PLANNING PRECISION AQUACULTURE ACTIVITIES IN A CHANGING AND CROWDED SEA

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Submission date: August 2022

Submitted to: Aquaculture

This manuscript has now been published as:
Mangano, M.C., Corbari, L., Giacoletti, A., Berlino, M., Kay, S., Ciraolo, G., Sarà, G., (2023) Planning precision aquaculture activities in a changing and crowded sea, Aquaculture, Volume 577, 739881.
https://doi.org/10.1016/j.aquaculture.2023.739881

Abstract

Extreme climate events are increasingly challenging the growth of the marine aquaculture sector, causing local influences on species performance and affecting production and yield - impacting where to locate cage aquaculture facilities. Here we produced scenario-based quantitative maps using modelled species-specific performance combined with predicted high-resolution future IPCC temperature scenarios. We ran a species-specific Dynamic Energy Budget mechanistic model for four model species, up to 2050, and mapped functional trait-based outcomes as: *i)* time to reach the commercial size, *ii)* feces produced and iii) uneaten food. A high spatial resolution suitability index allowed the sustainability of farming strategies for single- and multi-species to be identified across a 159.696 km2 surface extension (Italian Exclusive Economic Zone; 6% of the Mediterranean basin surface). Providing a good case study to shed light on difficult questions facing aquaculture planning around the world. Good future performance under both representative concentration pathway (RCP) scenarios were modelled for Sea bream and European seabass in inshore waters. Performance of Mediterranean mussels and Japanese oysters was found to decrease slightly when compared to the 2007 – 2010 time interval. Scenario-based quantitative maps represent a heterogeneous species-specific knowledge layer that is critical to better inform aquaculture management and development strategies. Yet this knowledge layer is missing from the process to develop climate-resilient risk maps and associated adaptation measures, as well as when informing stakeholders on potential site expansion and/or the establishment of nascent aquaculture industry sites.

Keywords: Climate change scenarios, DEB model, adaptive spatial planning, human uses, climate resilience, vulnerability patterns, RCP 4.5, RCP 8.5

Introduction

The detrimental - sometimes irreversible - damage to resources and related socio-economies caused by the increased frequency, intensity and duration of adverse climate change phenomena are pushing scientists, stakeholders and policy makers to research and design more adaptive tools and strategies (Sumaila et al., 2011) that will help society better cope with these changes. Researchers from all over the world are attempting to engage with stakeholders and inform policy decision-making processes by promoting evidence-based management measures and integrated strategies (Holsman et al., 2019) that will encourage conservation and sustainable use of marine resources in an equitable way (Shyamsundar et al., 2013; Norström et al., 2014). One third of aquaculture production is marine aquaculture, a sector that has grown at an impressive rate over the past decades, keeping the overall price of fish down and making fish and seafood more accessible to consumers worldwide (FAO 2018; HLPE 2014; Béné et al., 2015; World Bank 2013; Kobayashi et al., 2015; Tacon and Metian, 2016). There remains potential to further exploit molluscs and seaweeds to support global nutritional security (Naylor et al., 2021) despite some salient exceptions (see the decrease of aquaculture production of mussels at EU level, an important contributor to the stagnation of EU aquaculture; Avdelas et al., 2021). The increased occurrence of extreme climatic events will undoubtedly challenge the future growth of this sector, by locally influencing species' performance affecting production and yield (e.g., temperature increase; Hernandez et al., 2007; Naylor et al., 2021; Blanchard et al., 2017; Froehlich et al., 2018; Sarà et al., 2018a; Mangano et al., 2019; Giacoletti et al., 2021) and threatening the location potential of these facilities (e.g., sea level rise, storm surges, diseases caused by parasites, bacteria, viruses, and biotoxins; Rosa et al., 2012; Sarà et al., 2018b). This will exacerbate existing environmental problems in focal productive areas, such as the Mediterranean basin (Cramer et al., 2018); the world's biggest marginal sea which hosts around 480 million people and whose diets are mainly based on fish proteins, with ¼ of this seafood coming from aquaculture activities. The Mediterranean accounts for 3.4% of global aquaculture production value, with sea bream and sea bass being the two most produced species followed by Mediterranean mussel and Japanese oyster (FAO 2018; STECF 2018; EUROSTAT 2019).

