locked_constraints function. Existing or upcoming projects for MRED or MPAs can be added in a same way, by using spatial layers of inclusion/exclusion as inputs.

2.2.5. Batch processing

The goal of our framework is to test multiple combinations of target values to visualize, compare and discuss solutions depending on their cost, equity, outcomes, and other aspects. Each combination consists in a set of targets (Fig. 1), and the range and increment of values is totally up to the user. In our example, we set the MRED targets for all scenarios ranging from 1 to 15 GW in a 0.5 GW increment. Fisheries targets were set to 80%, 85% and 90% for the scenario with MRED, ES and biodiversity targets, and a target at 95% was added for the MRED-only scenarios. This latter target proved too constraining for the full scenario, leading to no solution or excessively fragmented solutions. Provisioning ES targets were arbitrarily set to 75%. Biodiversity and regulating ES targets were set to 10%, linked to Aichi Target 11. We chose *prioritizr* as a more computationally efficient prioritization algorithm than Marxan with Zones – thus more time effective – which is not negligible when batch-computing a high number of scenarios and different sets of targets. We ran *prioritizr* in parallel with the *future.apply* package (Bengtsson, 2021) to minimize computation time.

We stored the best solution for each set of targets inside three objects (Fig. 1): (i) a scenario ID table comprising the values for parameters and targets, permitting the identification of each run by a unique combination, (ii) a features' scores table containing the ID and scores achieved for each feature (*e.g.* 18% conservation for a given species, 12% for a given regulation ES, 97% for a given GPF) and (iii) a list of rasters for spatial statistics and visualization of results as a map.

2.3. Visualization of results with Shiny

We developed a code on Shiny (*https://shiny.rstudio.com*) to provide a visualization tool, comprised of different panels (Fig. 1): (i) a panel with sliders corresponding to the targets, in which users can independently change the values; (ii) a map of the best solution for the user-defined set of targets containing the distribution of the different types of zones inside the GV, along with diverse information such as total cost and surface proportions inside each type of zone; (iii) a panel with scores and statistics presented as figures (one related to fleet-ports features and the other related to ES and biodiversity). Users can therefore directly vary the target values with the sliders and observe in real time the consequences of their choices. This code uses as input the three objects obtained in the previous step to quickly get the corresponding ID number in the scenario ID table based on the combination of values chosen by the user (Fig. 1). It then plots the results based on the scores stored in the features' scores table, as well as the corresponding map from the list of rasters. The code is accessible on the GitHub Repository: [https://github.com/gboussarie.](https://github.com/gboussarie)

3. Results

3.1. Equity does not necessarily come at a high price

We show that accounting for equity with 95% GPF targets (maintenance of revenue for each) is not detrimental to the total cost for professional fishing. Indeed, the difference of opportunity cost between the MRED scenarios, with and without GPF targets is low in the studied range of MRED targets (Fig. 2). More precisely, at 12 GW, the cost difference is equal to 0.1% of the total cost (respectively 4.2% and 4.3%; Fig. 3A *vs.* 3B). Such difference is negligible at the scale of the entire professional fishing sector. Above 12 GW, this difference in cost is rising (Fig. 2), but with a maximum difference of 0.9% of the total cost at 15 GW (5.7 *vs.* 6.6%).

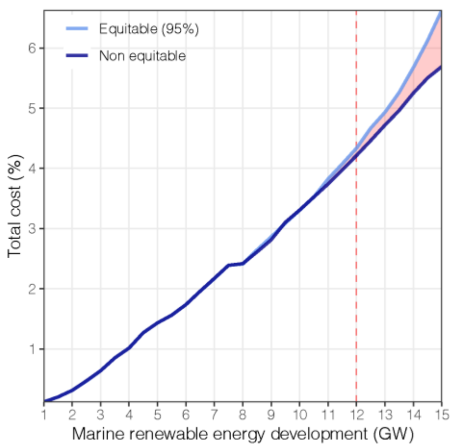

Fig. 2. Total cost of prioritization for the MRED-only scenarios (in percentage of total yearly landings value) as a function of MRED target, without accounting for equity (dark blue) and accounting for equity (light blue, 5% maximum in yearly revenue loss for each GPF). The red area represents the cost difference between the equitable and non-equitable scenarios. The dashed vertical red line corresponds to a 12 GW target, presented in Fig. 3 and 4.

However, as expected, the repartition of opportunity costs among GPFs is different in the scenarios with and without GPF targets (Fig. 4). In this example with a 12 GW target, some GPFs are more heavily impacted than others by the spatial restrictions of MRED areas under the scenario not constrained for equity. Several are particularly impacted, suffering a loss of more than 5% in yearly revenue, while others suffer less than 1% loss.

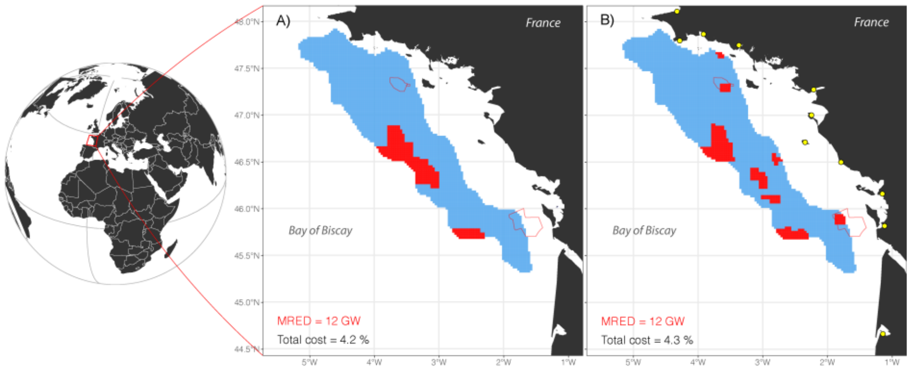

Fig. 3. Maps showing the best solution for each of two scenarios, with blue PUs in the Fishing zone and red PUs in the MRED zones: A) a basic scenario with only MRED as target and B) an equitable scenario with 82 GPF targets (5% maximum in yearly revenue loss). MRED targets for both scenarios were fixed at 12 GW in OWF development. Total cost was computed as a proportion of total yearly landings value. Red lines delineate the current OWF requests for proposals overlapping the GV. Yellow dots in B) represent the landing ports linked to the GV, associated with the GPF targets (except for Spain, not represented).

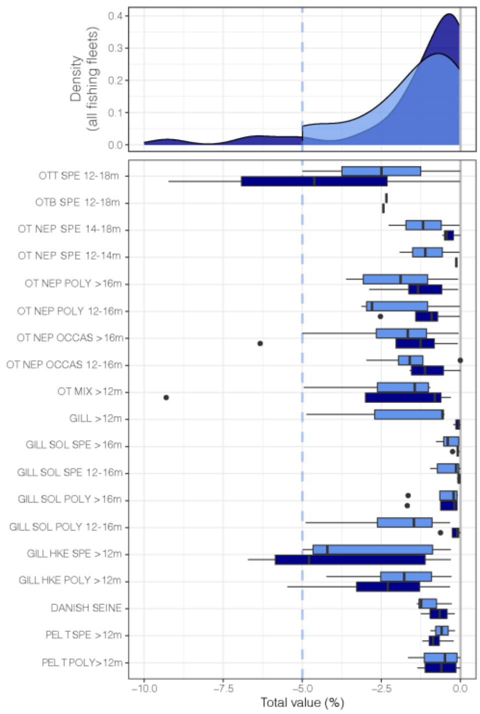

Fig. 4. Density plot and proportions of fishery features lost in MRED zones by scenario, with (light blue) and without (dark blue) GPF targets. The target of 5% maximum of yearly revenue loss per GPF is represented by the

dashed vertical line. Each pair of boxplots corresponds to a single fleet, and values constituting the boxplots represent the corresponding GPFs.

3.2. Accounting for territoriality and diversity of fleets can lead to alternative prioritizations

Accounting for equity leads to different spatial outcomes. Comparing the repartition of prioritization areas in the best solutions of the scenarios with and without GPF targets, we observe very different siting of MRED areas (Fig. 3A *vs.* 3B). Indeed, for nearly the same cost, the first scenario suggests two wide areas (1,994 km^2 and 406 km^2), whereas the equitable scenario suggests 8 smaller areas more evenly distributed along the coast (ranging from 56 km^2 to 1,038 km^2). Interestingly, two of the suggested MRED areas are currently overlapping with OWF requests for proposals (AO5 and AO7).

3.3. Prioritization with MRED zones and MPAs in the GV

Bringing MPAs in the balance with the conservation of 10% of each species and regulating ES leads to a solution with partial or total restrictions of activities inside more than 25% of the surface of the GV (Fig. 5). The total cost of such prioritization is of 9.1% of the total yearly landings value, and less than 10% of yearly landings value for each GPF (10% maximum loss targets).

This best solution suggests 4 MRED areas (Fig. 5), including one inside a current request for proposals (AO7). This request for proposals has already been postponed to widen the area and push it more offshore. Moreover, the obtained solution shows a network of 8 total MPAs and 4 benthic MPAs, possibly biologically connected and scattered all over the GV. However, the overlap with the already existing network of MPAs (in which no restrictions of activities are yet implemented) is weak, highlighting a mismatch between these and our optimal prioritized areas for biodiversity and regulating ES conservation for this set of targets.

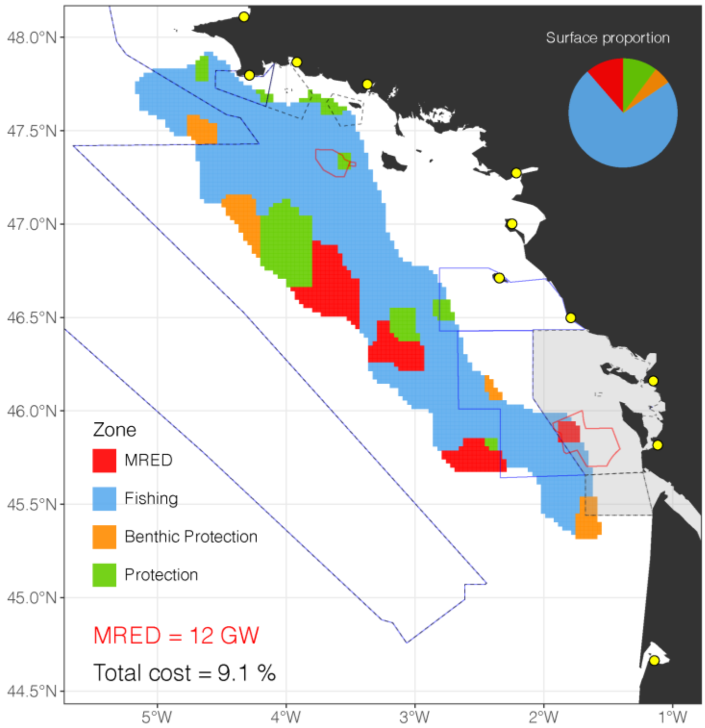

Fig. 5. Map of the best solution of the equitable scenario (10% maximum yearly landings value for each GPF) showing the repartition of the different zones while validating a 12 GW MRED target, a 10% conservation target for each species and regulating ES, and a 75% target of maintenance of provisioning ES. The grey shaded area delimits the Marine Natural Park, the blue lines are the Natura 2000 areas for seabirds' conservation, and the dashed lines the Natura 2000 areas for the conservation of habitats, fauna and flora. Red lines delineate the current OWF requests for proposals overlapping the GV. Yellow dots represent the landing ports linked to the GV, associated with the GPF targets (except for Spain, not represented).

