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Spatial multi-criteria analysis based on food web model results: application to a marine conservation area

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ABSTRACT

Effective marine management requires balancing conservation and sustainable use of resources. Food web models are useful for simulating direct and indirect effects of management scenarios on ecosystem functioning by using multiple indicators. However, a key challenge is consolidating these indicators into a single, comprehensive, measure, which is often required to guide management decisions, such as in Strategic Environmental Assessment. This study applies spatial multi-criteria analysis to food web model outputs to develop a single index for different marine management applications. We applied this framework to the case of the "Tegnùe di Chioggia", a Special Area of Conservation (SAC; IT3250047) under the Natura 2000 European network, located in the northern Adriatic Sea (Italy). This area, characterised by the presence of biogenic rocky outcrops, currently lacks a formal management plan. Using the Ecospace module of the Ecopath with Ecosim software, we simulated three management scenarios: 1) SAC expansion; 2) winter artisanal fishing in the SAC; 3) a combination of both. In line with ecosystem-based management, we focused on economically important trophic groups in the region, such as the Mediterranean mussel, *Mytilus galloprovincialis,* and striped venus clam, *Chamelea gallina*, which are present near the SAC. We also considered the efforts of the local fishing fleets. Ecosystem structure and functioning indicators, generated by the spatial food-web model, were linked to three criteria aligned with the management priorities of the area: nature conservation, aquaculture productivity, and fishing productivity. These criteria were aggregated into a final score to compare the management scenarios. The results showed that none of the scenarios would significantly alter community composition or ecosystem functioning compared to the current situation. However, they did show contrasting responses in the food web model. The SAC expansion scenario notably increased total biomass and commercial fish biomass, especially pectinids and cephalopods. The fishing scenario had a minimal impact on trophic groups. Ecosystem resilience and structure indicators were less sensitive to management scenarios than biomass indicators. However, the multi-criteria analysis revealed that the fishing scenario limited the benefits of expanding the SAC, due to reduced catches. The final score effectively ranked proposed scenarios, highlighting key indicators that influenced these variations. The proposed approach

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shows potential for supporting participatory modelling and engaging stakeholders in developing management scenarios.

1. Introduction

The global human population's growth is placing immense pressure on natural resources, impacting terrestrial and marine ecosystems (Halpern et al., 2015). Marine ecosystems face a multifaceted challenge, with various overlapping stressors (Kappel, 2005; Halpern et al., 2008; Coll and Libralato, 2012). These stressors encompass activities such as fishing, aquaculture, tourism, maritime transportation, sand extraction, etc., which collectively strain ecosystems and complicate management efforts (Jackson et al., 2001; Lotze et al., 2006). In Europe, to conserve habitats and species while promoting sustainable resource use, Marine Protected Areas (MPAs) have been established through different types of initiatives (Agnesi et al. 2020). These include national designations, regional sea conventions and the Natura 2000 network, which is framed under two European Directives (i.e. 92/43/EEC, 2009/147/EC). Natura 2000 network includes Special Protection Areas (SPAs), Sites of Community Importance (SCIs) and Special Areas of Conservation (SACs). These regulated areas can sustain biodiversity, acting as nurseries, feeding grounds, and refugia (Marcos et al., 2021), and support maritime activities, such as sustainable tourism (Eagles and McCool, 2002) and environmental education.

Considering the different and simultaneous challenges in marine ecosystems is essential for producing a sound environmental management (Curtin and Prellezo, 2010). On multiple occasions, management strategies focused on single species, limited areas, and target economic sectors, and failed to balance resource utilization and conservation goals (Levin et al., 2009; Leslie and McLeod, 2007; Menzel et al., 2013). A more holistic view is promoted by the ecosystem-based management (EBM), embraced by current international policy frameworks and directives, such as the European Maritime Spatial Planning Directive (MSPD; EC 2014/89/EU) and the Marine Strategy Framework Directive (MSFD; 2008/56/EC). The ecosystem-based management considers both the natural and human dimensions of a system (Arkema et al., 2006; Tallis et al., 2010; Menzel et al., 2013) and seeks to balance economic growth and ecosystem conservation, accounting for changing environmental and socio-economic conditions (Curtin and Prellezo, 2010; Katsanevakis et al., 2011). Yet, EBM is not always applied successfully, especially in the case of limited data and resources for research (Tallis et al., 2010; Berg et al., 2015).

Despite considerable technical efforts in their development, ecological models support the implementation of EBM, simplifying complex ecosystem interactions and phenomena, while maintaining predictive and forecasting capabilities, especially in management scenario simulations (Coll and Libralato, 2012; Shabtay et al., 2018). Food web models have been used extensively to represent the complex dynamics of marine ecosystems (Tam et al., 2017); in particular, these models capture trophic interactions among species or functional groups, and socio-economic actors (e.g., fishing fleets) in different scenarios.

Ecological models produce ecological indicators, proxies to quantify and monitor model information, making it more manageable and comparable (Smit et al., 2021; Karnauskaitė et al., 2019). Indicators effectively support decision-making, especially when they are easy to communicate and understand (Tam et al., 2017; Karnauskaitė et al., 2019). However, numerous sets of indicators are available, as long as various application frameworks, being overly general and, consequently, inadequate for meeting the specific objectives of management applications (Karnauskaitė et al., 2019). The absence of a standardised framework for practical applications is often attributed to insufficient political and scientific endorsement, data limitations, and uncertainty regarding potential benefits (Reed et al., 2006; Schernewski et al., 2014). Aggregating diverse indicators into a single measure can simplify the description of complex ecosystem transformations under synergistic pressures (Elliott et al., 2018) has led to the exploration of various indicator integration methods (Borja et al., 2016), each presenting its own distinct limitations (Borja et al., 2012; Borja et al., 2014; Villnäs et al., 2015).

This study aims to address the needs of the EBM by integrating various ecosystem indicators into a single, easily interpretable score for environmental planners and stakeholders. To do so, for the first time, we apply multi-criteria analysis, a tool commonly used in environmental planning, to the outputs of a food web model.

Multi-criteria analysis is a synthetic mathematical evaluation of multiple alternative scenarios, which can have an explicit spatial dimension (spatial multi-criteria analysis), based on different criteria, often in conflict with the decision-making process (Chakhar and Mousseau, 2017; Khalili and Duecker, 2013). Multi-criteria analysis has been applied to assist in zoning within marine protected areas, across national borders, in coastal areas, and for large-scale marine management (Stelzenmüller et al., 2013; Tammi and Kalliola, 2014; Dapueto et al., 2015; Portman et al., 2016; Nelson and Burnside, 2019). Spatial Multi-Criteria Analysis (SMCA) is used for evaluating and ranking alternative scenarios with a spatial dimension (Chakhar and Mousseau, 2017).

The study focuses on the Special Area of Conservation (SAC) "Tegnùe di Chioggia". According to the Habitat Directive (92/43/EEC), a Site of Community Interest (SCI) must be designated as a SAC within six years of its establishment, accompanied by specific management and conservation measures. However, such a plan is still missing for the "Tegnùe di Chioggia". With this tool we aim to support the evaluation of different management measures for the study area, such as its expansion, the introduction of regulated artisanal fishery, or their combination. We also aimed to understand how various management scenarios would impact the spatial dynamics of trophic levels and related fishing activities.

2. Methods

2.1. The study area

In the north-western Adriatic Sea, mesophotic biogenic reefs, locally called *tegnùe*, are arrayed over the muddy–sandy bottom of a large area of the continental shelf at depths ranging from 15 to 40 m (Tosi et al., 2017; Gordini et al., 2023). They serve as natural hard substrates, fostering spatially heterogeneous assemblages, providing habitats for sessile species (Ponti et al., 2011; Falace et al., 2015; Fava et al., 2016; Gianni et al., 2023) and playing moreover a crucial role for the local fish communities in terms of food source, nursery, and refuge area (Casellato et al. 2007). Recognised for its ecological importance, the marine area of "Tegnùe di Chioggia" was initially designated as Biological Protection Zone in 2002 (DM 05-08-2002), and ultimately received Special Area of Conservation (SAC) status under the European Habitat Directive in 2018 (92/43/EEC; DM 27-07-2018; Code: IT3250047). However, being located off the shores near the city of Chioggia (Fig. 1), the site is subjected to multiple pressures, primarily of anthropogenic origin, including the presence of mussel farms, maritime traffic routes, sand extraction sites, and trawling and mechanical dredging fishing activities (Pranovi et al. 2000; Melli et al. 2017; Moschino et al. 2019).