Here, we underline the importance of providing species-specific scenario-based maps built on functional traits (FT-DEB) as a baseline to better inform adaptive spatial planning strategies of marine aquaculture systems under increasing water temperature scenarios. This FT-DEB approach (Montalto et al. 2015), has already been shown (Sarà et al., 2018a; Giacoletti et al., 2021; Thomas et al., 2011) to produce spatially contextualized layers that can be used to assess the sustainability of modern aquaculture and recent advances have allowed decision makers to be provided with an overview of local carrying capacity within shellfish aquaculture (Klinger et al., 2017; Lavaud et al. 2020). We produced easy-to-read outcomes based on species-specific modelled performance resulting from the incorporation of future IPCC predicted temperature scenarios (RCP 4.5 and 8.5). We ran a species-specific Dynamic Energy Budget (DEB) mechanistic model for each of our model species by mid-century, then, we mapped functional trait-based outcomes as: *i)* time to reach the commercial size, *ii)* feces produced and iii) uneaten food (for the two fish species). A suitability index was designed to distinguish where to locate single and multispecies farms, always maintaining the produced environmental impact below a certain environmentally sustainable threshold. Scenario-based quantitative maps represent a missing layer when informing climate-resilient risk maps, otherwise known as a site-selection exercise. Once aquaculture potential (i.e., if species grow under local environmental conditions) was spatially expressed, the resulting functional trait-based layers were overlapped with layers of existing human activities to extrapolate areas representing the available zones for aquaculture (i.e., where aquaculture can be carried out with no biological limitations and no human activity restrictions) both inshore and offshore.

Material and Methods

With a total surface extension of 159,696 km^2 the Italian Exclusive Economic Zone (EEZ) occupies 6% of the Mediterranean basin. Italy is a crucial country for the aquaculture sector at both European and Mediterranean level, representing the third biggest European producer of the Gilted seabream *Sparus aurata* (8,700 t, 15.50 EUR/kg) and of the European seabass *Dicentrarchus labrax* (7,039 t, 8.02 EUR/kg), the second biggest producer of the Mediterranean mussel *Mytilus galloprovincialis* (62,502 t, 0.9 EUR/kg) and the penultimate of the Japanese oyster *Crassostrea gigas* (80 t, 6.9 EUR/kg, one among the highest in EU; EUMOFA 2019).

Modelling approach and related forcing variables. The Dynamic Energy Budget model selected was based on a generalized, individual-based modelling framework (Dynamic Energy Budget theory; Kooijman, 2010), able to investigate and link different levels of metabolic organization. Using mechanistic rules, the standard DEB model (Sarà et al., 2014) describes the bioenergetics of an organism through the dynamics of three main state variables: structure (V), reserves (E), and maturity (E_H), that track the individual development and are controlled by six energy flows formulated in units of J d^{-1}: assimilation flow ($\dot{p}_A$), mobilization flow ($\dot{p}_C$), somatic maintenance flow ($\dot{p}_S$), maturity maintenance flow ($\dot{p}_J$), growth flow ($\dot{p}_G$), maturation/reproduction flow ($\dot{p}_R$) (Sarà et al., 2014; see Figure 1 in Mangano et al. 2020). Here, four model species were used to simulate the growth rate responses to climate change under both the Representative Concentration Pathway IPCC scenarios RCP 4.5 and 8.5 (see Table S1 Supplementary Materials for the full list of DEB parameters used throughout this study). DEB parameters used for three of the four model species - *Dicentrarchus labrax*, *Mytilus galloprovincialis* and *Crassostrea gigas* - were collected from Mediterranean case studies (i.e., *D. labrax* from Sará et al. 2018; *C. gigas* from Sará et al. 2012; *M. galloprovincialis* from Monaco et al. 2019), and the fourth – *Sparus aurata* – from a Portuguese study (Serpa et al. 2013). Our simulations started from a specific seeding volume computed from the corresponding seeding size (L_s, length at seeding) reported for each selected model species (see Table S1 Supplementary Materials) using:

$$Vs = (Ls \, * \, \delta_M) \, \hat{} 3$$

commonly reported in terms of length for bivalves. Conversely, for fishes it is often given in terms of weight. Hence for modelling purposes the L_s of *S. aurata* was first computed (Giacoletti et al., 2021) by the mean of the length-weight relationship (Gould, 1966):

$$W = aL^b$$

with W representing the total weight (in grams), L the total length (in centimeters) while a and b were the species-specific intercept and slope of the curve (when the relationship is linearized through the log-transformation). Both a and b parameters were collected from Mediterranean cases studies (Koutrakis and Tsikliras, 2003; Dulčić and Glamuzina, 2006) and used to calculate the L_s corresponding to the seeding size used in Sicilian farms (8.02 cm for 7 g fingerlings; Giacoletti et al., 2021).