Results from this scenario show that the outcomes are heterogenous depending on the feature. Indeed, individual inspection of the features' scores for the best solution provides insights on the consequences of the prioritization for any given taxonomic group or individual ES or species (Fig. 6). For instance, in this case, we can see that provisioning of rays is limiting the zonation of priorities, with 25% of reduction in ray fishing in this solution (target set at 75% maintenance). In contrast, provisioning of Norway lobsters is the less impacted provisioning ES, with 4.6% of reduction. Bioturbation, hake nursery and sole spawning are also the limiting features in the prioritization. Indeed, their conservation in MPAs does not exceed 10% of the total value in the GV, as opposed to, for instance, filter feeding that is preserved at twice the same proportion in MPAs. Similarly, some groups of species are more protected than others in MPAs. Echinoderms are well protected (mean conservation of 31.6 ± 9.5 SD) while many teleosts are protected at the minimum of 10% (mean 12.8 ± 3.0 SD).

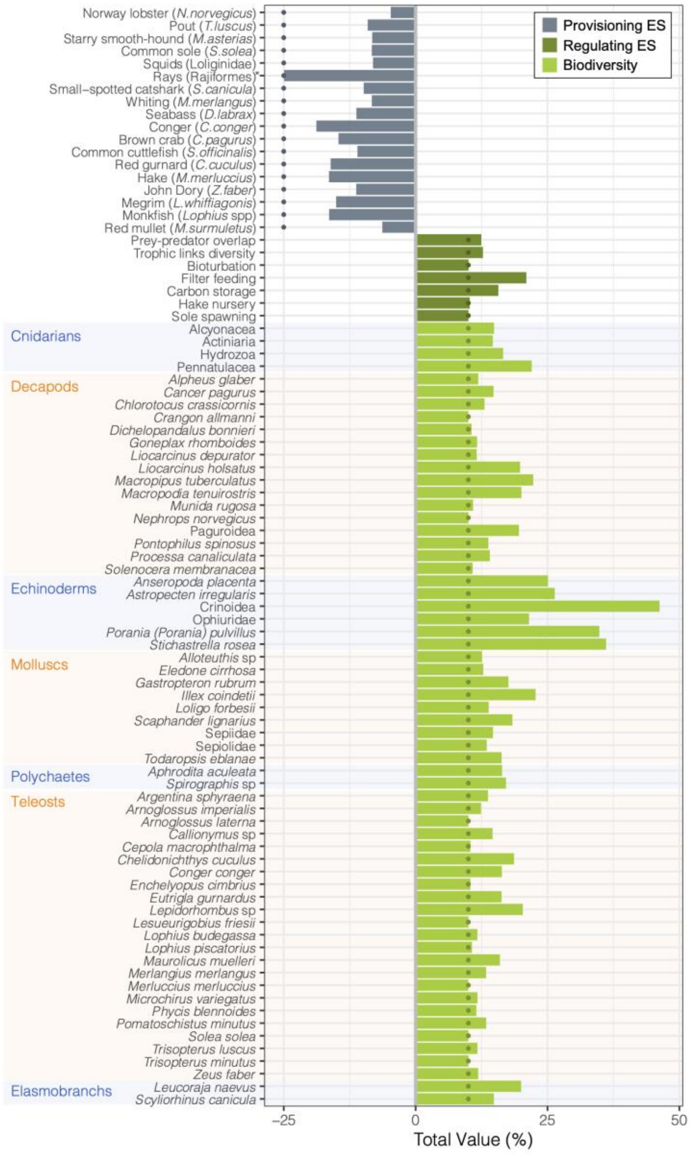

Fig. 6. Biodiversity and ecosystem services scores for the best solution of the equitable scenario involving MRED, benthic and total protection zones. Each bar represents the percentage of loss for provisioning ES (dark grey) or the percentage of conservation for biodiversity (light green) and regulating ES (dark green). Darker dots correspond to target values (75% maintenance of provisioning ES, 10% conservation of biodiversity and regulating ES).

4. Discussion

4.1. On the importance of including ecosystem services in MSP

Our study is original as it is one of the rare considering not only provisioning ES but also regulating ES alongside biodiversity. Many MSP studies do not include ES as part of the features to conserve, either because these studies are targeted toward the protection of specific taxa (*e.g.* elasmobranchs, Giménez et al., 2020; seabirds, Afán et al., 2018), biodiversity (Flower et al., 2020), ecosystem or habitat types (Arafeh-Dalmau et al., 2017; Gurney et al., 2015; Kirkman et al., 2019), or a combination of all (Holness et al., 2022, though the authors claim that work on ES is underway). Sustainable delivery of ES to people is however important as part of ecosystem-based MSP processes (Frazão Santos et al., 2021; White et al., 2012). Compared to management by stakeholders' preferences only, informed management based on this sustainable delivery of ES leads to better outcomes, enhancing nature's contributions to people (NCP), including revenue from fishing (Arkema et al., 2015; Van der Biest et al., 2020). Furthermore, NCP are now important components of environmental policies, and ignoring them comes down to pushing aside a whole section of conservation targets.

Here, we show how including provisioning (18 commercial species) and regulating ES (7 ES related to food web functioning, nutrient cycling and storage, and life cycle maintenance) in an MSP process with other features (human activities and biodiversity), can be beneficial. This is advocated by the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) group that calls for transformative changes in society, policy, governance, proving that ES and NCP facilitate the connections between conservation scientists and managers/decision-makers.

4.2. Avoid ocean grabbing and improve acceptability

We provide a clear example, through this case study of prioritization in the GV, of what could be done in every spatial planning study: produce a significant effort to thoroughly characterize the plurality of actors depending on space and explore the implications of accounting for equity. Indeed, here we show that including 82 targets related to gear-port-fleet (GPF) features does not cost significantly more in terms of yearly total landings than not including them. We found the cost of such equity minor, similarly to Gurney et al. (2015). This is not necessarily the case in every socioecosystem (Pascual et al., 2010; Weeks et al., 2010), hence the importance of exploring the relationship between equity and cost and evaluating the potential resulting tradeoff. It is important to highlight at this point that we considered total landings value instead of total net profits as a cost per planning unit because of the complexity of estimating the latter. Such data is rarely available at our spatial scale. Moreover, if net profits are expected to be correlated to the distance to the coast – linked to fuel costs and time – it is also highly variable depending on various parameters: notably vessel size (crew size, trip duration) and home port. The cost would therefore be boat- or fleet-dependent. We indirectly accounted for such variety by using a mix of cost and fisheries-associated targets. The use of this mixed approach consisting in relying on fisheries data not only through fishing opportunity cost but also through targets aimed at protecting fisheries must be generalized and is done by Yates et al. and Gurney et al., both in 2015, or Kockel et al. in 2020. Chollett et al. show in 2022 that the vast majority of studies simplistically aggregate stakeholders groups together (84% of studies), while others only give different weights to the groups depending on importance or vulnerability. By using this combined approach with a target for each stakeholder group (GPF), the risk of ocean grabbing during the MSP process is reduced (Bennett et al., 2015; Queffelec et al., 2021), and the acceptability and social sustainability of spatial management plans is increased (Chollett et al., 2022). Ocean and land grabbing (Yang and He, 2021) can therefore be avoided by careful inclusion of specific targets aimed at equally sharing the direct restrictions resulting from spatial planning between human activities.

Additionally, further work must be done to account for fishing activities of vessels smaller than 12 meters, concentrating their activities in the more coastal areas and not equipped with VMS, and for which the only spatial data available consists in survey-based data (such as VALPENA; Trouillet et al., 2019).

Our framework, by also considering multiple sets of targets, aims at providing the means to explore and evaluate the consequences of defining different values for targets related to human activities, for instance the maintenance of 85%, 90% or 95% of each GPF. Varying this degree of equity is important, especially if accounting for equity comes at a high cost. To the best of our knowledge, no study has yet proposed to explore in this direction (multiple targets for equity). Tuning the targets' values allows for an optimization of the socio-economic cost of MSP for each small group of actors (here GPFs), which can endanger their sustainability (*e.g.* fuel costs, climate change, invasive species) if too high and cumulated with other constraints. The theoretical loss in yearly revenue is however compensated by a redistribution of fishing effort, that we do not take into account here, meaning that we adopt a conservative approach for fisheries (like many MSP studies using DSTs: Chollett et al., 2022; but see Reecht et al. (2015) that we discuss in section 4.4.4).

4.3. Prioritization with MRED zones and MPAs in the GV

We have provided specific results (Fig. 5-6) for one set of targets, representative of management and development objectives in the GV. These results, along with the Shiny app to explore multiple sets of targets corresponding to realistic variations, could be used to provide useful information to decision-makers in an MSP process at a local scale.

In this scenario, we have noted the mismatch between already implemented MPAs and potential prioritization areas into total and benthic MPAs. The network already in place was not necessarily aimed at protecting the bentho-demersal species and ES in the GV. Indeed, two MPAs in the southeastern part of the GV are Natura 2000 areas for seabirds' conservation, and none of their PU fall in the benthic or total protection zones. This raises the question of the need to encompass all compartments of the ecosystems when considering MSP: not only the bentho-demersal ecosystem but also the pelagic one and vice versa. Indeed, the final choice in OWF and MPA positioning has consequences on all human activities, ES and biodiversity in the area, and future work should be focused on including all marine domains (sea surface, water column and seabed). This is especially true in France where feedback is lacking compared to other European countries where OWF impacts and prioritizations are better-known.