2.2. Food web model for the "Tegnùe di Chioggia"

EwE is a free software (https://ecopath.org/) used for modelling marine trophic networks (Christensen and Walters, 2004). Version 6.6 was used for the present study. EwE has three main components:

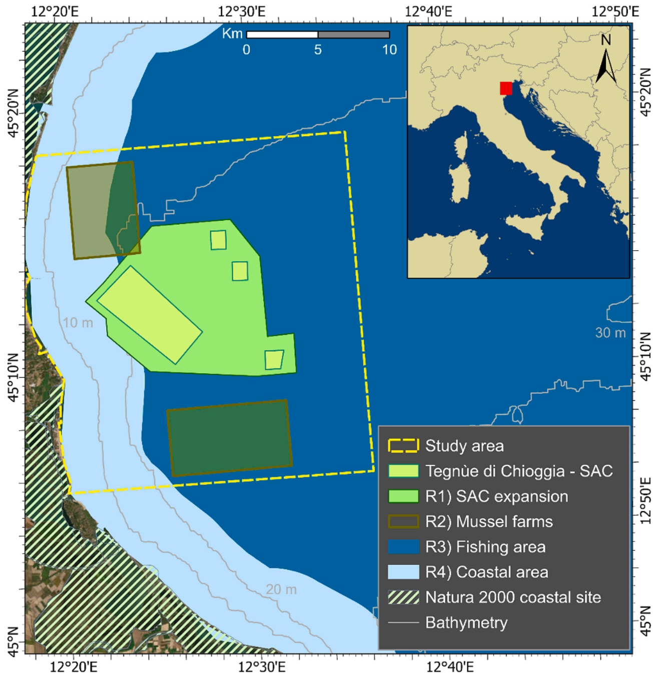


Fig. 1. Study area. Natura 2000 site "Tegnùe di Chioggia" is marked in green boxes. The extension of the model domain is marked in yellow dashed line. Regions where indicators for the multi-criteria analysis were extracted are shown. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

- Ecopath – a static, balanced snapshot of the mass of the trophic network (Christensen and Pauly, 1992);
- Ecosim – a dynamic temporal module, used to simulate temporal variation of trophic groups biomass and analyse the efficiency of management policies (Walters et al., 1997);
- Ecospace – a spatial and temporal dynamic module designed primarily to explore the effectiveness of marine protected areas (MPAs) establishment (Christensen et al., 2009; Walters, 1999).

In the case of "Tegnùe di Chioggia", we adapted a previous Ecopath model of the northern Adriatic Sea (Libralato et al., 2015). This version initially featured 22 trophic groups, from primary producers, to fish compartments. It also incorporated various fishing fleets, including pelagic mid-water trawl (*Volante*), beam trawl (*Rapido*), otter trawl (*Coccia*), hydraulic dredges (*Vongolara*), artisanal fishing, and recreative fishing (Lucchetti et al. 2023). We introduced the trophic group *Mytilus galloprovincialis* (Lamarck, 1819; MYT), to represent the presence of mussel farms in the area, and the trophic group *Chamelea gallina* (Linnaeus, 1758; CHA), which replaced the existing group of the family Veneridae. We also included trophic groups specific to rocky outcrops: Primary producers (PPT); Filter feeders (FFT); *Pagellus erythrinus* (Linnaeus, 1758; PAG); *Spicara smaris* (Linnaeus, 1758; SPI) and *Diplodus annularis* (Linnaeus, 1758; DIP).

A comprehensive list of trophic groups and species is provided in Appendix A. To parameterize these additional trophic groups, we drew from literature sources (Sala et al., 2012; Šantić et al., 2011a; Šantić et al., 2011b; Karachle and Stergiou, et al., 2014), databases (Fishbase.org and Sealifebase.org), or assumed parameter values identical to those of similar trophic groups, already included in the model. The mean percent cover of the rocky outcrop organisms (PPT and FFT) has been estimated through photographic sampling as in Ponti et al. (2011). For primary producers (PPTs), which included calcareous and non-calcareous algae, we estimated the wet mass per unit area of the trophic group through cover-biomass conversion factors (for benthic bioconstruction rate, see also Turicchia et al., 2022). The mussel (MYT) diet matrix was updated to account for both phytoplanktonic and non-phytoplanktonic carbon in the water column, assuming non-selective filtration (Brigolin et al., 2009). Assuming a one-year lifespan (P/B = 1), the average mussel farm biomass was estimated at 180 t km-2, based on an average individual weight of 0.6 g and a harvest weight of 1 g (Brigolin et al., 2009).

To balance the network, we incrementally adjusted biomass, parameters, and diets of the most unbalanced trophic groups, starting with the most uncertain parameters (Heymans et al., 2016).

2.3. Food web model spatialisation in Ecospace

Ecospace estimates the spatial distribution of functional group biomasses on a 2-D horizontal grid (Walters, 1999; Pauly, 2000). Each trophic group can be spatialised as it is assigned to specific habitats within the study area, or based on its tolerance responses to different environmental factors; the combination of environmental responses defines the 'capacity' of each grid cell to forage the trophic group (value from 0 to 1; Christensen et al., 2014; Hernvann et al., 2020); the capacity then determines the distribution of trophic group biomass across space (Christensen et al., 2014). Ecospace also provides a plugin to easily extract a set of ecosystem indicators (ECOIND; Coll and Steenbeek, 2017). By modifying the spatial inputs of the food web model, different management scenarios can be simulated. The spatial food web model for the "Tegnùe di Chioggia" was built to reflect environmental and trophic groups biomass gradients. Three base maps were integrated into the study: a) study area defined with a grid of spatial cells at 1 km resolution; b) primary productivity map, quantifying the chlorophyll-a concentration in the water column, normalised between 0 and 1, obtained from Copernicus Marine Service for the Mediterranean Sea (Ocean-colour-MED-CHL-L4, doi: 10.48670/moi-00110; spatial resolution of 0.1 × 0.1 km upscaled to 1 km); c) bathymetric profile, characterizing the underwater topography (EMODnet Digital Bathymetry DTM, https://emodnet.ec.europa.eu/; spatial resolution of 0.115 km, upscaled to 1 km).

Within our study area, we delineated four distinct habitats based on seabed composition and the presence of mussel farms in the water column. Seabed types included sandy bottoms and muddy bottoms, with percent coverage data obtained from EMODnet Seabed substrates Multiscale (https://drive.emodnet-geology.eu). Additionally, rocky outcrops were identified, with percent coverage estimated from various studies including Ponti (2020a, 2020b), Fortibuoni et al. (2020a, 2020b), Gordini and Ciriaco (2020), and Andreoli et al. (2010). Finally, the presence or absence of mussel farms was included, with percentage coverage sourced from the "Mariculture – Adriatic Sea" spatial layer (Emilia-Romagna Region, 2015) downloaded from the Adriatic ATLAS of the SHAPE Project Tools4MSP Geoplatform (https://geoplatform.tools4msp.eu/). To account for the habitat preference of trophic groups in these environments, we assigned preference coefficients ranging from 0 to 1 based on expert knowledge (Appendix B). Moreover, for specific trophic groups, such as *C. gallina* (CHA), Pectinidae (PEC), Benthic feeders (BFD), Cephalopods (CPH), Flat fishes (FFS), Nekton feeders (NFD), Planktivorous fishes (PLT), *D. annularis, S. smaris, and P. erythrinus* (see Appendix A), we considered environmental responses to bathymetry (Appendix C), following the approach by Bentley et al. (2017). This environmental response assesses the suitability of bathymetry to the presence of these species and contributes to defining each cell capacity for supporting these trophic groups (Christensen et al., 2014; Hernvann et al., 2020). Bathymetric optima were calculated based on data from Aquamaps (https://aquamaps.org/) with the optimal bathymetry determined as the mean of the minimum and maximum bathymetric optima for each species (Appendix C). In cases where trophic groups comprised multiple species, the optimal bathymetric range was calculated by averaging species-specific values within the group. To assess bathymetric tolerance, we computed standard deviations for both minimum and maximum bathymetric optima based on species