Forcing variables within the model: temperature and food. The connection between body temperature, usually approximated in ectotherms by mean seawater temperature, and metabolism is well-captured by the Arrhenius relationship (Kooijman, 2010; Arrhenius, 1889). Metabolic rates of all living organisms mainly depend on body temperature, but also the density of food available in the environment. Both temperature and food, the main driving variables within mechanistic models, assume an important role in determining species' persistence over time (Montalto et al., 2014), and allow DEB models to predict the most important individual life history traits (Pecquerie et al., 2011; Sarà et al., 2011; Mangano et al., 2020). Daily Sea Surface Temperatures (SST; spatial resolution 0.1 degree; [c.a. 11 km]) and Chlorophyll-a (CHL-a; spatial resolution 0.1 degree; [c.a. 11 km]) relative to the RCP 4.5 and 8.5 IPCC scenarios were downloaded (Proudman Oceanographic Laboratory Coastal Ocean Modelling System [POLCOM] containing the outputs of regionally downscaled projections for European seas generated using coupled European Regional Seas Ecosystem Model [ERSEM] 15.06 hydrodynamic-biogeochemical models - as part of CERES and TAPAS 2017 projects; Butenschön et al., 2016) and divided into five-time intervals of four years each (2007-2010; 2017-2020; 2027-2030; 2037-2040; 2047-2050). The time interval 2007-2010 has been selected as a present and past reference period against which the model outputs obtained on the future time intervals could be compared. SST and CHL-a daily data in NetCDF format were transformed in comma-separated values (CSV) and each datum was then repeated twenty-four times to allow simulation on hourly time-steps for a 4-year period (Sarà et al., 2018a; Mangano et al., 2019). SST and CHL-a datasets were then restricted by depth from 0 to 100 and from 100 to 200 meters below sea level, as identified via the EMODnet bathymetry data (http://www.emodnet-hydrography.eu/), and further confined to the Italian EEZ (Flanders Marine Institute, 2014). Two vector grid feature classes were generated (pixel of 0.1° x 0.1° [c.a. 121 km^2]), of 660 pixels (covering a total surface of 79,860 km^2) relative to the 0-100m bathymetry referred to as inshore, and of 448 pixels (total surface of 54,208 km^2) relative to the 100-200m bathymetry referred to as offshore (see Supplementary Materials Figures S1, S2). Food availability is another important driving variable within DEB models. For wild bivalve species food was derived from remote sensing or model data (Mangano et al., 2019) with CHL-a used as a proxy of available food for suspension feeding bivalves (Handå et al., 2011; Lavaud et al., 2014). For cultivated fish species a daily food intake scale, based on the body weight estimated by the DEB model at that specific time, was applied. Food is represented by farmers' common feeding schemes (Hoşsu et al., 2005), thus for *S. aurata* we used data from Sicilian farms (Table S2) and for *D. labrax* we used data from Sarà et al. 2018a (Table S3). The uneaten food was estimated by the difference between the provided and the ingested amount; feces were calculated by summing the hourly release given by:

$$IF * (1 - AE)$$

where *IF* stands for ingested food and *AE* for the assimilation efficiency of food, until commercial size (Sarà et al., 2018a).

Model outcomes synthesis. The duration of the grow-out phase, in terms of days needed to reach the commercial size (TTCS, Time To Commercial Size; days) was computed (commercial sizes were considered using those recommended by FAO https://www.fao.org/fishery/en/culturedspecies/search). We then calculated the potential environmental impact (IMP) of the two fish species fed by humans as the sum of the "Feces" released in the environment (in grams) and the "Uneaten food" dropped just beneath the cages (in grams; only for *D. labrax* and *S. aurata;* model already developed and tested in Giacoletti et al., 2021) assuming these to be the two main recognized sources of impact from cages on the surrounding environment (Kalantzi & Karakassis 2006; Sarà et al., 2007a, b). For unfed (i.e., naturally feeding) bivalve species, we considered only feces as a source of impact (IMP). DEB model outputs were produced for each species at both inshore and offshore spatial extensions, under RCPs 4.5 and 8.5, for all five-time intervals and then spatially contextualized around the Italian EEZ. These two scenarios were chosen as representing, respectively, a moderate carbon concentration still showing a clear climate signal (4.5) and the upper end of plausible carbon concentrations (8.5). Projected global SST temperature rise under RCP 4.5 is approximately 2°C (IPCC 2013), in line with the goal set in the Paris COP Agreement. TTCS values were then plotted against IMP, the mean value of TTCS (MTTCS) and the mean value of IMP (MIMP) were detected and used as reference points for sustainable conditions for each species (i.e., environmental sustainability *sensu* Sarà et al., 2018a). Quadrants around the mean values define four main conditions to which we then assigned a value (Figure 1), respectively: Worst = 0.25 (TTCS ≥ MTTCS & IMP ≥ MIMP; red color), Bad = 0.5 (TTCS ≤ MTTCS & IMP ≥ MIMP; orange color), Good = 0.75 (TTCS ≥ MTTCS & IMP ≤ MIM; yellow color P), Best = 1 (TTCS ≤ MTTCS AND & ≤ MIMP; green color). Pixels on the border of two conditions were classified considering the value of the nearby pixels. Pixels belonging to the four defined categories of environmental sustainability were then mapped. To check for changes in environmental sustainability between temperature scenarios, the pixels belonging to each category under changing RCP scenarios and time interval for each species at each spatial extension were counted; data were also grouped by Italian regions. To represent only pixels that can be devoted to farming, we removed the pixels already occupied by other human activities and protected areas and habitats (i.e., layers from the World Database on Protected Areas, layers of *Posidonia oceanica* meadows, maërl beds and coralligenous from the Mediterranean Sensitive Habitats, MediSeH project; see Table S4; S5 Supplementary Materials for an exhaustive list of the human use and protected areas and habitat layers applied). We also considered all the buffer areas (Figure S3 Supplementary Materials) required when looking for Allocated Zones for Aquaculture (AZA) in Italian waters (Marino et al., 2020). In absence of layers forecasting the future human use scenarios at sea, we fixed the currently available information and applied it to all the time intervals we considered.