4.4. Flexibility is key for management

We present as output a single best solution, but we do so in the context of batch processing. Approaches consisting in computing several hundreds of solutions and averaging them to approximate an irreplaceability value for each PU would be time-consuming, and would complexify the message for decision-makers, especially in a multi-zone context. Such approach could however be used after our framework, also to investigate multiple solutions for each scenario when the number of interesting combinations of parameters has been narrowed down. It would therefore provide flexibility in spatial prioritizations. We discuss four other aspects of flexibility in this section.

4.4.1. Flexibility in target values

It is possible to individually vary the targets to protect the features 'à la carte'. As discussed before, one can control the features' scores *a posteriori*, but can also vary the targets beforehand. Regarding biodiversity for instance, one could provide increasing protection target values depending on the species. This has been done in various studies, defining different values depending on the IUCN Red List of Threatened Species' conservation status (*e.g.* Afán et al., 2018; Giménez et al., 2020; Mazor et al., 2014) or based on factors such as rarity, endemism or intrinsic vulnerability (Lagabrielle et al., 2018). Conversely, biodiversity targets could be lowered for species already managed by total allowable catch (TAC).

Moreover, the 10% target for biodiversity and regulating ES that we chose to present here is actually subject to debate (Hagerman et al., 2021; Obura et al., 2021). Political objectives are usually set for a percentage of surface under protection in MPAs ('Bringing nature back into our lives', EU Biodiversity Strategy for 2030, European Commission, 2020). But just protecting an area without consideration for the species it hosts and the ES it provides to society might fail to provide optimal outcomes for both ecosystems and society (Barnes et al., 2018; Maron et al., 2021; Williams et al., 2021). As an alternative, we chose to set targets aimed at protecting each species and ES, based on theoretical outcomes for individual layers, and therefore at the ecosystem level. Because the debate still exists and political objectives are not often clear or miss important considerations when defining targets, providing flexibility in the framework to present multiple target values is of importance in this context.

4.4.2. Flexibility in solution compactness

The way adjacent PUs can be allocated to numerous types of zones, therefore determining the degree of scattering of solutions, is defined by the choice of the BLM value (or equivalent in *prioritizr*). Even if an ideal range of BLM can be approximated with a calibration process (Ardron et al., 2010; Domisch et al., 2019), such values are often chosen arbitrarily (*e.g.* Adame et al., 2015; Davidson and Dulvy, 2017; Nhancale and Smith, 2011; Flower et al., 2020). How prioritization areas are clumped together will determine if a proposed solution can be implemented or not. Indeed, too scattered areas complicate the (i) management for MPAs, (ii) operation for OWFs, and (iii) compliance of fishermen. On the contrary, too clumped solutions are too costly and not necessarily optimal for multiple reasons (*e.g.* OWF megapark supplying a single location, giant MPA valuable for mobile species but not connected and opposed by fishermen). Such trade-off in the choice of BLM requires multiple values to be tested and presented if MSP is considered for management. Stakeholders and decision-makers could be presented with multiple solutions obtained with various BLM values (Supplementary Fig. S7), leading to interesting discussions.

4.4.3. Flexibility in the types of zones

The four types of zones presented in this case study are only examples of what could be pertinent to implement. We have developed the methodology and code to add other types of zones, like for instance a fifth type of zone to our case study, corresponding to areas of priority for sediment extraction. Here though, the stakes were low with no current development of the activity on the GV. Should the need arise, such type of zone can be easily added to the problem. Also, all types of zones presented here are theoretical, as the diversity of area-based management tools (ABMT) is greater than what we defined in this study (Gissi et al., 2022). Other types of zones could be added to the problem, corresponding, among others, to seasonal closures, gear selectivity zones or protected areas targeted on specific objectives (Gissi et al., 2022; Maxwell et al., 2020; Roberts et al., 2018; Trouillet and Jay, 2021). This is theoretically possible to parametrize, but if more complex types of zones are added, the different zones contributions to reach the targets can be more difficult to define and a community-based approach as developed by Mills et al. in 2011 or a risk assessment study could be pertinent (Hobday et al., 2011; Roberson et al., 2022).

4.4.4. The framework proposes spatial solutions, but what about flexibility in time?

Solutions obtained by the prioritization algorithm are static and do not account for spatio-temporal changes in the distribution of the features nor fishing effort redistribution.

Nonetheless, accounting for the former is of particular importance, especially considering the significant consequences of climate change on ES, species distributions and habitat perturbations (Frazão Santos et al., 2020; Gissi et al., 2019). To build meaningful spatial plans, recent data must be used (Lagasse et al., 2015) and more than 4 years of data have to be considered to provide consistent results (García-Barón et al., 2021). We use data that meet both requirements. However, we lack insight regarding future species and ES distributions, and on integrating climate change into our scenarios (Frazão Santos et al., 2020; Magris et al., 2014). Effort must be made to predict shifts in species distributions (Guisan et al., 2013; Schwartz, 2012) linked to climate change, using tools like species distribution models (Elith and Leathwick, 2009). Yet, data is lacking in our study to obtain reliable long-term predictions of abundance for many species and ES.

Parallelly, we adopt a conservative approach for fisheries by not accounting for fishing effort redistribution, but the longer-term consequences on resources (fish stocks) and habitats, because of the potential increase in pressure outside OWFs and MPAs, are not accounted for (Hilborn et al., 2004). To counteract this problem, one could use mixed fisheries dynamics simulation models (*e.g.* ISIS-Fish, Mahévas and Pelletier, 2004) or other complex system models (see Lehuta et al., 2016 for an overview) to predict changes in fishing fleet and fish population dynamics. In 2015, Reecht et al. evaluated the pertinence of combining Marxan-like approaches with such models in iterations. Even if much work is still needed in this direction, the combination of approaches is promising but will not solve the issue of the slow speed of MSP which is hardly compatible with such dynamic approach. Indeed, there is much inertia inherent to the implementation of management plans and OWF planning process. Similarly, further research is needed to evaluate if a step-by-step strategy is as efficient as a single evaluation.

4.5. Direct visualization as a powerful discussion tool

The involvement of stakeholders in the MSP process is undeniably necessary (Janßen et al., 2019; Pomeroy and Douvere, 2008; Zaucha and Kreiner, 2021). Direct interaction between them and scientists provides a great perspective for improvement (Flower et al., 2020; Holness et al., 2022; Said and Trouillet, 2020). Such involvement should happen at different stages of the process, even early for dialog and expression of concerns (Gopnik et al., 2012), or for instance through contribution to spatial data gathering, or later by engaging in participatory mapping and providing feedback on early results. For the latter, visualization of preliminary results should be used as a way to connect, and the framework we present in this study contributes to encourage stakeholders to participate and engage in discussions (Fig. 1). DSTs are often seen as a black box (Ball et al., 2011), and providing the possibility to tinker with target sliders on the Shiny app during meetings and directly visualize the consequences of varying the combinations of parameters enlightens the process. This is rendered possible by exploring multiple problems corresponding to various hypotheses and associated scalable targets, contrary to the common use of prioritization algorithms that aim only at providing an optimal set of solutions.

However, this framework should not be used alone in the dialogue with stakeholders as it does not replace complementary work like qualitative approaches (*e.g.* Marzloff et al., 2011) or human and social sciences approaches (Ban et al., 2013; Gourguet et al., 2021; Weiand et al., 2021). It should be used as part of a greater dynamic of inclusive and multidisciplinary MSP (Perino et al., 2022).

5. Conclusion

The urgency of the situation in the 2020s (climate change, geopolitics of fossil fuel) pushes decision-makers to accelerate the rate of development of marine renewable energies. In parallel, restrictions of extractive activities inside current or to-be-defined MPAs are expected in the near future, potentially threatening the social sustainability of fisheries, if inclusivity, equity, and flexibility are not central in the process. We provide a thorough methodological framework that we believe should be used in every spatial planning study. First, the inclusion of biodiversity as individual species layers and ecosystem services (not only provisioning but also regulating) should be encouraged. Second, historical activities (here fisheries) should be well characterized and included not only as cost layers but also as individual targets to promote equity in spatial planning. Then, we propose to render the spatial planning process accessible by using a flexible visualization approach during meetings with stakeholders, such as the one we developed in this study. The increasing complexity of space management requires a common effort from different scientific disciplines to coordinate and bring to the table complementary approaches, to convince decision-makers that accelerating the rate of development does not necessarily entail an oversimplification of the complexity of the task.

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Data Availability

Data will be available on reasonable request. The code required for the framework in this paper will be made freely available on a publicly accessible GitHub repository (https://github.com/gboussarie).

Code de champ modifié

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Supplementary Table S1. Number of stakeholders consulted during the PACMAN project, and guide for interviews used as basic outline for discussion. This guide has originally been used in French but we translated it in English for this publication. We provide here the text in both languages.

Stakeholder	Number of interviews/meetings	Number of people
Producers' organization (fishers' representatives)	1	2
Fishing committees	Two fishing committees were part of the PACMAN project and two others were invited at three technical workshops. Exchanges took place on a regular basis during the project.	
Marine Natural Park	1	2
Electricity network manager	1	2
French marine administration	1	1
French scientists	2	2
Marine sediment extraction company	1	1
Windfarm company	1	2