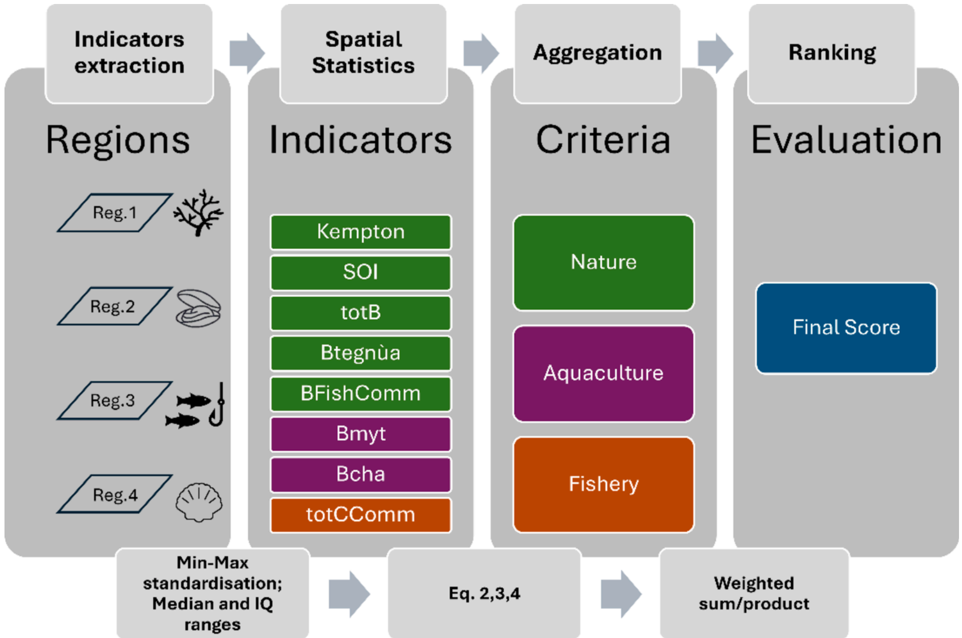


Fig. 2. The multi-criteria analysis process. Indicators from Ecospace spatial outputs are extracted in relevant regions. After a min–max standardisation, median and IQ ranges are calculated for each indicator. Indicators are coloured according to the corresponding criteria. Criteria are then computed using Eqs. 2, 3, and 4, followed by a weighted sum and product to determine the final scenario score.

occurrence data (Bentley et al., 2017). This allowed us to construct skewed normal bathymetry tolerance curves for each trophic group. In the absence of species composition data for biomass and catch in the area, we assumed equal contributions from each species to the bathymetric suitability profile for the trophic group.

Within the study area, three fishing closure zones were delineated. The first is the "Tegnùe di Chioggia" SAC, which remains closed to fishing year-round for all types of boats. The second encompasses the coastal zone within 3 nautical miles (NM), where trawling is prohibited throughout the year for vessels such as pelagic mid-water trawl, beam trawl, and otter trawl. Lastly, there is the clam dredging no-take zone, which restricts *C. gallina* harvesting within 3 m of bathymetry. For dispersal rates (intrinsic random mobility of the species), we adopted values based on the study by Fouzai et al. (2012), fixing values at a rate of 300 km y^{-1} for pelagic species, 30 km y^{-1} for demersal species, and 3 km y^{-1} for sessile or poorly mobile species.

2.4. Model corroboration

Before analysing indicators and developing management scenarios, we compared fishing effort maps obtained from the steady-state Ecospace base model with real-world data, collected using the Automated Identification System (AIS) from the pelagic mid-water trawl and the beam trawl (Russo et al., 2020). We calculated annual average fishing effort indices at a 1 km cell resolution.

To assess the correlation between paired maps, we used Pearson's product-moment correlation coefficient with the *cor.test()* function from the *stats* package in R software v4.3.3. We conducted the test 1000 times on randomly selected subsamples of 100 cells from the study area, as recommended to mitigate potential spurious correlations due to large sample sizes (Haig, 2003; Ward, 2013). The test was repeated excluding cells where fishing effort was zero due to fishing restrictions. Finally, we determined the average correlation coefficient on the repeated tests and the percentage of significant correlations ($\alpha = 0.05$).

2.5. Management scenarios considered

The proposed management options seek to balance biodiversity conservation and the socio-economic well-being of the study area. These alternative measures comprise:

- SAC expansion: stands for the unification of the entire portion of sea laying within the perimeter of the currently protected spots, thus promoting connectivity and dispersion (ECOSS D3.2.1, 2020; Piazzi et al., 2012).
- Fishing in the Special Area of Conservation: controlled winter artisanal fishing openings, inspired by successful examples like the Torre del Cerrano Marine Protected Area (Vallarola et al., 2015; SAC IT71202015), could control impacts on fish stocks and foster collaboration with fishermen to prevent major offenses to the habitat.

Table 1
Criteria, indicators and respective regions used in the analysis. Region codes used in Eqs 2–4 are: 1 for Special Area of Conservation (SAC); 2 for mussel farms area; 3 for fishing area; 4 for coastal area.

Criteria	Indicator	Unit	Description	Region
Nature	totB	t km^{-2}	Total biomass (B)	Reg. 1 (SAC area)
Nature	Btegnua	t km^{-2}	Biomass of species associated with the presence of rocky bottoms	Reg. 1 (SAC area)
Nature	BFishComm	t km^{-2}	Biomass (B) of commercial fish species	Reg. 1 (SAC area); Reg. 3 (Fishing Area)
Nature	K		Kempton's Q index	Reg. 1 (SAC area) and outside Reg. 1
Nature	SOI		System Omnivory Index (Hernvann et al., 2020; Libralato, 2013)	All model domain
Fishery	totCComm	t $km^{-2}year^{-1}$	Total catch (C)	Reg. 3 (Fishing area)
Aquaculture	Bmyt	t km^{-2}	Biomass of *M. galloprovincialis*	Reg. 2 (Mussel farms)
Aquaculture	Bcha	t km^{-2}	Biomass (B) of *C. gallina*	Reg. 4 (Coastal area)