A second index was created to explore the opportunity to farm different species in the same spatial pixel, used as a proxy of coexistence in the same aquaculture facilities, providing effective information on the best area to build an aquaculture farming facility for different trophic levels (e.g., Integrated Multi-Trophic Aquaculture) by respecting a higher environmental sustainability target (TTCS ≤ MTTCS). For each species a matrix was created by associating values equal to 1 for all those pixels whose TTCS values were lower or equal to MTTCS, and values equal to 0 for all those pixels that did not respect this condition. The species were then considered together, evaluating for each pixel, the mean value (for each time interval, RCP scenario and inshore/offshore spatial extension). The obtained five values (0 = red color, 0.25, 0.5, 0.75, 1 = increasing shadows of blue color) were used to indicate how many species can be farmed in the same aquaculture facility whilst maintaining the environmental sustainability target (respectively none; one species; two species; three species; four species). All spatial analyses were performed using QGIS and R software (R Core Team, 2019), and then represented through the ggplot2 package (Wickham, 2016). A further important advancement of this study is represented by the use of R software together with an adaptation of the R code made available by Monaco et al. (2019) that solves the computational effort needed to run the DEB model with high resolution and site-specific data, representing a strong improvement from simulations performed using daily SST values of each SATR ("Similar Average Temperature Regions" in Sarà et al. 2018a).

The three outputs produced by each species-specific DEB model under the different environmental scenarios (inshore/offshore, RCP 4.5/RCP 8.5) generated scenario based quantitative outputs for each period of: days needed to reach the commercial size (Time To Commercial Size, TTCS; Figures S4 - S11 Supplementary Materials), uneaten food for the two fish species fed by humans (Figures S12 - S15 Supplementary Materials) and produced feces for the four model species (Figures S16 - S23 Supplementary Materials). Pixels already occupied by human activities layers and the main protected areas and habitats layers (Tables S4, S5; Figure S3 Supplementary Materials) were reported in black. Outcomes of the models were then combined to create an environmental suitability index, by plotting TTCS against IMP values and looking at the mean values (MTTCS and MIMP, Figure 1; Figures S24 - S27 Supplementary Materials) and used as reference point of a sustainable environmental condition.

Results

By plotting Italian EEZ Sea Surface Temperature (SST) values from 2007 to 2050 a clear increasing temperature trend of more than +1.5 °C by 2050 was highlighted for both 4.5 and 8.5 RCP scenarios, with the warmest average values predicted under the RCP 8.5 (Figure 2, S1) scenario. Chlorophyll-a showed a less steady increase and a more stable trend with the lower values recorded under the 8.5 RCP scenario, and the highest values recorded for the 2035 - 2043 time-interval and 4.5 scenario (Figure 2; S2).

The number of free pixels along the Italian Exclusive Economic Zone and *per* each condition of environmental sustainability index (critical trade-offs between environmental costs, IMP and benefits TTCS), *per* each species, RCP scenarios, time intervals and considered spatial extension are reported in Figure 3 (detailed scenario-based quantitative maps *per* each species, scenarios and time interval are also reported in Supplementary Materials Figures S28 - S35). An increasing pattern of the “Best” condition (i.e., green color) was highlighted for the Seabream in the future, under both scenarios, with the highest percentage of surface experiencing this predicted condition for the 2027 – 2030 time interval under 8.5 RCP scenario and inshore (Figure 3; Table S6, Max number of pixels 81). The highest number of pixels experiencing the “Worst” condition (i.e., red color) was predicted for the 2017 – 2020 time interval under the 8.5 RCP scenario, inshore (Figure 3; Table S6, Max number of pixels 83). A stable pixel pattern for the “Best” condition was predicted for the European seabass in the future, under both scenarios, with the highest percentage of surface predicted to experience this condition during the 2047 – 2050 time-interval, under the 8.5 RCP scenario and inshore (Figure 3; Table S6, Max number of pixels 286). The highest number of pixels experiencing the “Worst” conditions were predicted for the 2017 – 2020 time-interval under the 8.5 RCP scenario, offshore (Figure 3; Table S6, Max number of pixels 159). The bivalve *M. galloprovincialis* showed a stable pattern of “Best” condition pixel into the future under the 4.5 scenario and a reduction under the 8.5 scenario (Figure 3; Table S6, Max number of pixels 152). The “Worst” condition predicted for *M. galloprovincialis* was recorded for the 2027 – 2030 time-interval under 4.5 RCP scenario, inshore (Figure 3; Table S6, Max number of pixels 264). The Japanese oyster showed a stable number of “Best” pixels into the future under both scenarios (Figure 3; Table S6, Max number of pixels 297). Increasing trends were shown offshore for all four species (Figure 3, Table S6).