PACMAN Interview Guide – Activities and uses of the Grande Vasière

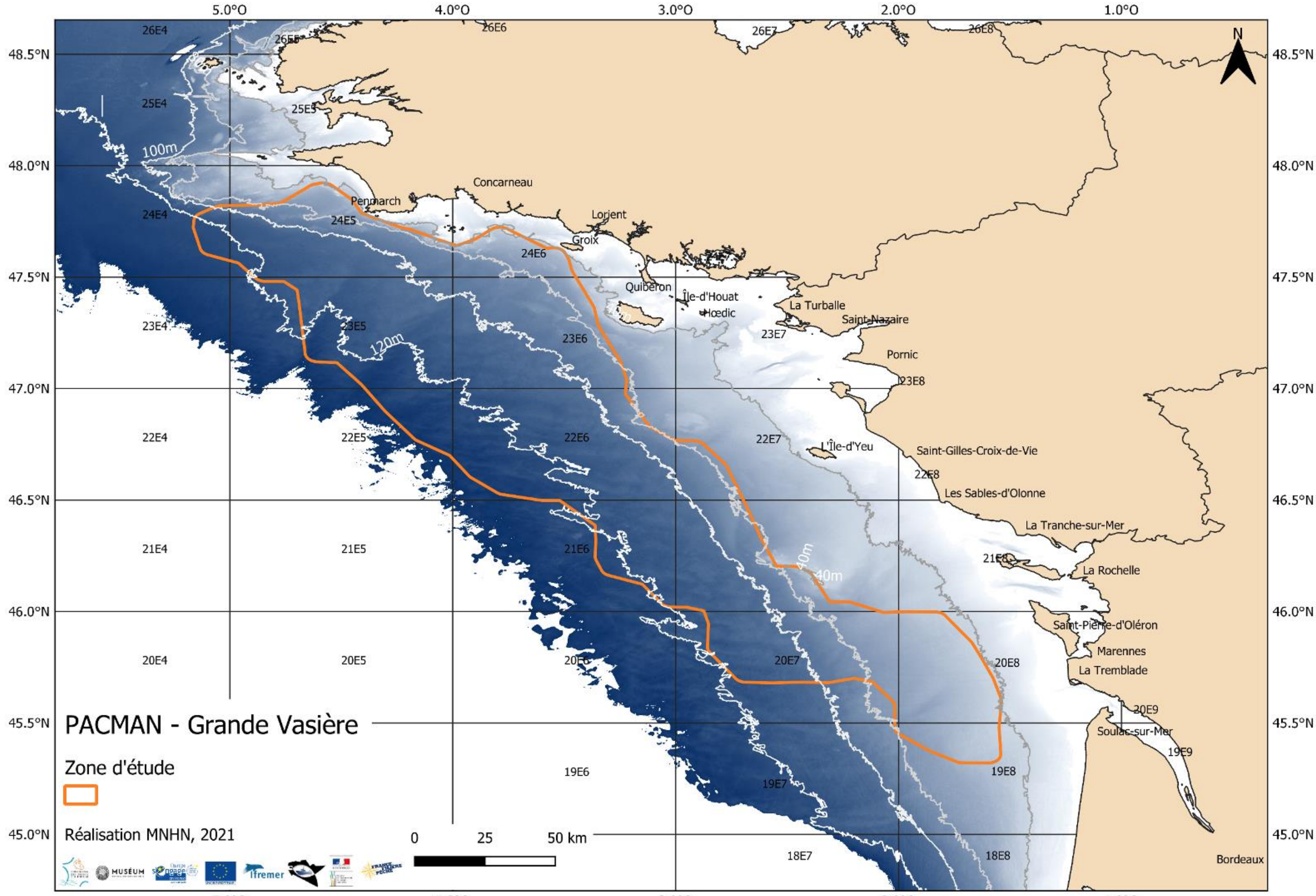
Ce guide est à destination de l'enquêteur. Plusieurs questions sont ouvertes afin d'appréhender l'ensemble des avis et connaissances de l'interviewé sur le sujet. Seuls certains matériaux seront mis à disposition de l'interviewé (cartes et liste d'activités) afin d'alimenter et faciliter la discussion.
Les questions posées sont simplement à titre indicatif, selon le fil de la discussion l'enquêteur les formulera surement différemment.
L'objectif de cet entretien est d'apporter des précisions concernant (i) l'activité de l'enquêté sur la GV et (ii) les conditions de cohabitation avec d'autres activités ou zones identifiées.
This guide is intended for the interviewer. Some questions are open, to fully understand the opinion and knowledge of the interviewee on the subject. Only a few materials will be presented to the interviewee (maps and list of activities) to feed the discussion.
The wording of the questions is purely informative: depending on the discussion, the interviewer will probably present them differently.
The objective of this interview is to clarify and better identify (i) the interviewee's activity on the GV and (ii) the conditions for compatibility with other activities or zones identified.

General presentation of the project and the objectives of this interview
Présentation succincte concernant l'enquêteur : nom, structure.
Présentation de l'objectif du projet : optimiser la cohabitation entre les activités historiques et émergentes et l'écosystème.
A préciser : (i) la confidentialité des informations issues de l'entretien, (ii) l'usage à des fins d'identification et de compréhension des enjeux et non de statistiques.
Quick presentation of the interviewer: name, employer.
Presentation of the project's objectives: optimize cohabitation between historical and emerging activities, and the ecosystem.
Specify that the information from this interview is (i) confidential and (ii) used for identification and understanding of the stakes and not for statistics.

Your activity and the Grande Vasière
[Introduction ayant pour vocation de lancer la discussion sur le sujet et confirmer les zones d'intérêt de l'activité.]
[Introduction to start the discussion on the subject and confirm the areas of interests of the interviewee's activity.]
1. Pourriez-vous décrire en quelques mots votre activité ou celle de la structure que vous représentez ?
1. Could you describe in a few words your activity or the one of the structures you are representing?
2. Cette carte présente les contours de la Grande Vasière et certaines des informations disponibles concernant votre type d'activité sur la zone (hors pêche). Les éléments présentés sur cette carte permettent-ils d'identifier les zones prioritaires pour votre activité ? Si non, pouvez-vous compléter ? [Pour la pêche, demander directement les zones d'importance sur la GV pour l'activité de l'interviewé].
2. This map presents the extent of the Grande Vasière and some of the available information of your type of activity on the area (except fishing). Can the elements represented on this map allow the identification of the priority areas for your activity? If no, could you complete? [For fishing activities, directly ask the areas of importance for the interviewee's activity on the Grande Vasière].
[L'objectif de cette partie consiste à identifier les zones les plus importantes pour l'activité pratiquée par l'interviewé et s'assurer que les données à disposition permettent de les identifier. Si ce n'est pas le cas, ces zones peuvent êtres

complétées et corrigées à main levée. Pour la pêche, cette question est facultative car les données de pêche sont assez abondantes et précises pour notre échelle d'étude.]

[The goal of this part consists in identifying the most important areas for the interviewee's activity and make sure that the available data can identify them. If not, these areas can be completed or corrected freehand. For fishing activities, this is an optional question because data are precise and abundant.]



Generic map used as support for discussion. It has been adapted for each category of activity represented by the interviewees, with specific layers of data.

3. D'autres acteurs ont-ils une activité similaire à la vôtre dans ces zones ? Si oui, sont-ils nombreux ?

[L'objectif est de juger du caractère générique ou singulier de l'activité de l'acteur.]

3. Do other actors have a similar activity than yours in these areas? If yes, are they numerous?

[The goal is to judge of the generic or singular character of the interviewee's activity.]

4. Pourquoi chacune des zones identifiées est importante pour votre activité ?

[Objectif : vérifier l'attractivité des zones (zones à langoustine, à fort potentiel éolien, type sédiments à granulats, etc.)]

4. Why is each of these identified areas important for your activity?

[Goal: check the attractiveness of these areas (*e.g.*, Norway lobsters area, high wind energy potential, sediments type…)]

5. Question spécifique aux acteurs de l'éolien : comment sont définies les zones d'importance pour l'éolien ? Est-il possible de définir des critères en fonction du vent, des zones d'exclusion, de la distance à la côte, etc. afin de graduer l'importance de chaque partie de la zone d'étude ?

5. Specific question for offshore windfarms actors: how are the areas of importance defined? Is it possible to define criteria such as wind, exclusion zones, distance to the coast (and others) to graduate the importance of each part of the area of study?

<u>Compatibility between activities</u>

6. Parmi les activités suivantes, pourriez-vous indiquer celles avec lesquelles vous cohabitez ? Celles avec lesquelles vous pourriez/ne pourriez pas cohabiter ? Détaillez.

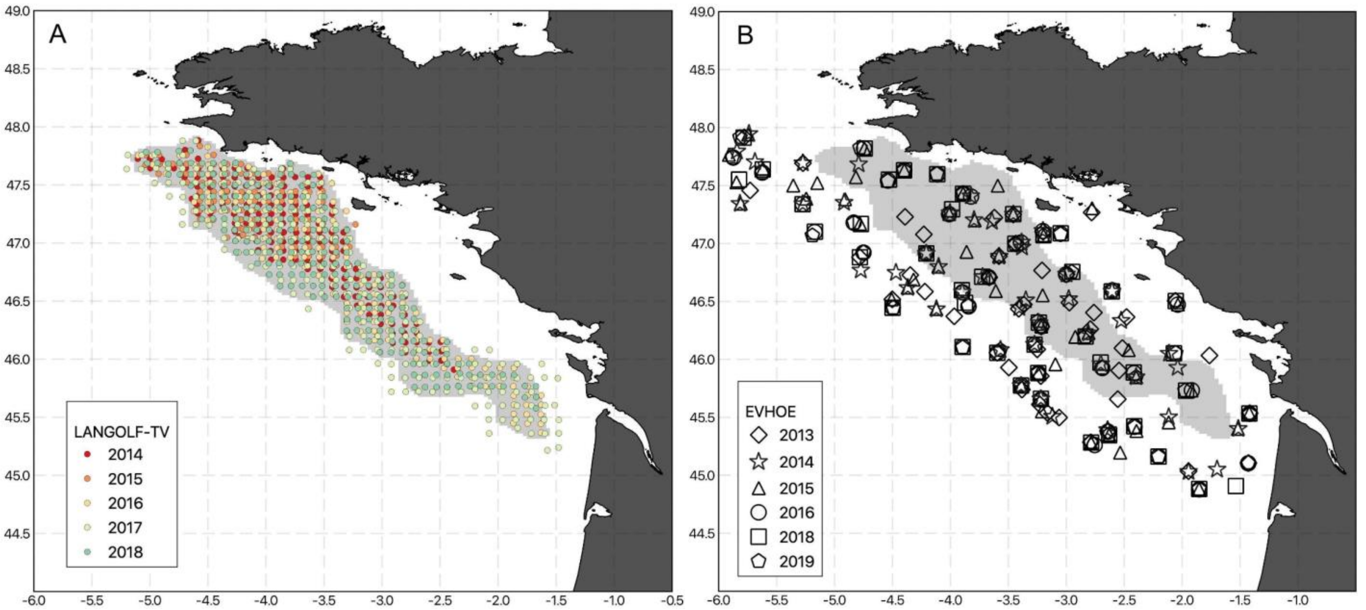
[En cas de conflit précis demander à préciser sur la carte]

6. Among the following activities, could you indicate the ones with which your activity is already in cohabitation with? Which ones are/are not compatible? Detail.

[In case of specific conflict, ask to point out the area on the map]

Activity	Always compatible	Never compatible	Details on the conditions for compatibility (*e.g.*, temporal, spatial)
Maritime transport			
Sediments extraction			
Disposal at sea			
Underwater cabling			
Professional fishing – *bottom trawling gear*			
Professional fishing – *static and pelagic gear*			
Recreational activities and tourism			
Offshore windfarms			
Defense			
Environmental protection			

Supplementary Fig. S2. LANGOLF-TV and EVHOE survey stations used in this study (n = 860 and n = 269, respectively). The Grande Vasière is represented in light grey (3,372 planning units). The EVHOE survey spans wider than the area depicted here, but we filtered stations to keep only the hauls in depths between 30 and 160 meters, similar to the LANGOLF-TV sampling. The mean distance between stations is 42 km for EVHOE and 18 for LANGOLF-TV, with a mean swept area of respectively 64,187 m^2 (trawl) and 158 m^2 (video transect).