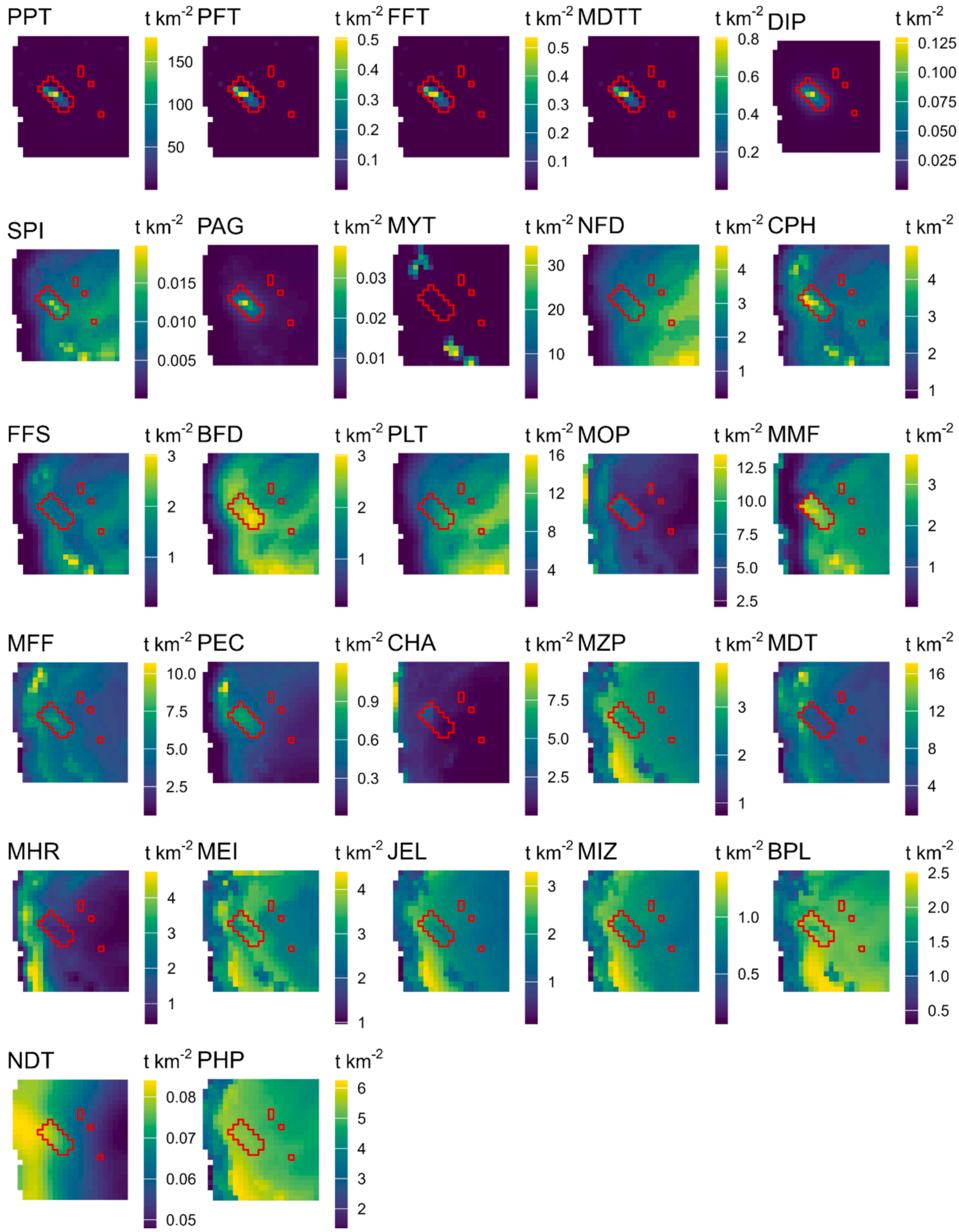


Fig. 3. Ecospace biomass outputs. Maps produced by Ecospace showing the biomass distribution (t km^{-2}) of the trophic groups for the baseline scenario at the steady state. In red, the borders of the SAC. Primary Producers Tegnùe (PPT), Porifers Tegnùe (PFT), Filter Feeders Tegnùe (FFT), Macrobenthic Detritivorous Tegnùe (MDTT), *Diplodus annularis* (DIP), *Spicara smaris* (SPI), *Pagellus erythrinus* (PAG), *Mytilus galloprovincialis* (MYT), Nekton Feeders (NFD), Cephalopods (CPH), Flat fish (FFS), Benthic Feeders (BFD), Planktivorous Fish (PLT), Nekton Detritivorous Feeders (NDT), Macrobenthic Predators (MOP), Macrobenthic Mixed Feeders (MMF), Macrobenthic Filter Feeders (MFF), *Chamelea gallina* (CHA), Pectinidae (PEC), Mesozooplankton (MZP), Macrobenthic Detritivorous (MDT), Meiobenthos (MEI), Jellyfish (JEL), Microzooplankton (MIZ), Bacterioplankton (BPL), Phytoplankton (PHP), Carcass (CAR), Detritus (DET). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

- Combination of expansion and fishing in the Special Area of Conservation: exploring a combined approach to account for synergistic effects resulting from the implementation of multiple scenarios.

2.6. Spatial multi-criteria analysis

SMCA combines standardised spatial layers to synthesise complex information generated by management scenarios, affecting both the ecosystem and different production sectors. Each scenario is assessed using a combination of criteria, which represent essential factors in evaluating the spatial alternatives, measurable through an array of indicators. The assignment of weights to these criteria reflects their relative importance in the decision-making process. The analysis is schematically represented in Fig. 2. We identified three criteria (Nature, Fishery, Aquaculture) for the "Tegnùe di Chioggia", each quantified by one, or more, ecosystem structure, functioning and biomass indicators (Table 1). We used the ECOIND plugin, available with the free EwE software version (Coll and Steenbeek, 2017), to derive the Kempton's Q index, a measure of evenness and functional diversity of the ecosystem (Hernvann et al., 2020; Piroddi et al. 2022). This plugin simplifies the generation of standardised tables, time-plots, or indicator maps for Ecopath, Ecosim, and Ecospace, respectively. The System Omnivory Index (SOI; Libralato, 2013) was calculated following the approach of Hernvann et al. (2020), using absolute biomass distribution maps of trophic groups per km^{-2} from Ecospace, and Ecopath's estimations of Trophic Level and Omnivory Index. SOI assesses trophic network complexity and connectivity (Libralato, 2013; Hernvann et al., 2020), giving an indirect measure of the resilience of the ecosystem. Biomass and catch indicators were calculated from the basic spatial outputs of Ecospace, aggregating trophic groups of interest. All these indicators were subjected to a min–max standardisation of their spatial maps, considering the minimum and maximum values across scenarios. Subsequently, median and interquartile range values for each indicator were calculated for specific sub-regions of interest (Reg. 1 = SAC area; Reg. 2 = mussel farms; Reg. 3 = fishing area outside the 3 NM; Reg. 4 = coastal area; Table 1). Indicators are then aggregated to calculate the respective criteria, which in the end are use to derive the Final Score (FS). The final score was calculated using a weighted combination of the criteria (C_{nature}, $C_{fishing}$, $C_{aquaculture}$; Eq. (1a and 1b)). We used both the weighted sum (Eq. (1a)) and weighted product methods (Eq. (1b)) to see how sensitive the results were to the combination approach. We assigned a weight (α) to each criterion (C), reflecting its importance.

$$FS = (\alpha_{nature} \cdot C_{nature}) + (\alpha_{fishing} \cdot C_{fishing}) + (\alpha_{aquaculture} \cdot C_{aquaculture}) \quad (1a)$$

$$FS = (\alpha_{nature} \cdot C_{nature}) \cdot (\alpha_{fishing} \cdot C_{fishing}) \cdot (\alpha_{aquaculture} \cdot C_{aquaculture}) \quad (1b)$$

Different weight combinations, adding up to 1, were tested to represent 3 different priorities between nature conservation goals and socio-economic objectives: "equal weight" ($\alpha_{nature} = \alpha_{aquaculture} = \alpha_{fishery} = 0.33$); "equal priority to nature and socio-economic activities" ($\alpha_{nature} = 0.50$; $\alpha_{aquaculture} = \alpha_{fishery} = 0.25$); "nature priority" ($\alpha_{nature} = 0.90$; $\alpha_{aquaculture} = \alpha_{fishery} = 0.05$). Each criterion was calculated as the mean of its associated indicators extrapolated in the relevant regions (Table 1 and Eq. (2), (3) and (4) where apeces indicate regions where the indicator was extracted). If an indicator spanned multiple regions (Table 1), we calculated the mean values for those regions before criterion aggregation (Eq. (2), (3) and (4)).

$$C_{nature} = mean(mean(K^1, K^{2,3,4}), totB^1, Btegnua^1, BFishComm^1, SOI^{1,2,3,4}) \quad (2)$$

The Nature criteria (Eq. (2)) is the mean of the Kempton's Q index median value in Reg. 1 and in Reg. 2, 3, 4 separately and then averaged together; the total biomass (totB) in Reg. 1 (median value); the biomass of tegnùe (Btegnua) species in Reg. 1 (median value) and the SOI in Reg. 1, 2, 3, 4 (median value).

$$C_{fishery} = totCComm^3 \quad (3)$$

The Fishery criteria (Eq. (3)) is the total catches of commercial fish (totCComm) in Reg. 3 (median value).

$$C_{aquaculture} = mean(Bmyt^2, Ccha^4) \quad (4)$$

The Aquaculture criteria (Eq. (4)) is the mean value of the biomass of *M. galloprovincialis* (Bmyt) in Reg. 2 (median value) and the catched of *C. gallina* (Bcha) in Reg. 4 (median value).