To facilitate a regional visualization of the mechanistic-based outcomes, the results were reported for each Italian region with a coastline (Table S7), once again by considering only the free pixels. Figure 4 specifically represents the time-interval 2027-2030 with differences reported per inshore and offshore spatial extensions for each species. Our modelling predicted the largest number of “Best” and “Good” pixels along inshore Abruzzo and Emilia Romagna for *S. aurata*; inshore of Apulia, Lazio, Sardinia and Sicily and offshore Campania, Sardinia and Sicily for *D. labrax*; inshore Marche and offshore Apulia for *M. galloprovincialis;* inshore Molise and Veneto, inshore and offshore Abruzzo, and offshore Tuscany (Figure 4; Table S7).

When looking at the four species in combination the number of pixels that can host the maximum combination of four species (1, dark blue; Figure 5; Table S8) will increase with time (2031 - 2040 and 2047 - 2050 respectively 40 and 35 pixels, inshore) with the highest numbers offshore (2047 - 2050 213 pixels). Under both scenarios 4.5 and 8.5 - both inshore and offshore - the combination of two species (0.5; Figure 5; Table S8) under best conditions is the most represented across the Italian EEZ followed by one, three and four species (respectively 0.25, 0.75 and 1; Figure 5; Table S8). The number of pixels where no species reach the best conditions (red color value 0; Figure 5; Table S8) – on average across the 4-time intervals – is stable both inshore and offshore under both scenarios. Looking on the regional scale for the 2027 – 2030 time interval, the combination of four species under best conditions will be achieved for Apulia, Lazio and Tuscany offshore only and under both scenarios, by Campania offshore only and under scenario 4.5, Sardinia inshore only and under scenario 8.5; Sicily inshore and offshore under scenario 8.5 (Figure 5; Table S9). The combination of two species under best conditions will be possible for Abruzzo, Apulia, Calabria, Campania, Lazio, Liguria, Marche, Molise, Sardinia, Sicily and Tuscany both inshore and offshore under both scenarios, Emilia Romagna and Friuli Venezia Giulia and Veneto will achieve it only inshore, under both scenarios (Figure 5; Table S9). The number of pixels where no species will reach the best conditions have been predicted, respectively: inshore, under both considered scenarios, in Apulia, Lazio and Sicily; inshore, under scenario 4.5 in Tuscany; offshore under scenario 4.5 in Abruzzo and Emilia Romagna; inshore, under scenario 8.5 in Calabria; inshore and offshore, under scenario 4.5 in Marche (Figure 5; Table S9).

Discussion

Managing aquaculture resources in the attempt to preserve both ecosystems and the related goods and services has been already recognized as a main challenge of the Anthropocene (He et al., 2019; Luypaert et al., 2020). Stakeholders should address their investment to adapt to local changing conditions, adopt effective settings, including newer and safer technologies (e.g., engineering technology for farming seafood in the open ocean; Langan et al., 2012). Policy decision-makers should invest more in capacity building and food security programs and strategies (e.g., training and recruitment of new staff, access to viable broodstock, employment of selective breeding programs; Leung et al., 2007; Klinger et al., 2017; Kim et al., 2019). Interestingly the approach applied here highlights the general strength of using models when preparing climate resilience, and adaptive marine spatial plans, as there is the possibility to simulate species functioning in response to a range of alternative global warming scenarios allowing the most appropriate and cost-effective development options for an area to be identified. In this regard, the rapid evolution of *in situ* data collection, particularly using new technology such as real-time sensors that monitor daily conditions on farming sites (e.g., sea temperature and dissolved oxygen variability) can be used to feed these models increasing the accuracy of the outcomes, as well as the data collected via sensors which can allow for the creation of large datasets with long time-series, that could be useful for model validation.

Our approach, and its outcomes, may represent a proactive - and easy to read tool - when engaging with stakeholders and policy decision-makers. Our spatial analysis can inform the participatory planning process by facilitating stakeholder engagement, an essential component throughout the broader spatial planning process. Similarly, our species-specific scenario-based maps can provide valuable decision support for aquaculture planning and licensing, by integrating existing decision-support tools, from simple spreadsheets and checklists to complex computationally intensive models (Falconer et al., 2022). It offers promise to strengthen the dialogue in the context of marine policy, maritime spatial planning, future scientific research and farming practice development. To disentangle species-specific climate resilience and vulnerability patterns may help design more effective and successful adaptation strategies which are crucial to foster the blue economy sector - of which aquaculture represents a main component - and support the Blue Growth Initiative from local to global scale. This is crucial in a context of resilience building of the sector strongly affected by the COVID-19 crisis and disruption (Sarà et al., 2021; Love et al., 2021) inside the view of the “collaborative, multisectoral, and transdisciplinary” One Health approach (Jamwal and Phulia, 2021).