Supplementary Table S3. List of the 62 taxa selected representing the biodiversity features. Codes in the "Rank" column correspond to: GN = Genus, SP = Species, F = Family, O = Order, C = Class and SF = Super-Family.

CAMPAIGN	PHYLUM	CLASS	ORDER	FAMILY	RANK	TAXON
EVHOE	Mollusca	Cephalopoda	Myopsida	Loliginidae	GN	*Alloteuthis*
EVHOE	Chordata	Actinopterygii	Perciformes	Cepolidae	SP	*Cepola macrophthalma*
EVHOE	Chordata	Actinopterygii	Scorpaeniformes	Triglidae	SP	*Chelidonichthys cuculus*
EVHOE	Arthropoda	Malacostraca	Decapoda	Pandalidae	SP	*Chlorotocus crassicornis*
EVHOE	Chordata	Actinopterygii	Anguilliformes	Congridae	SP	*Conger conger*
EVHOE	Arthropoda	Malacostraca	Decapoda	Crangonidae	SP	*Crangon allmanni*
EVHOE	Arthropoda	Malacostraca	Decapoda	Pandalidae	SP	*Dichelopandalus bonnieri*
EVHOE	Mollusca	Cephalopoda	Octopoda	Eledonidae	SP	*Eledone cirrhosa*
EVHOE	Chordata	Actinopterygii	Gadiformes	Lotidae	SP	*Enchelyopus cimbrius*
EVHOE	Chordata	Actinopterygii	Scorpaeniformes	Triglidae	SP	*Eutrigla gurnardus*
EVHOE	Mollusca	Gastropoda	Cephalaspidea	Gastropteridae	SP	*Gastropteron rubrum*
EVHOE	Arthropoda	Malacostraca	Decapoda	Alpheidae	SP	*Alpheus glaber*
EVHOE	Mollusca	Cephalopoda	Oegopsida	Ommastrephidae	SP	*Illex coindetii*
EVHOE	Chordata	Actinopterygii	Perciformes	Gobiidae	SP	*Lesueurigobius friesii*
EVHOE	Chordata	Elasmobranchii	Rajiformes	Rajidae	SP	*Leucoraja naevus*
EVHOE	Arthropoda	Malacostraca	Decapoda	Polybiidae	SP	*Liocarcinus depurator*
EVHOE	Arthropoda	Malacostraca	Decapoda	Polybiidae	SP	*Liocarcinus holsatus*
EVHOE	Mollusca	Cephalopoda	Myopsida	Loliginidae	SP	*Loligo forbesii*
EVHOE	Chordata	Actinopterygii	Lophiiformes	Lophiidae	SP	*Lophius budegassa*
EVHOE	Chordata	Actinopterygii	Lophiiformes	Lophiidae	SP	*Lophius piscatorius*
EVHOE	Arthropoda	Malacostraca	Decapoda	Polybiidae	SP	*Macropipus tuberculatus*
EVHOE	Arthropoda	Malacostraca	Decapoda	Inachidae	SP	*Macropodia tenuirostris*
EVHOE	Echinodermata	Asteroidea	Valvatida	Asterinidae	SP	*Anseropoda placenta*
EVHOE	Chordata	Actinopterygii	Stomiiformes	Sternoptychidae	SP	*Maurolicus muelleri*
EVHOE	Chordata	Actinopterygii	Gadiformes	Gadidae	SP	*Merlangius merlangus*
EVHOE	Chordata	Actinopterygii	Gadiformes	Merlucciidae	SP	*Merluccius merluccius*
EVHOE	Chordata	Actinopterygii	Pleuronectiformes	Soleidae	SP	*Microchirus variegatus*
EVHOE	Chordata	Actinopterygii	Gadiformes	Phycidae	SP	*Phycis blennoides*
EVHOE	Chordata	Actinopterygii	Perciformes	Gobiidae	SP	*Pomatoschistus minutus*
EVHOE	Arthropoda	Malacostraca	Decapoda	Crangonidae	SP	*Pontophilus spinosus*
EVHOE	Echinodermata	Asteroidea	Valvatida	Poraniidae	SP	*Porania (Porania) pulvillus*
EVHOE	Arthropoda	Malacostraca	Decapoda	Processidae	SP	*Processa canaliculata*
EVHOE	Mollusca	Gastropoda	Cephalaspidea	Scaphandridae	SP	*Scaphander lignarius*
EVHOE	Annelida	Polychaeta	Phyllodocida	Aphroditidae	SP	*Aphrodita aculeata*
EVHOE	Chordata	Elasmobranchii	Carcharhiniformes	Scyliorhinidae	SP	*Scyliorhinus canicula*
EVHOE	Mollusca	Cephalopoda	Sepiida	Sepiidae	F	Sepiidae
EVHOE	Mollusca	Cephalopoda	Sepiida	Sepiolidae	F	Sepiolidae
EVHOE	Chordata	Actinopterygii	Pleuronectiformes	Soleidae	SP	*Solea solea*
EVHOE	Arthropoda	Malacostraca	Decapoda	Solenoceridae	SP	*Solenocera membranacea*
EVHOE	Echinodermata	Asteroidea	Forcipulatida	Stichasteridae	SP	*Stichastrella rosea*
EVHOE	Mollusca	Cephalopoda	Oegopsida	Ommastrephidae	SP	*Todaropsis eblanae*
EVHOE	Chordata	Actinopterygii	Gadiformes	Gadidae	SP	*Trisopterus luscus*
EVHOE	Chordata	Actinopterygii	Gadiformes	Gadidae	SP	*Trisopterus minutus*

EVHOE	Chordata	Actinopterygii	Zeiformes	Zeidae	SP	*Zeus faber*
EVHOE	Chordata	Actinopterygii	Osmeriformes	Argentinidae	SP	*Argentina sphyraena*
LANGOLF	Cnidaria	Anthozoa	Alcyonacea		O	Alcyonacea
LANGOLF	Cnidaria	Anthozoa	Actiniaria		O	Actiniaria
LANGOLF	Chordata	Actinopterygii	Perciformes	Callionymidae	GN	*Callionymus* sp
LANGOLF	Echinodermata	Crinoidea			C	Crinoidea
LANGOLF	Arthropoda	Malacostraca	Decapoda	Goneplacidae	SP	*Goneplax rhomboides*
LANGOLF	Cnidaria	Hydrozoa			C	Hydrozoa
LANGOLF	Chordata	Actinopterygii	Pleuronectiformes	Scophthalmidae	GN	*Lepidorhombus* sp
LANGOLF	Arthropoda	Malacostraca	Decapoda	Munididae	SP	*Munida rugosa*
LANGOLF	Arthropoda	Malacostraca	Decapoda	Nephropidae	SP	*Nephrops norvegicus*
LANGOLF	Echinodermata	Ophiuroidea	Ophiurida	Ophiuridae	F	Ophiuroidae
EVHOE	Chordata	Actinopterygii	Pleuronectiformes	Bothidae	SP	*Arnoglossus imperialis*
LANGOLF	Arthropoda	Malacostraca	Decapoda		SF	Paguroidea
LANGOLF	Cnidaria	Anthozoa	Pennatulacea		O	Pennatulacea
LANGOLF	Annelida	Polychaeta	Sabellida	Sabellidae	GN	*Spirographis* sp
EVHOE	Chordata	Actinopterygii	Pleuronectiformes	Bothidae	SP	*Arnoglossus laterna*
EVHOE	Echinodermata	Asteroidea	Paxillosida	Astropectinidae	SP	*Astropecten irregularis*
EVHOE	Arthropoda	Malacostraca	Decapoda	Cancridae	SP	*Cancer pagurus*

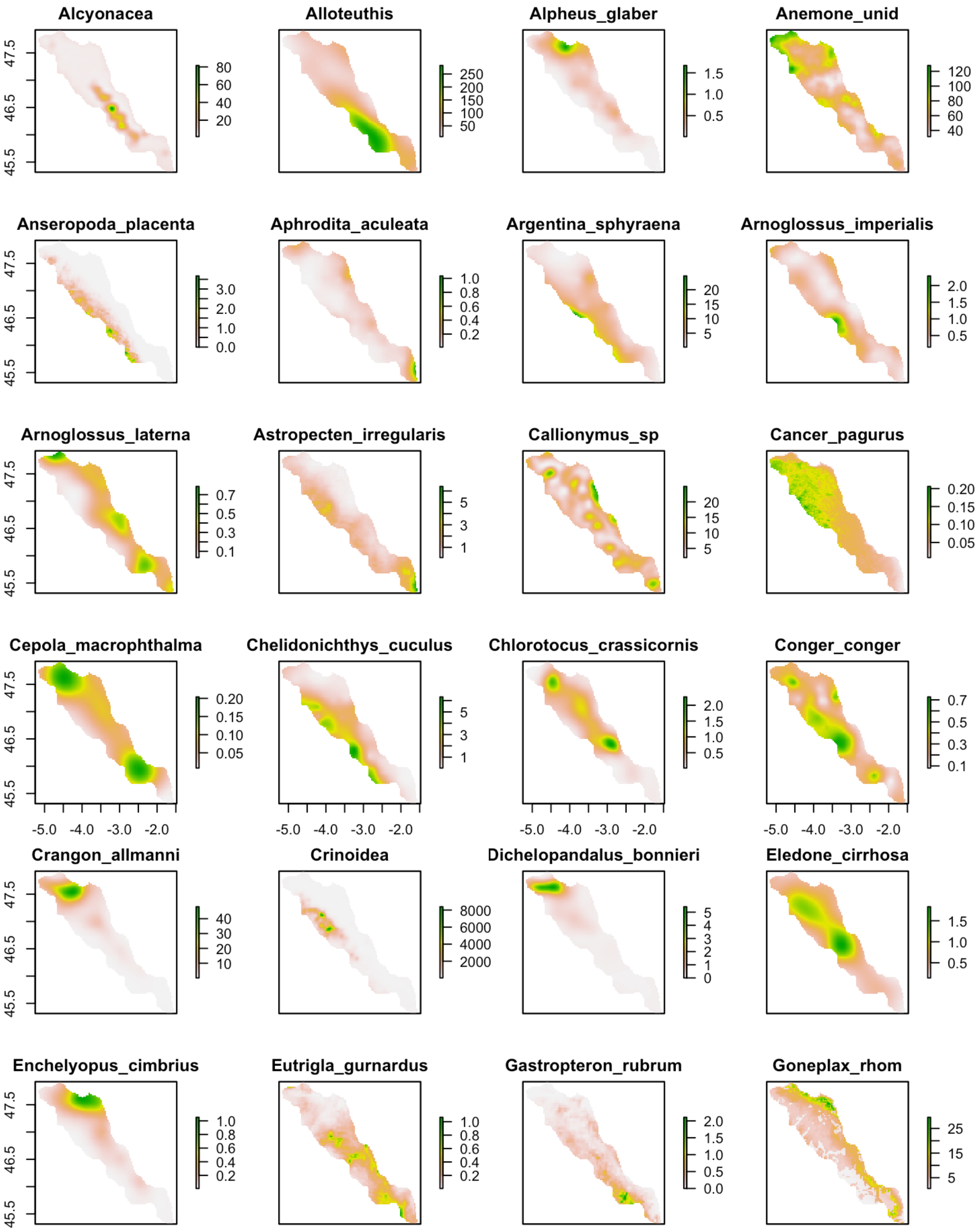
Supplementary Table S4. For each taxon is reported a set of predictive performance indicators estimated by cross-validation between the predicted and observed values: Root Mean Square Error of Prediction for both the kriging and the GLMM approaches (RMSEP_K and RMSEP_GLMM respectively), the mean observed abundance (MEAN), and the modelling method retained (SELECTION). Note that for 7 taxa (underlined), the final selection of the modelling method was not only based on the RMSEP but also on expert judgement based on visualization of the results.