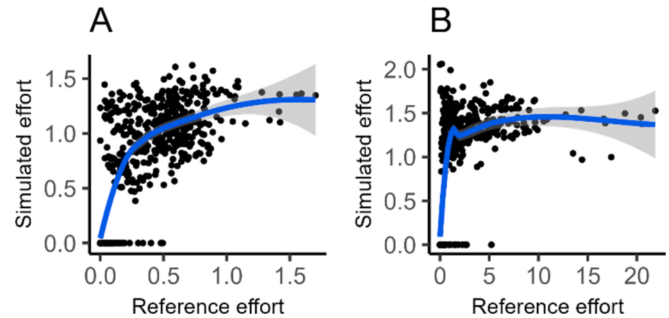


Fig. 4. Scatterplots of AIS and simulated efforts. Simulated effort from the Ecospace module is plotted against observed effort from AIS for the pelagic mid-water trawl fleet (A) and the beam trawl fleet (B) to show their correlation.

3. Results

3.1. Spatialisation of the food web: Biomasses and corroboration

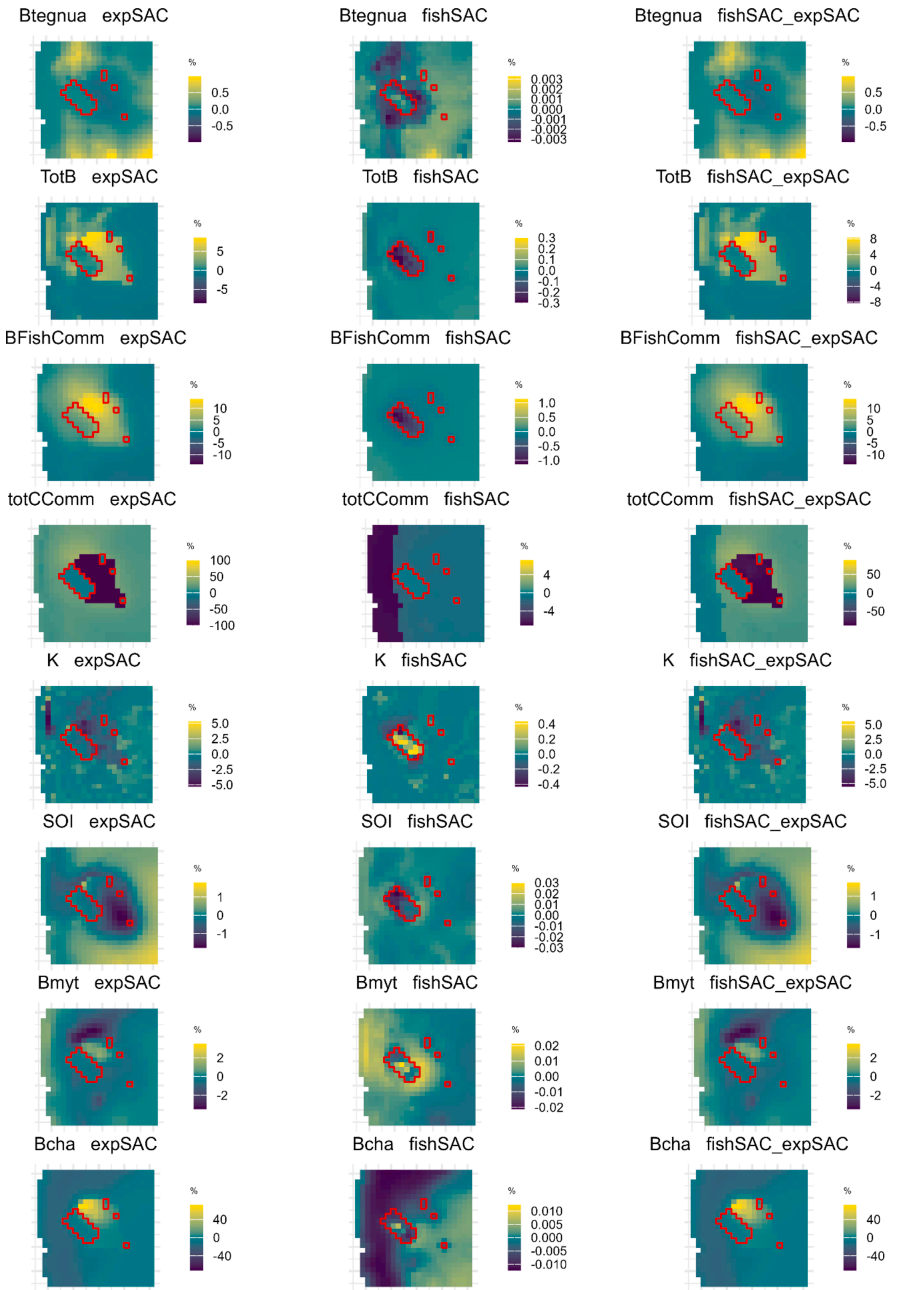
The spatialisation of the food web, driven by environmental factors (Fig. 3), mirrored biomass gradients for trophic groups expected from the general ecological knowledge of the area. Trophic groups associated with rocky outcrops notably clustered in the SAC, peaking Primary Producers Tegnùe (PPT) biomass density at around 20 t km^{-2}. The fish community responded to spatialisation, with tegnùe habitat species (*D. annularis* and *P. erythrinus*) with maximum concentration at 0.15 t km^{-2} and 0.015 t km^{-2} (Fig. 3; DIP and PAG). *S. smaris*, due to its higher dispersal rate (fixed at 300 km year $^{-1}$; Fouzai et al., 2012), exhibited a more homogeneous distribution (Fig. 3; SPI).

Some trophic groups benefited from the SAC, leading to increased biomass concentrations (Fig. 3; CPH, SPI, MMF, BFD, PEC). Specific examples include Macrobenthic Predator and Macrobenthic Mixed Feeders, significant components of the bycatch of the professional fishing fleets in the food web model, with a maximum value of 13 t km^{-2} and 4 t km^{-2} respectively. Cephalopods showed a twofold increase in biomass density within the SAC Area, indicating a possible protective effect (Fig. 3; CPH, 5 t km^{-2}). The presence of mussel farms showed a positive effect on the biomasses of trophic groups like Flat Fishes, Cephalopods, Macrobenthic Filter Feeders and Pectinidae (Fig. 3; FFS, CPH, MFF, PEC). Invertebrate trophic groups (MOP, MMF, MFF, CHA, PEC) exhibited higher biomass concentrations nearby the coastline, reflecting the positive gradient of trophic resources in these regions (Fig. 3).

The corroboration attempt led to an average correlation for the pelagic mid-water trawl fleet of 0.70, with 100 % significant correlations. However, this value is reduced to 0.36 (97.5 % of significant correlations) when cells without fishing effort are not considered. When compared with the observed fishing effort data obtained through AIS (Russo et al., 2020), the fishing effort simulated by the base model in Ecospace showed only a partial positive correlation with the AIS-derived data (Fig. 4). In the case of the beam trawl, the average correlation was 0.45, with 100 % of the correlations significant, but it dropped to just 0.17 (37.1 % significant correlations) when only cells with positive effort values were considered.

3.2. Ecosystem indicators

While some indicators showed low percentage variation, observed spatial patterns of indicator values revealed that management scenarios had a notable influence on the spatial dynamics of different trophic groups. The SOI decreased slightly in proximity of the SAC when the protected area was expanded (Fig. 5; SOI – expSAC), while both biomass of commercial fish and total biomass increased by around 5–10 % in the SAC area (Fig. 5; BFishComm and totB – expSAC). Interestingly, the Kempton's Q index increased slightly on the rocky outcrops (~ 0.5 %)



(caption on next page)

Fig. 5. Variation (%) in space of absolute indicators values. Indicators for the three implemented scenarios were compared in % variation to the baseline scenario (fishSAC_expSA = fishing in the SAC combined with SAC expansion; fishSAC = fishing in the SAC alone; expSAC = expansion of the SAC). In red, the borders of the SAC. Bcha: Biomass of *Chamelea gallina* (t km^{-2}); Bmyt: Biomass *Mytilus galloprovincialis* (t km^{-2}); SOI: System Omnivory Index; BFishComm: Biomass of Commercial fish species (t km^{-2}); K: Kempton's Q index; totCComm: Total Catch of Commercial species (species caught by professional fleets; t km^{-2}); Btegnua: Biomass of tegnùe species (t km^{-2}); TotB: Total Biomass of all species (t km^{-2}). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

with the winter opening to artisanal fishing in the SAC (Fig. 5; K – fishSAC).