Given its central position in the Mediterranean basin, its highly-recognized role among countries leading the aquaculture sector worldwide and thanks to the long latitudinal extension (almost 8,000 km - the longest coastline extension in the Mediterranean Sea), the Italian peninsula is a perfect area to test how to disentangle the species-specific responses to regional climate changing scenarios.

Italian waters are among the most crowded seas in the world, thereby the Italian Exclusive Economic Zone represents a perfect case study to explore how to tailor human activities at sea that helps avoid or reduces potential conflicts. The lessons learned could be applied to all countries facing difficulties finding the required space to allocate (or relocate) human activities. Additionally, Italy is a country where the access to space has been perceived as a major weakness, specifically there is a lack of suitable space to enlarge or establish new farms and there is difficulty to obtain permits (Avdelas et al., 2021). Thus, by mapping the free pixels along the Italian Exclusive Economic Zone for each species as a function of RCP scenarios, time intervals, both inshore and offshore, we could visualize the spatial extension and future patterns (increasing and decreasing) of the considered aquaculture environmental sustainability index. Our approach highlighted a general increasing performance for seabream and seabass in the future and a slightly declining performance for mussels and oysters. The investigation at the regional scale permitted the environmental sustainability index to be localized and represented in a cumulative way by looking at the combination of the number of species that can be farmed *per* unit of space by respecting higher levels of environmental sustainability.

Our approach allowed a high spatial resolution and functional resolution (based on mechanistic species-specific model outcomes) to be maintained providing salient and credible information that is useful to proactively inform more effective adaptive farming strategies as well as site selection for farms, aspects of crucial importance when dealing with species of high economic value such as the four model species in this study (Gentry et al., 2017; Froehlich et al., 2018; Sarà et al., 2018a; Giacoletti et al., 2021). The ability to specifically predict the potential impact (i.e., IMP, feces / uneaten food) of each farmed species on the surrounding area is particularly useful for planning and licensing decisions when coupled with waste dispersion models (Sarà et al. 2018b) and can be used to determine acceptable production levels. Our outputs may be integrated into bioeconomic models and used to develop trade-off analysis and to reduce conflicts, environmental impacts and promote the sustainable use of marine ecosystems (Lester et al., 2018). Promising trends for all four species were shown in the offshore area of the Italian EEZ for the future years (e.g., 2027-2030 *D. labrax* offshore of Campania, Sardinia and Sicily and *M. galloprovincialis* offshore of Apulia) and also for the combination of farmed species (with differences between regions) which could further incentivize the interest of stakeholders and policy makers in the expansion of offshore aquaculture (e.g., to search for European/national/local economic resources to finance offshore technologies deployment/testing). This latter spatial explicit information can be used as a measure of future potential diversification power. This is crucial for the long-term performance and viability of the aquaculture sector with respect to sustaining food production (both under economic and social-ecological perspectives) and to increase resilience against changing environmental conditions (Metian et al., 2020). For a decade, spatial diversification (i.e., increasing the number of farmed species) was advocated as the main path for achieving sustainable development for future aquaculture at both regional and country level (Walker et al., 2004; FAO, 2016). Additionally, selective environment specific breeding programs (Klinger et al., 2017 and references therein) of culture organisms, as well as the seeding size selection (Giacoletti et al., 2021), represent another exploitable tool that can be promoted to improve the profitability of the sector by compensating for growth losses in areas that reported lowest environmental sustainability index values. The development of effective breeding and seeding selective programs will require an increase in capital and extension of the financial assistance provided to farmers at regional level across the Italian peninsula. In this regard our high-resolution maps of overlapped environmental sustainability index for the four model species (and their combination) represents a useful resource for managers and policymakers and being scenario based, allows the potential future evolution of the industry to be better understood and thus supports plans for future businesses and will help set policies to reach the long-term goal of increased environmentally sustainable food security.

Offshore aquaculture offers promise in minimizing the ecological risk of aquaculture development (e.g., cages based away from essential habitats; Froehlich et al., 2017; Mengual et al., 2021) but it still in its infancy characterized by a lack of an adequate planning framework (Gentry et al., 2017b; Falconer et al., 2022). In this context, the integration of our findings into a modelling effort designed to understand the interactions with the surrounding environment and that incorporates robust economic and political factors would help determine the future national production potential of this sector. Producing species-specific scenario-based maps up to the offshore spatial extension allowed us to provide, to the best of our knowledge, the first models for these four species at this spatial resolution and extension, providing a novel baseline for the future extension of the sector as well as for the co-development of the sector with other offshore industries that already exist and/or future offshore installations (e.g., offshore wind farms, mothballed oil platforms; Kaiser et al., 2010). This knowledge can be exploited into the future and used as a base-layer that can be integrated with other site-specific information such as: current velocity, frequency of storms, distance from onshore facilities, navigation hazards, fishing grounds, cost associated to system installation, maintenance and endurance among the others when considering the location, design and budget for new farming sites (FAO, 2013; Gentry et al., 2017b).