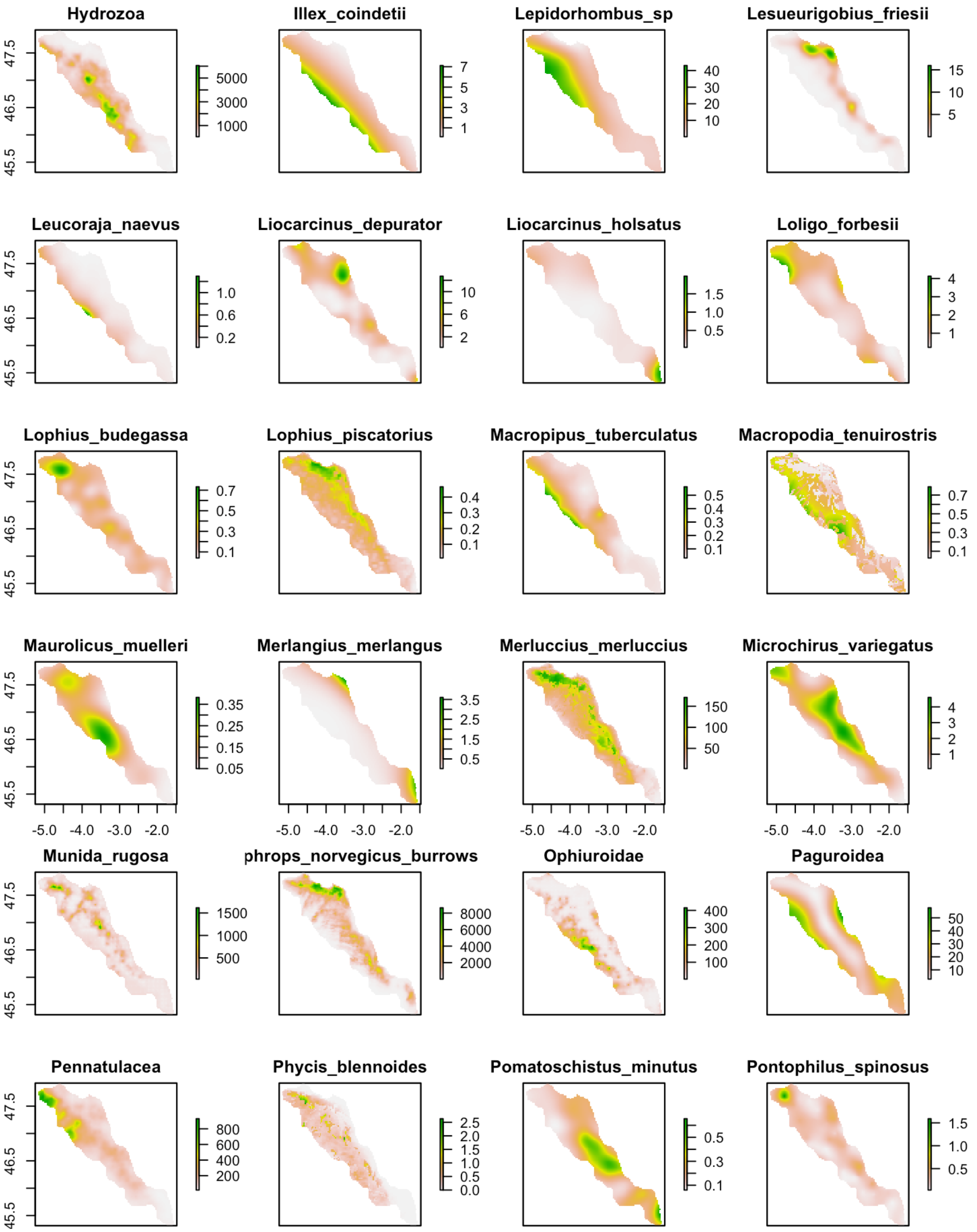
TAXON	RMSEP_K	RMSEP_GLMM	MEAN	SELECTION
<u>*Alloteuthis*</u>	1117.97	859.32	370.45	KRIGING
Cepola macrophthalma	3.44	3.65	0.76	KRIGING
Chelidonichthys cuculus	20.65	21.36	20.39	KRIGING
Chlorotocus crassicornis	11.18	11.71	3.29	KRIGING
Conger conger	2.97	3.09	2.72	KRIGING
Crangon allmanni	140.47	538.63	38.65	KRIGING
Dichelopandalus bonnieri	24.51	26.45	4.73	KRIGING
Eledone cirrhosa	6.31	7.07	4.82	KRIGING
<u>*Enchelyopus cimbrius*</u>	2.56	2.43	0.9	KRIGING
Eutrigla gurnardus	26.68	26.63	4.96	GLMM
Gastropteron rubrum	32.93	30.82	6.56	GLMM
Alpheus glaber	3.03	3.25	1.11	KRIGING
Illex coindetii	237.7	245.88	70.12	KRIGING
Lesueurigobius friesii	45.85	533.74	10.51	KRIGING
Leucoraja naevus	5.58	6.6	3.3	KRIGING
Liocarcinus depurator	34.21	38.21	16.35	KRIGING
Liocarcinus holsatus	60.64	104.13	8.46	KRIGING
Loligo forbesii	119.24	121.7	25.71	KRIGING
Lophius budegassa	1.96	2.09	1.68	KRIGING
Lophius piscatorius	2.11	1.81	1.27	GLMM
Macropipus tuberculatus	7.9	12.56	3.12	KRIGING
Macropodia tenuirostris	6.32	6.3	2.98	GLMM
Anseropoda placenta	29.79	27.64	11.67	GLMM
Maurolicus muelleri	14.49	52.63	2.42	KRIGING
Merlangius merlangus	268.24	898.52	27.84	KRIGING
<u>*Merluccius merluccius*</u>	463.58	494.05	326.65	GLMM
Microchirus variegatus	16.11	16.49	9.46	KRIGING
Phycis blennoides	3.44	2.96	1.61	GLMM
Pomatoschistus minutus	21.93	299.93	5.22	KRIGING
<u>*Pontophilus spinosus*</u>	5.8	5.78	2.08	KRIGING
Porania (Porania) pulvillus	54.42	58.32	20.95	KRIGING
Processa canaliculata	12.19	13.9	4.03	KRIGING
Scaphander lignarius	8.78	8.35	2.08	GLMM
Aphrodita aculeata	10.86	11.08	2.61	KRIGING
Scyliorhinus canicula	28.49	27.65	23.96	GLMM
Sepiidae	13.27	13.29	5.87	KRIGING
Sepiolidae	85.95	83.91	33.45	GLMM
Solea solea	2.36	2.26	0.84	GLMM
Solenocera membranacea	26.57	33.59	5.88	KRIGING
Stichastrella rosea	24.82	27.33	11.77	KRIGING
Todaropsis eblanae	21.63	20.85	11.63	GLMM