Looking at the spatial statistics (Fig. 6), in response to SAC expansion scenario, total biomass (totB) increased by ~2 % in the SAC area, while commercial fish biomass (BFishComm) increased by ~ 1 % (Fig. 6; totB and BFishComm – expSAC). This increase occurred independently or combined with artisanal fishery initiation, suggesting the SAC expansion scenario drove the observed increase. Total biomass rise (Fig. 6; totB Reg1:SAC) was driven primarily by a significant Pectinidae (~50 %) and Cephalopods (~20 %) increase, followed by Benthic Feeders, *C. gallina*, Macrobenthic Predators, Nekton Detritivorous feeders, Flat Fishes, Macrobenthic Mixed Feeders, Nekton Feeders, Macrobenthic Filter Feeders, Meiobenthos, and Planktivorous fishes groups (~10 % or less biomass variation; Fig. 7, Reg.1:SAC). Total catch beyond the 3 NM coastal boundary increased (Fig. 6; totCComm, Reg3:FishingArea) with SAC expansion (~18 %), less when coupled with fishing (~17 %). Around 2–3 % increase for Nekton Feeders (NFD) and Flat Fishes (FFS) biomass was observed in Reg. 3 when expanding the SAC (Fig. 7, Reg. 3), regardless of the artisanal fishing; however, the median value of commercial fish biomass in the region did not detect this variation (Fig. 5; BFishComm – expSAC; Fig. 6; BFishCom, Reg3:FishingArea). The expansion of the SAC prohibited fishing in previously allowed areas (small corridors of sandy and muddy bottoms among rocky outcrops), leading to a complete cessation of catches (totCComm; Fig. 5 and Fig. 6). Conversely, *C. gallina* biomass (Bcha) declined (~7.5 %) in the coastal area with the SAC expansion, also when combined with artisanal fishery opening in the area (Fig. 6; Bcha, Reg4:Coast). Ecosystem indicators such as Kempton's Q index and SOI fluctuated by 1 % of the variation (Fig. 5 and Fig. 6). The SOI had a contrasting trend between mussel farms (increasing; Fig. 6, Reg2:Farms) and the SAC area (decreasing; Fig. 6, Reg1:SAC) in the expansion scenario, regardless of the artisanal fishing. This could be attributed to divergent changes in Pectinidae and *C. gallina* biomass, with an increase of both groups observed in the SAC and a decrease in mussel farms, for both mentioned scenarios (Fig. 7, Reg. 1 and 2). Both groups are impacted by resource competition (PHP), particularly in densely populated mussel farming facilities.

3.3. Spatial multi-criteria analysis

The spatial multi-criteria analysis was insensitive to the aggregation method, whether employing the weighted sum or the weighted product procedure (see Tables 2 and 3), consistently favouring the baseline scenario. In scenarios with equal priority (Table 2) the baseline exhibited the highest Final Score (FS) at 0.434, exceeding values of 0.390 for SAC expansion, 0.432 for artisanal fishing in SAC, and 0.398 for their combination. A marked decline of the Fishery criterion was observed in the SAC expansion scenario, logically as a result of excluding fishery activities in a larger area (Table 2): normalised total catches (totCComm) declined from 0.114 in the baseline to 0.072 in the SAC expansion, compensated slightly in combined scenarios (0.081). Even the opening to artisanal fisheries showed a slight decrease (Table 2) in fishery catches (0.114 to 0.112), possibly due to increased fishing pressure within the SAC. SAC expansion slightly enhances Nature criterion performance (0.131 to 0.133; Table 2), linked to improvements in SOI and total biomass (0.286 to 0.299 and 0.449 to 0.474, respectively). However, Aquaculture criterion decreased when expanding the SAC, also in combination with artisanal fishing, mainly due to the reduced *C. gallina* biomass (Table 2; Bcha, from 0.484 to 0.452). Applying equal priority to nature and socio-economic activities (Aquaculture and Fishery criteria) maintained the higher performance of the baseline (FS 0.428; Table 3), while SAC expansion yielded 0.395, artisanal fishery in SAC 0.427, and the combined scenario 0.402 (Table 3). Finally, when increasing nature priority, the benefits of SAC expansion emerged, also when combined with artisanal fishing, scoring similarly to the baseline scenario (Table 3). In contrast, with same priority to nature and socio-economic activities, the combination of expanding the SAC and artisanal fishing scored less than the baseline scenario (0.402 and 0.428 respectively; Table 3).

4. Discussion

In this study, it was possible to test, on a real case study, the applicability of a novel procedure to support the comparison of alternative management scenarios of a Special Area of Conservation. Outputs of a spatially explicit food web model were combined through a spatial multi-criteria analysis. This allowed the production of a synthetic final score for each management scenario. The food web spatialisation, driven by environmental factors, reproduced biomass gradients for the different trophic groups that match the general knowledge of distribution patterns in the area. Comparing the spatialised results of the model with the general ecological knowledge available on the area follows the approach recently used by Anelli Monti et al. (2021). Notably, trophic groups associated with rocky outcrops clustered within the SAC area. The SAC demonstrated a positive effect on trophic groups affected by fishery, like Macrobenthic Predators, Macrobenthic Mixed Feeders, and Cephalopods, accounting for significant components of the bycatch of professional fishing fleets. The same pattern was also evident in Macrobenthic Filter Feeders and Pectinidae. Interestingly, mussel farms provided shelter for trophic groups such as Flat Fishes and Cephalopods, resembling the effect observed in marine protected areas. However, biomass concentration at mussel farms did not achieve the expected values (180 t km^{-2}; Brigolin et al., 2009). Invertebrate trophic groups exhibited higher biomass concentrations in proximity to the coastline, reflecting the higher concentration of trophic resources in these nearshore regions and the suitable conditions for their survival (Cerrano et al., 2015). The model highlights how crucial it is to include spatial information on morphological and environmental gradients, and maritime activities when modelling food webs, since local habitat diversity and human impacts greatly influence the abundance of important trophic groups. In the present work, to test a quantitative way of analysis, we additionally attempted to compare the fishing effort distribution maps derived from the AIS with those generated by Ecospace. However, only a partial correlation was found when cells with fishery restrictions (zero fishing effort) were excluded from the analysis (e.g., SACs). This highlights the sensitivity of correlations to data selection. Moreover, the partial failure in reproducing observed fishing effort patterns may be attributed to the omission of significant migrations of some trophic groups, particularly cephalopods, which constitute a substantial portion of the fishery catches and seasonally drive the distribution of the fleets in the sea (Barausse et al. 2011; Bettoso et al. 2015).