The modelled species-specific scenario-based maps allowed us to forecast the four target species' production potential in an Integrated Multi-Trophic Aquaculture context. Despite IMTA being considered as an option for sustainable aquaculture development (Troell et al., 2009), its development in several countries has been hindered by poor or absent licensing and regulation systems (Falconer et al., 2022). Our findings can facilitate the dialogue among parties for the creation of economic and environmental feasibility studies, as well as licensing and regulatory systems in national and regional contexts.

Possible effects of model limitations

Apart from the common limitation of mechanistic modelling (e.g., time consuming, too data-hungry etc.), once the DEB species models are calibrated, validated, and tested for skill and stationarity

(Helmuth et al., 2014), there are really few limitations preventing the use at large scale to explore performances of cultivated species in every realm (marine and freshwater). The initial effort for DEB species parametrization (i.e., to set boundaries of theoretical species functioning) and calibration is certainly large and time-consuming (from 1 month to 6 months as a function of the zero-variate and univariate data availability across the current literature), but once done the mechanistic power of DEB modelling is high, allowing growth performance to be explored at fine spatial and temporal resolution. Limitations for current spatial resolution: the 0.1° x 0.1° (c.a. 11 x 11 km) scale is small enough to give an overview of change for different Italian regions, but it may lack some needed spatial detail for example local information such as individual bays. Limitations for current temporal resolution: predictions about future climatic trends of course carry within them an intrinsic bias given the nature of modelling environmental data into the future that require a fine temporal modelling-resolution (e.g. 1-hour) to generate predictions as close as possible to those generated by environmentally-measured data (Montalto et al., 2014). To compare the future predictions generated, we considered the 2007-2020 time period as a present and past reference period (even if it does not stand for an accurate representation of present and past conditions) vs. selected multiple scenarios (*sensu* Thomas and Bacher, 2018).

The DEB network is now well-deployed around the world and, compared to only 5-10 years ago, there is sufficient and well dispersed expertise that facilitates access to this modelling by many scientists. This can facilitate the use of mechanistic modelling worldwide and under the whole array of possible environmental conditions and assist stakeholders and decision makers to solve local spatial issues and conflicts. Thus, the major limitation is no longer the DEB but more likely the availability of more accurate scenarios of human uses along all the coastlines of the world's oceans. Once more accurate scenarios of human use are available both for the Mediterranean Sea and for other seas (i.e., at the highest spatial-temporal resolution), it would be easy to increase the resolution of the tailoring exercise that up to now – in the absence of high-resolution data – assumes that the use at sea and the protection levels will remain the same. In this context, our species-specific scenario-based maps can be integrated into human use sensitivity analysis scenarios to simulate increase and/or decrease of human use per each Italian region and at the regional scale based on future development scenarios. This predictive capacity could then be coupled with regional monitoring, production and economic income data per region and per species, once these data are available.

The model does not take into account all the secondary changes related to climate change - specifically increasing temperatures – and all the potential local acting drivers of change that can affect growth and production (e.g., dissolved oxygen concentrations, eutrophication, harmful algal blooms, storminess, acidification, spread of pathogens and disease, molluscs' seed mortalities) that in a multiple stressors context may affect species growth and farm productivity (Sarà et al., 2018b). Similarly multiple stressors frameworks must be integrated into modelling exercises (e.g., by increasing the complexity of the approach discussed here) considering interaction among multiple stressors (e.g., changes in oceanic circulation and mixing, eutrophication, oceanic acidification, oceanic deoxygenation, coastal hypoxia, and pollution; Sarà et al. 2018b). Additionally, the complex interactions of stressors affecting both inshore and offshore aquaculture, at different temporal and spatial scales, must be considered in the spatial planning and design of future sustainable aquaculture development.

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Figure captions

Figure 1 Applied framework to detect the environmental sustainability index resulting from plotting the duration of the grow-out phase, in terms of days needed to reach the commercial size, Time To Commercial Size; (TTCS, days) against potential impact values (IMP values, in terms of uneaten food + feces for the two fish species fed by humans and feces only for the unfed bivalves, grams). Once detected the mean values of both TTCS and IMP (MTTCS and MIMP) were used as reference points of sustainable condition (environmental sustainability *sensu* Sarà et al. 2018a) and the four quadrants around the mean values defining four main conditions to which we then assigned a value, respectively: Worst, (red color) Bad (orange color), Good (yellow color) and Best (green color).

Figure 2 Temporal trend of both Sea Surface Temperatures and Chlorophyll-a (respectively SST; upper graph and CHL-a; lower graph) relative to the RCP 4.5 and 8.5 IPCC scenarios (blue and red lines respectively). Data were downloaded and divided into five-time intervals of five years each (2007-2010; 2017-2020; 2027-2030; 2037-2040; 2047-2050). Data downloaded from POLCOM - Proudman Oceanographic Laboratory Coastal Ocean Modelling System containing the outputs of regionally downscaled projections for European seas generated using coupled ERSEM - European Regional Seas Ecosystem Model 15.06 hydrodynamic-biogeochemical models.