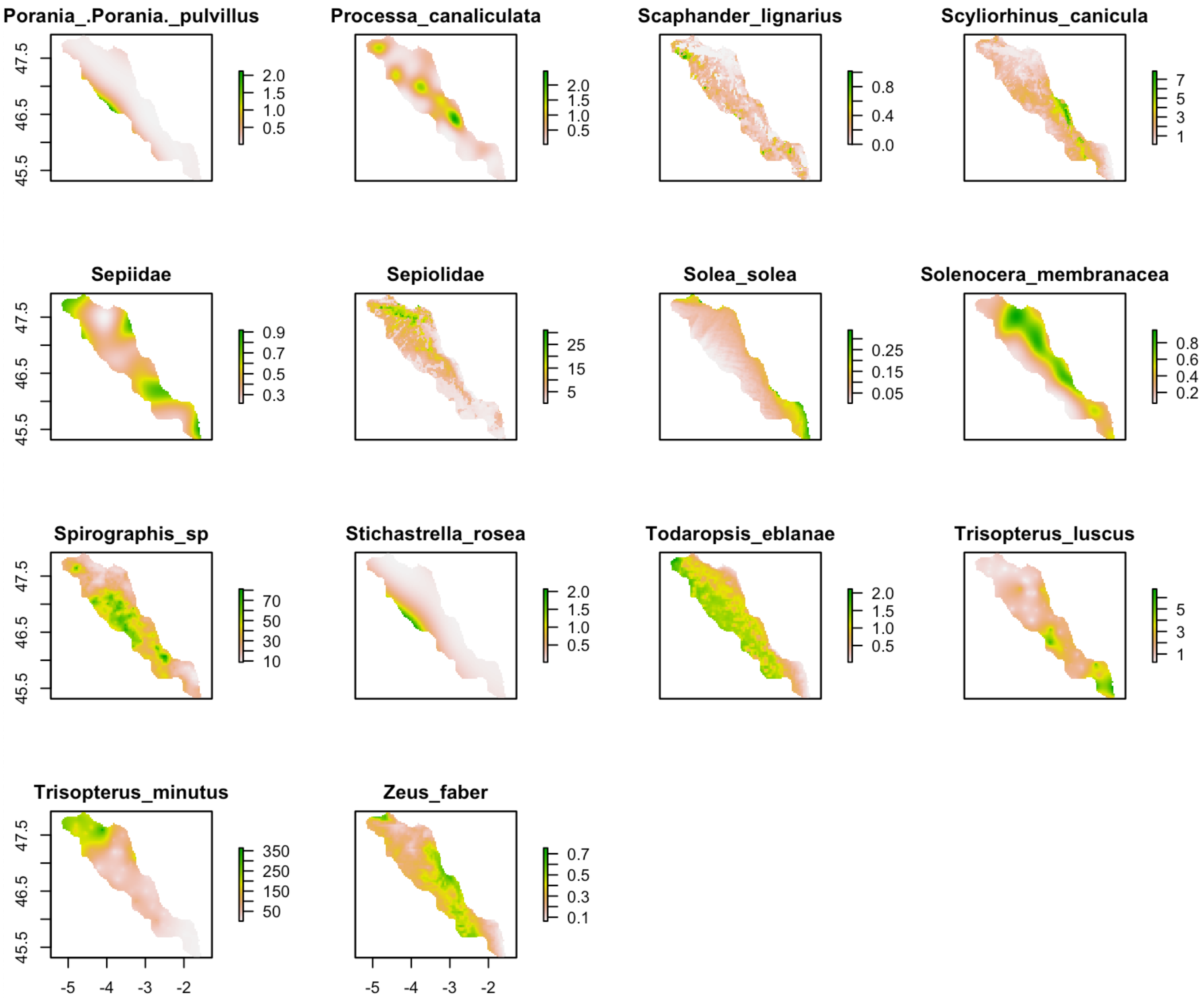
Trisopterus luscus	110.34	113.25	28.64	KRIGING
Trisopterus minutus	1839.38	1268.21	373.07	KRIGING
Zeus faber	5.64	3.78	3.77	GLMM
Argentina sphyraena	218.94	203.08	93.74	KRIGING
Alcyonacea	1.26	3.05	0.24	KRIGING
Actiniaria	8.57	8.58	1.84	KRIGING
Callionymus sp	0.65	0.66	0.18	KRIGING
Crinoidea	125.34	125.38	27.41	KRIGING
Goneplax rhomboides	0.39	0.39	0.13	GLMM
Hydrozoa	43.74	43.87	23.89	KRIGING
Lepidorhombus sp	0.6	0.61	0.3	KRIGING
Munida rugosa	18.48	20.39	5.76	KRIGING
Nephrops norvegicus	47.57	34.57	35.89	GLMM
Ophiuroidae	2.38	2.67	1,00	KRIGING
Arnoglossus imperialis	12.42	12.6	6.49	KRIGING
Paguroidea	4.17	5.47	0.68	KRIGING
Pennatulacea	7.34	7.68	4.51	KRIGING
Spirographis sp	1.32	1.34	0.93	KRIGING
Arnoglossus laterna	5.94	7.57	2.55	KRIGING
Astropecten irregularis	32.3	29.8	12.27	GLMM
Cancer pagurus	1.55	1.59	1.05	GLMM

Supplementary Fig. S5. Individual maps of the different features used in the prioritization framework.

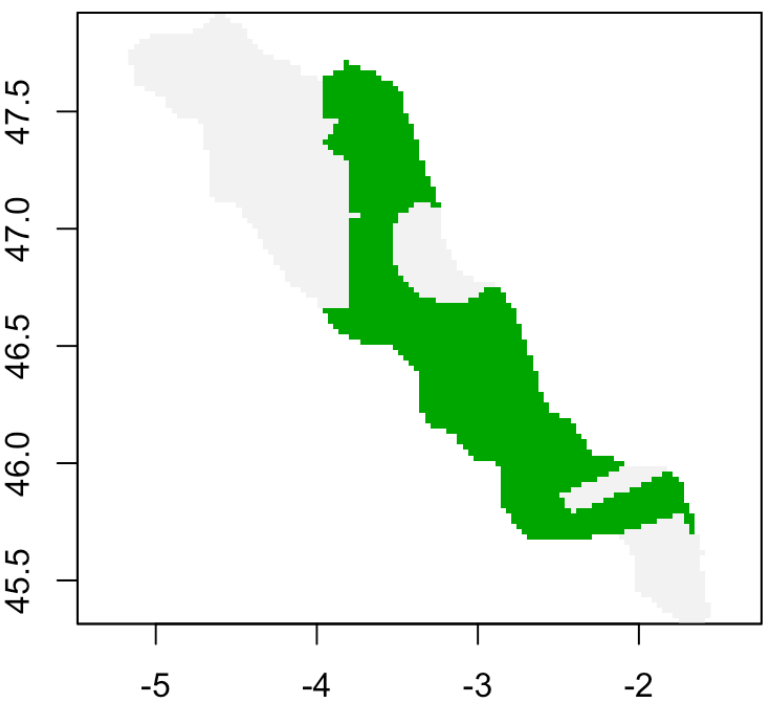
A) BIODIVERSITY. Values are in thousands of individuals per planning unit (6.25 km^2).



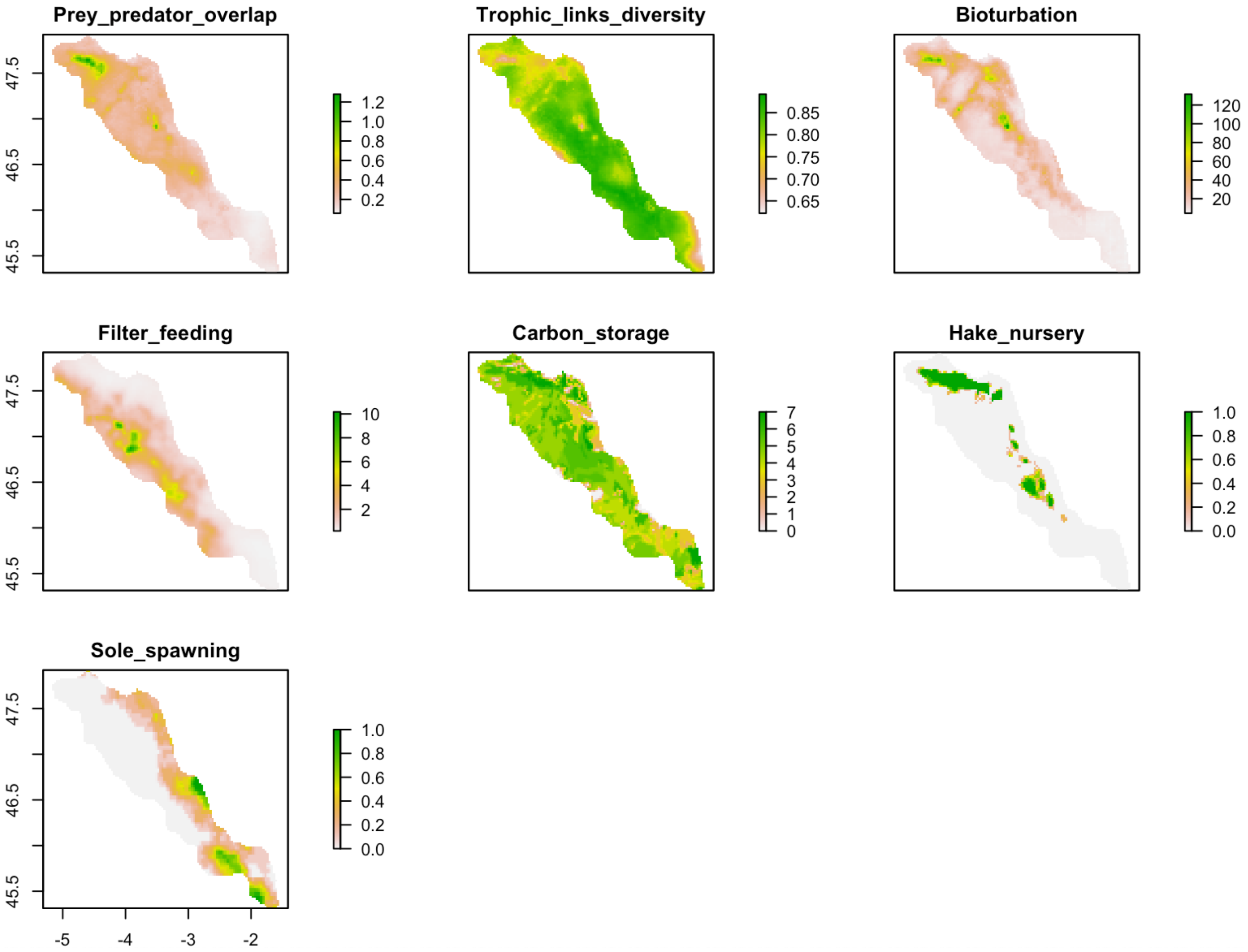

Hydrozoa
5000
3000
1000
Illex_coindetii
7
5
3
1
Lepidorhombus_sp
40
30
20
10
Lesueurigobius_friesii
15
10
5
Leucoraja_naevus
1.0
0.6
0.2
Liocarcinus_depurator
10
6
2
Liocarcinus_holsatus
1.5
1.0
0.5
Loligo_forbesii
4
3
2
1
Lophius_budegassa
0.7
0.5
0.3
0.1
Lophius_piscatorius
0.4
0.3
0.2
0.1
Macropipus_tuberculatus
0.5
0.4
0.3
0.2
0.1
Macropodia_tenuirostris
0.7
0.5
0.3
0.1
Maurolicus_muelleri
0.35
0.25
0.15
0.05
Merlangius_merlangus
3.5
2.5
1.5
0.5
Merluccius_merluccius
150
100
50
Microchirus_variegatus
4
3
2
1
Munida_rugosa
1500
1000
500
phrops_norvegicus_burrows
8000
6000
4000
2000
Ophiuroidae
400
300
200
100
Paguroidea
50
40
30
20
10
Pennatulacea
800
600
400
200
Phycis_blennoides
2.5
2.0
1.5
1.0
0.5
0.0
Pomatoschistus_minutus
0.5
0.3
0.1
Pontophilus_spinosus
1.5
1.0
0.5
47.5
46.5
45.5
-5.0
-4.0
-3.0
-2.0



B) MARINE RENEWABLE ENERGY DEVELOPMENT. Grey areas correspond to exclusion zones.