The selected indicators used to compare management strategies showed intricate interactions within the food web. The aim was to understand how different management scenarios would impact the dynamics of trophic levels and fishing activities. SAC expansion was the key factor driving the observed indicators changes, especially in total biomass and commercial fish biomass, while fishing scenarios had a

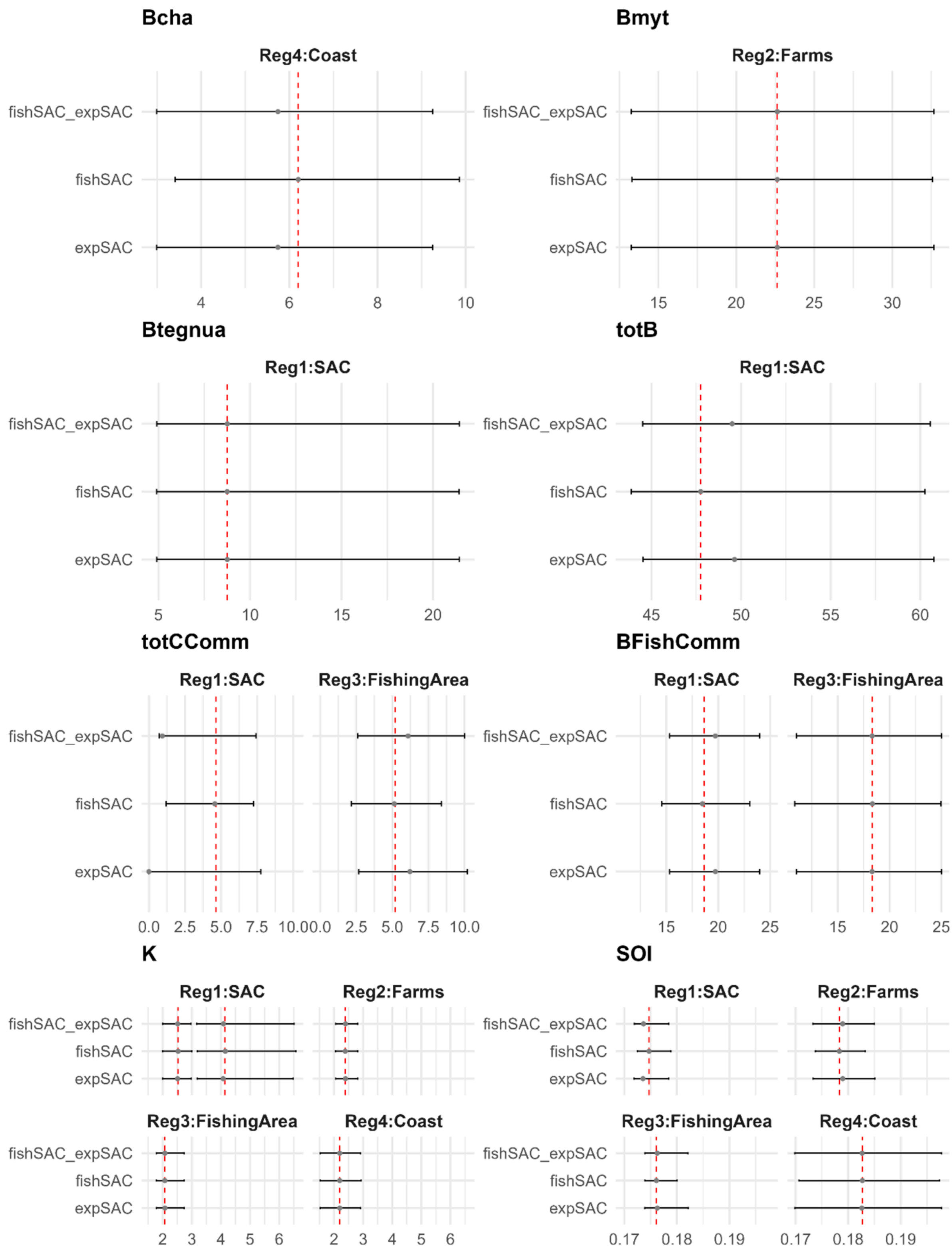


Fig. 6. Absolute indicators value variations. Indicators median values pre-normalization and interquartile ranges, in each region and for each scenario (fishSAC_expSAC = fishing in the SAC combined with SAC expansion; fishSAC = fishing in the SAC alone; expSAC = SAC expansion) compared to the baseline scenarios (red dashed line) in the relevant areas. From the top left to the bottom right: Biomass of *Chamelea gallina*; Biomass of *Mytilus galloprovincialis*; Biomass of tegnùe species; Total Biomass of all species; Catches of commercial fish species; Biomass of commercial fish species; Kempton's Q index; System Omnivory Index. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

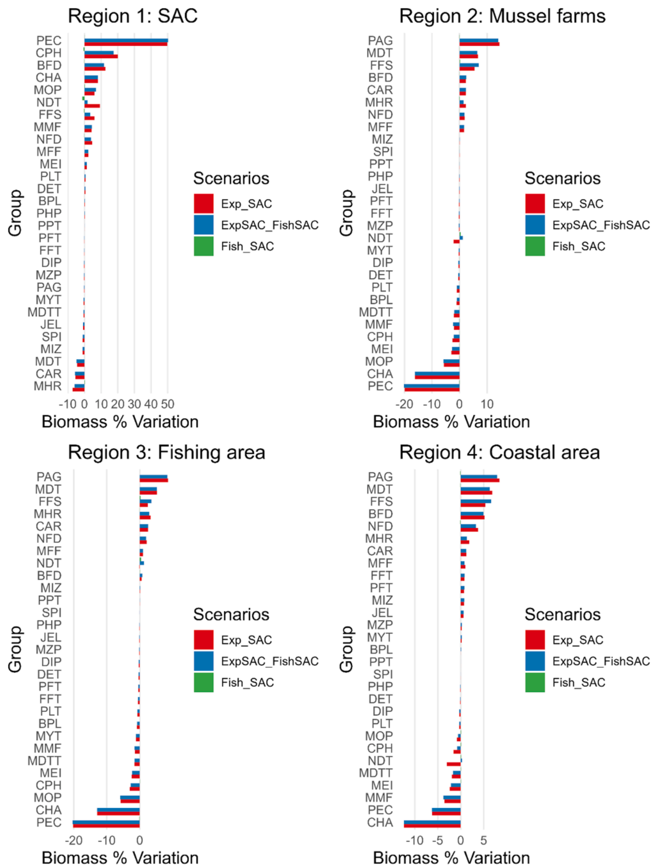


Fig. 7. Variation (%) of biomass. Biomass variation in %, for each trophic group at the steady state, and for the three implemented scenarios (fishSAC_expSAC = fishing in the SAC combined with SAC expansion; fishSAC = fishing in the SAC alone; expSAC = SAC expansion) compared to the baseline scenario. Bars on the right mean increment compared to the baseline scenario. Primary Producers Tegnùa (PPT), Porifers Tegnùa (PFT), Filter Feeders Tegnùe (FFT), Macrobenthic Detritivorous Tegnùe (MDTT), *Diplodus annularis* (DIP), *Spicara smaris* (SPI), *Pagellus erythrinus* (PAG), *Mytilus galloprovincialis* (MYT), Nekton Feeders (NFD), Cephalopods (CPH), Flat fish (FFS), Benthic Feeders (BFD), Planktivorous Fish (PLT), Nekton Detritivorous Feeders (NDT), Macrobenthic Predators (MOP), Macrobenthic Mixed feeders (MMF), Macrobenthic Filter Feeders (MFF), *Chamelea gallina* (CHA), Pectinidae (PEC), Mesozooplankton (MZP), Macrobenthic Detritivorous (MDT), Meiobenthos (MEI), Jellyfish (JEL), Microzooplankton (MIZ), Bacterioplankton (BPL), Phytoplankton (PHP), Carcass (CAR), Detritus (DET).

minimal impact on indicators. Moreover, SAC expansion resulted in higher fishery catch beyond the 3 NM coastal boundary. This increase was not due to a rise in the overall biomass available to the fishery, pointing to a redistribution of fishing effort (Cabral et al., 2017), rather than a spillover effect. The decline in *C. gallina* biomass in the coastal area with the SAC expansion was attributed to a shift in fishing effort and increased ecological pressure from competitors, particularly the Macrobenthic Filter Feeders group. Both the Kempton's Q Index and SOI displayed small variations in our simulations. This finding aligns with previous studies that reported limited impacts of fishing-related scenarios on these indices compared to the more pronounced effects of climate change and morphological gradients. For instance, in the study by Püts et al. (2023), Kempton's Q index was adopted to identify stable regions to protect: the indicator responded to bathymetry gradients and elevated biomass concentration, showcasing approximately a 10 % variation among scenarios. Consistently, Piroddi et al. (2022) noted that Kempton's Q Index showed high diversity between coastal and shelf areas and varied by −1 % to 7 % in the Mediterranean Sea between 1995 and 2016. In Nogues et al. (2022), the SOI exhibited minimal changes in response to fishing-related scenarios, but a 7 % increase was observed during simulations of Offshore Wind Farm openings. Conversely, all network indices demonstrated greater sensitivity to climate change scenarios and distinct environmental gradients such as bathymetry and productive regions (Nogues et al., 2022). Rather than excluding them from the analyses due to their low sensitivity to management scenarios, we suggest to consider employing methods of penalization or

Table 3
Weighting criteria: "equal priority to nature and economic activities" and "nature priority". Final scores for each scenario, calculated as weighted sum or product modifying criteria weights to reflect more and more nature priority in the spatial multi-criteria analysis. In bold, highest Final Scores for each priority.