C) REGULATING ECOSYSTEM SERVICES: Prey_predator_overlap: encounter rate estimated with Pianka's index (unitless) ; Trophic_links_diversity: estimated with Shannon's index applied to Pianka's encounter rate between preys and predators (unitless) ; Bioturbation: bioturbation potential of the community quantified with the BPc index from Solan et al. (2004) (unitless); Filter_feeding: abundance of filter feeders (in 10^6 individuals) ; Carbon_storage: scoring system based on the size of the sediment particles ; Hake_nursery: standardized abundance of hake juveniles (ranging from 0 to 1) ; Sole_spawning: standardized common sole biomass encountered in February and March (ranging from 0 to 1).

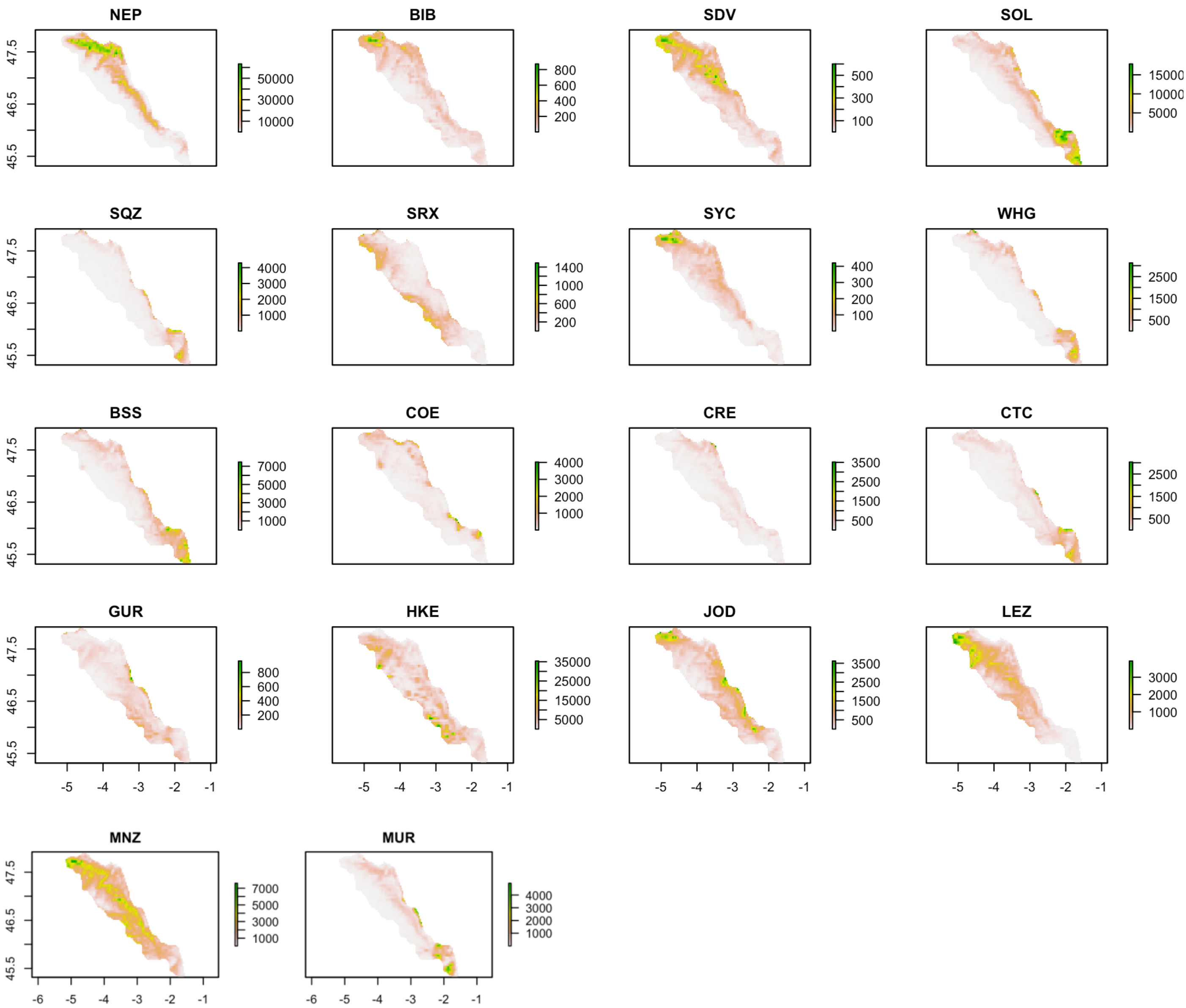


Reference

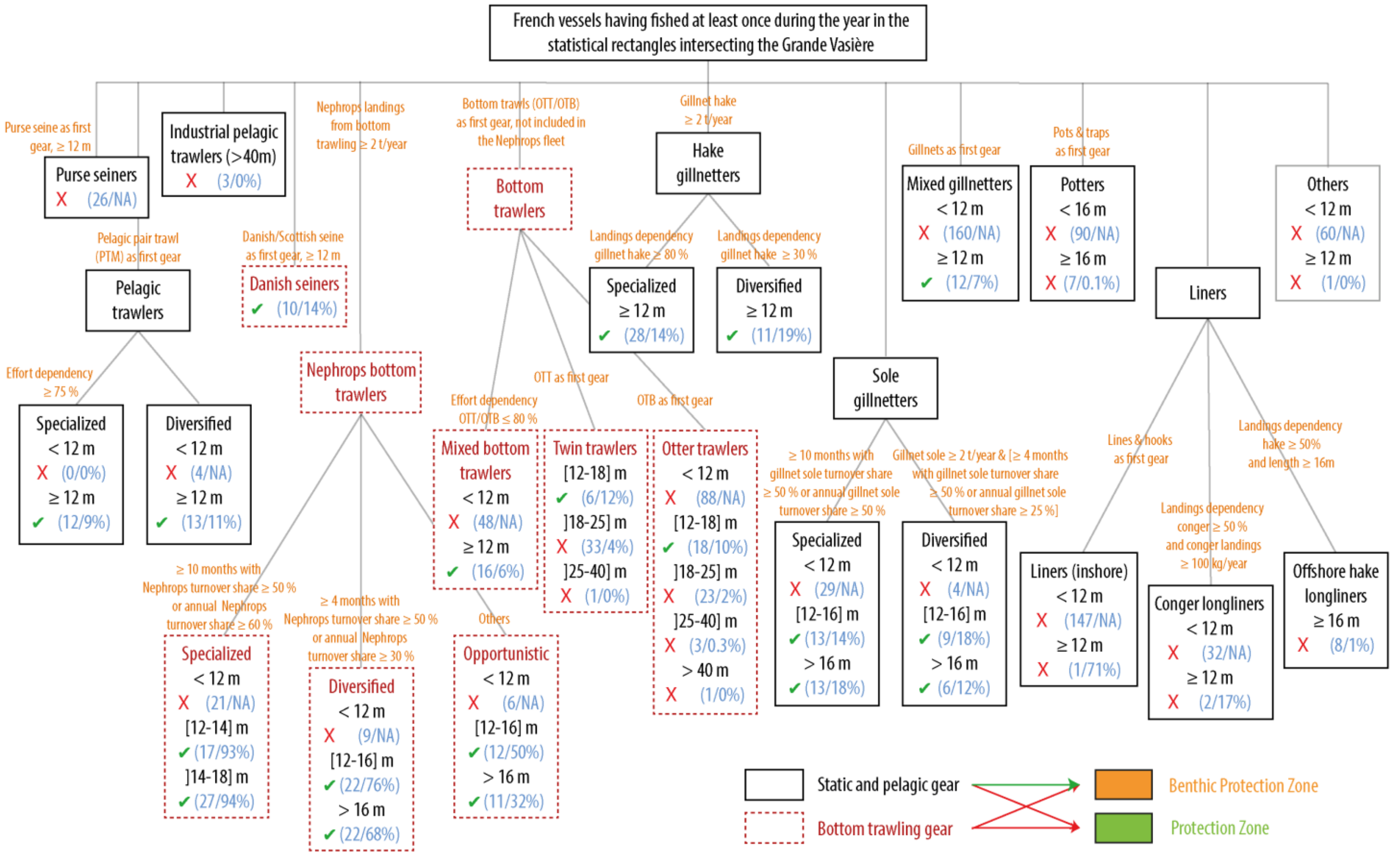
Solan, M., Cardinale, B. J., Downing, A. L., Engelhardt, K. A. M., Ruesink, J. L., and Srivastava, D. S. (2004). Extinction and Ecosystem Function in the Marine Benthos. *Science (1979)* 306, 1177–1180. doi: 10.1126/science.1103960

D) PROVISIONING ECOSYSTEM SERVICES. Yearly landings value (in euros) per planning unit (6.25 km^2) for each of the 18 commercial species.

NEP = Norway lobster (*Nephrops norvegicus*), BIB = Pout (*Trisopterus luscus*), SDV = Starry smooth-hound (*Mustelus asterias*), SOL = Common sole (*Solea solea*), SQZ = Squids (Loliginidae), SRX = Rays (Rajiformes)*, SYC = Small-spotted catshark (*Scyliorhinus canicula*), WHG = Whiting (*Merlangius merlangus*), BSS = Seabass (*Dicentrarchus labrax*), COE = Conger (*Conger conger*), CRE = Brown crab (*Cancer pagurus*), CTC = Common cuttlefish (*Sepia officinalis*), GUR = Red gurnard (*Chelidonichthys cuculus*), HKE = Hake (*Merluccius merluccius*), JOD = John dory (*Zeus faber*), LEZ = Megrim (*Lepidorhombus whiffiagonis*), MNZ = Monkfish (*Lophius* spp), MUR = Red mullet (*Mullus surmuletus*).



Supplementary Fig. S6. Decision tree for classification and selection of fishing fleets in the Grande Vasière, inspired by Lavialle et al. (2014) and updated with the help of fishermen representatives and scientific experts. Numbers in blue correspond to the number of vessels and the dependency on the GV (percentage of turnover inside the GV). Red crosses correspond to fishing fleets that were not selected in the end, because comprised of less than 3 vessels, or with a GV dependency < 5%, or because of known problems to spatialize fishing effort (purse seiners). In this case study, only static and pelagic gear (black boxes) are theoretically allowed in the benthic protection zone compared to bottom trawling gear (dashed red boxes) that are restricted in both type of protection zones.



Supplementary Fig. S7. Map of the best solutions of the equitable scenario (10% maximum yearly landings value for each GPF) for multiple boundary length modifier (BLM) values, showing the repartition of the different zones while validating a 12 GW MRED target, a 10% conservation target for each species and regulating ES, and a 75% target of maintenance of provisioning ES.