Priority	Scenario	FS Weighted Sum	FS Weighted Product
Equal priority to nature and socio-economic activities	Baseline	**0.428**	$2.4 \cdot 10^{-3}$
0.50 · Nature *0.25 · Aquaculture*	expSAC	0.395	$1.15 \cdot 10^{-3}$
0.25 · Fishery	fishSAC	0.427	$2.4 \cdot 10^{-3}$
	expSAC + fishSAC	0.402	$1.7 \cdot 10^{-3}$
Nature priority	Baseline	**0.403**	$1.7 \cdot 10^{-4}$
0.90 · Nature *0.05 · Aquaculture*	expSAC	0.402	$1.1 \cdot 10^{-4}$
0.05 · Fishery	fishSAC	0.378	$1.74 \cdot 10^{-5}$
	expSAC + fishSAC	**0.403**	$1.2 \cdot 10^{-4}$

Table 2
Weighting criteria: "equal weights". Standardised values of the indicators prior to the multi-criteria aggregation (Standardised Indicator) and after (Aggregated Criteria) for each scenario. Slight (+; −) and strong (+ +; − −) value variations are highlighted for the aggregated criteria. Final scores for each scenario are shown for the equal weights cases only (0.33 for each criterion). totB: total biomass; Btegnua: total biomass of species associated to the presence of tegnùe; BFishComm: total biomass of commercial fish species; K: Kempton's Q Index; SOI: System Omivory Index; totCComm: total catches of commercial fish species; Bmyt: biomass of *Mytilus galloprovincialis*; Bcha: biomass of *Chamelea gallina*.

Weight · Criteria	Indicator	Baseline		expSAC		fishSAC		expSAC + fishSAC	
		Standardised Indicator	Aggregated Criteria	Standardised Indicator	Aggregated Criteria	Standardised Indicator	Aggregated Criteria	Standardised Indicator	Aggregated Criteria
0.33 · Nature	totB	0.449	0.131	0.474	0.133 (+)	0.449	0.131	0.472	0.133(+)
	Btegnua	0.380		0.380		0.380		0.380	
	BFishComm	0.609		0.608		0.609		0.608	
	K	0.516		0.505		0.519		0.507	
	SOI	0.286		0.299		0.286		0.298	
0.33 · Fishery	totCComm	0.364	0.114	0.437	0.072 (–)	0.361	0.112 (-)	0.427	0.081 (–)
0.33 · Aquaculture	Bmyt	0.659	0.189	0.660	0.183 (-)	0.659	0.189	0.660	0.183 (-)
	Bcha	0.484		0.452		0.484		0.452	
Final Score		0.434		0.390		0.432		0.398	

enhancement when aggregating indicators with low sensitivity to fishing pressure but high ecological consensus. Moreover, we recommend to integrate more fishery-specific indicators when testing scenarios of fishery reduction.

In terms of methodological novelty, the most important aspect of this study is the choice to synthesize the spatial outputs of food web models into a final score, using multi-criteria analysis. To the best of the authors' knowledge, this approach was not priorly adopted for combining food web model outputs. The final score was built on criteria, specifically focusing on the fishery and aquaculture sectors as well as nature conservation. Despite the expansion of SAC area, leading to an increase in total biomass, this positive effect was counteracted by a substantial decrease in catches by professional fleets. The decline was not offset by potential benefits to artisanal fishermen permitted to operate within the SAC area. This outcome may raise concerns about the acceptability of the proposed SAC expansion scenario: the trade-off between increased biomass and reduced catches by professional fleets, without clear compensatory advantages at least for artisanal fishermen, may lead to lower acceptability from the fishery sector (Klein et al., 2008; Voyer et al., 2014). This aspect adds complexity to the overall evaluation of alternative management measures, yet the policy vision significantly influences the outcomes of comparing scenarios. To test the sensitivity of the spatial multi-criteria analysis to policy strategic priorities, we conducted tests involving different weights on criteria prioritization. This included increasing the priority of the Nature criterion up to 0.90. In this case, prioritizing nature conservation did offset the loss of fishery income when expanding the SAC but did not result in any net benefit compared to the current administration of the area. These results stress the importance of actively involving stakeholders in prioritizing criteria and therefore prioritizing management goals in the maritime spatial planning process. This collaborative effort is essential for effective management and in line with international agreements such as the Aarhus Convention (the convention on Access to Information, Public Participation in Decision-making and Access to Justice in Environmental Matters of the United Nations Economic Commission for Europe, n°37770, 1998), the MSPD (EC 2014/89/EU) and the European SEA Directive (2001/42/EC). Stakeholders can identify management proposals, quantify scores to prioritize criteria and indicators (Grafakos et al., 2010) and assess the feasibility, sustainability, and acceptability of proposed interventions (Richards et al., 2004; Reed et al., 2006; Reed, 2008). Moreover, potential interactions with individuals who have access to the area could foster mutual trust, increasing the likelihood of acceptance even for less conducive management measures (Richards et al., 2004; Reed, 2008). Including stakeholders in the decision-making process is possible, through workshops and questionnaires, but also by using participatory modelling approaches (Tippett et al., 2007). The SAC area has a value also for other activities, such as scuba diving, even if quantitative data are not available. The inclusion of this sector in the modelling could open further discussion on the scenarios' outcome.

While acknowledging the limitations of our food web model, which primarily focuses on trophic interactions and omits considerations on animal migrations and indirect effects of management scenarios, like reduced pollution and disturbance effects, we emphasise its potential utility as a tool for integrated maritime spatial management. In EBM, in fact, several sets of indicators extracted from food web models are available (Borja et al., 2016), but few attempts of integrating them were made to meet environmental management needs (Borja et al., 2012; Borja et al., 2014; Elliott et al., 2018). We argue that the tools and final scores employed in this study, particularly the spatial multi-criteria analysis, offer a valuable tool for simplifying complex information derived from diverse ecosystem indicators and making it clearer and more available for management purposes, even when involving stakeholders.

5. Conclusions

This study produced a spatialised food web model for the chosen northern Adriatic SAC area and applied an innovative approach by synthesising spatial outputs of a food web model into a final score, using multi-criteria analysis to rank spatial management scenarios. While the SAC expansion scenario showed positive effects on total biomass, it raised concerns due to a substantial decrease in catches by professional fleets, with limited compensatory benefits for artisanal fishers. Some indicators exhibited minimal variation, suggesting limited sensitivity. To address this, alternative spatial statistics or penalisation methods in multi-criteria analysis could enhance sensitivity. Despite its limitations, spatial multi-criteria analysis has proven valuable in simplifying complex ecosystem indicators, offering a practical tool for holistic marine ecosystem management and effective environmental decision-making. It is worth remarking that the model's structure can adapt to future updates, benefiting from the growing availability of spatial information from ongoing monitoring and new biotic indices (Piazzi et al., 2023).

CRediT authorship contribution statement

E. Donati: Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **M. Ponti:** Writing – review & editing, Validation, Resources, Data curation. **E. Turicchia:** Writing – review & editing, Validation, Resources, Data curation. **L. Airoldi:** Writing – review & editing, Validation, Resources, Data curation. **M. Mazzotta:** Data curation. **J. Bernardi:** Writing – review & editing, Validation, Resources, Data curation. **F. Calì:** Writing – review & editing, Validation, Resources, Data curation. **C. Mazzoldi:** Writing – review & editing, Validation, Resources, Data curation. **E. Russo:** Writing – review & editing, Validation, Resources, Data curation. **F. Pranovi:** Writing – review & editing, Validation, Resources, Data curation. **F. Fabbri:** Writing – review & editing, Resources, Data curation. **D. Brigolin:** Writing – original draft, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Data curation, Conceptualization.

Declaration of competing interest

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

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecolind.2024.112776.

Data availability

Data will be made available on request.

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