Figure 3 Trends of the number of pixels per condition of environmental sustainability index (Worst = red color; Bad = orange color; Good = yellow color; Best = green color). Data were reported per single species, at both RCP 4.5 and 8.5 scenarios for each of the five-time intervals (2007-2010; 2017-2020; 2027-2030; 2037-2040; 2047-2050). The areas occupied by human activities and the main protected areas and habitats (see Supplementary materials Figure S3 and Table S4, S5 for more details) were excluded.

Figure 4. Number of pixels per condition of environmental sustainability index at each region along the Italian Exclusive Economic Zone (EEZ); Worst = red color; Bad = orange color; Good = yellow color; Best = green color. Areas occupied by human activities and the main protected areas and habitats (see Supplementary materials Figure S3 and Table S4, S5 for more details) were excluded. Data were reported per single species (*Sparus aurata, Dicentrarchus labrax, Mytilus galloprovincialis, Crassostrea gigas*), at both RCP 4.5 and 8.5 scenarios for the 2027–2030-time interval. Numbers correspond to an Italian region: 1- Abruzzo, 2 – Apulia, 3 – Basilicata, 4 – Calabria, 5 – Campania, 6 – Emilia Romagna, 7 – Friuli Venezia Giulia, 8 – Lazio, 9 – Liguria, 10 – Marche, 11 – Molise, 12 – Sardinia, 13 – Sicily, 14 – Tuscany, 15 – Veneto.

Figure 5. Overlapped environmental sustainability index. From the top to the bottom line the five-time intervals considered, respectively 2007-2010, 2017-2020, 2027-2030, 2037-2040, 2047-2050. Respectively, the couple of maps on the left side represent the scenarios comparison between RCPs 4.5 and 8.5. The inshore and offshore areas are divided by a grey line. Maps were performed using QGIS; black pixels represent the areas occupied by human activities layers and the main protected areas and habitats layers. The obtained four values (0 = red colour, 0.25, 0.5, 0.75. 1 = increasing shades of blue colour) were used to indicate how many species can be farmed in the same aquaculture facility maintaining the environmental sustainability target (respectively 0 = none; 0.25 = one species; 0.5 = two species; 0.75 = three species; 1 = four species).

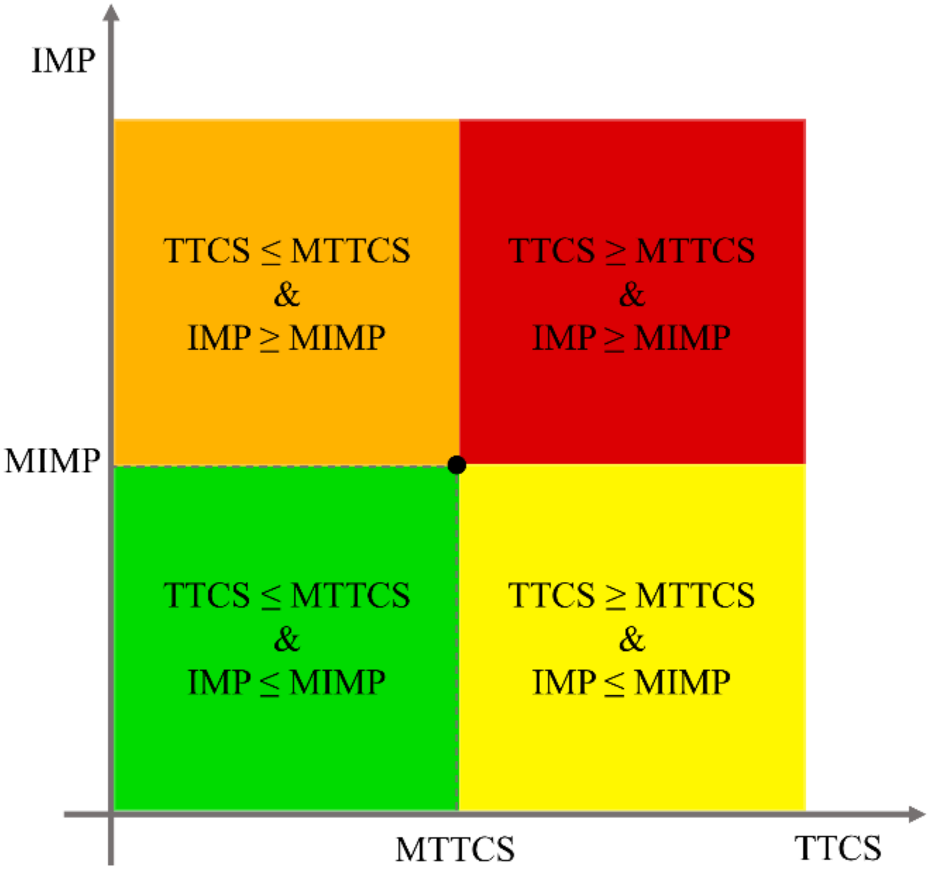
IMP
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Figure 1.

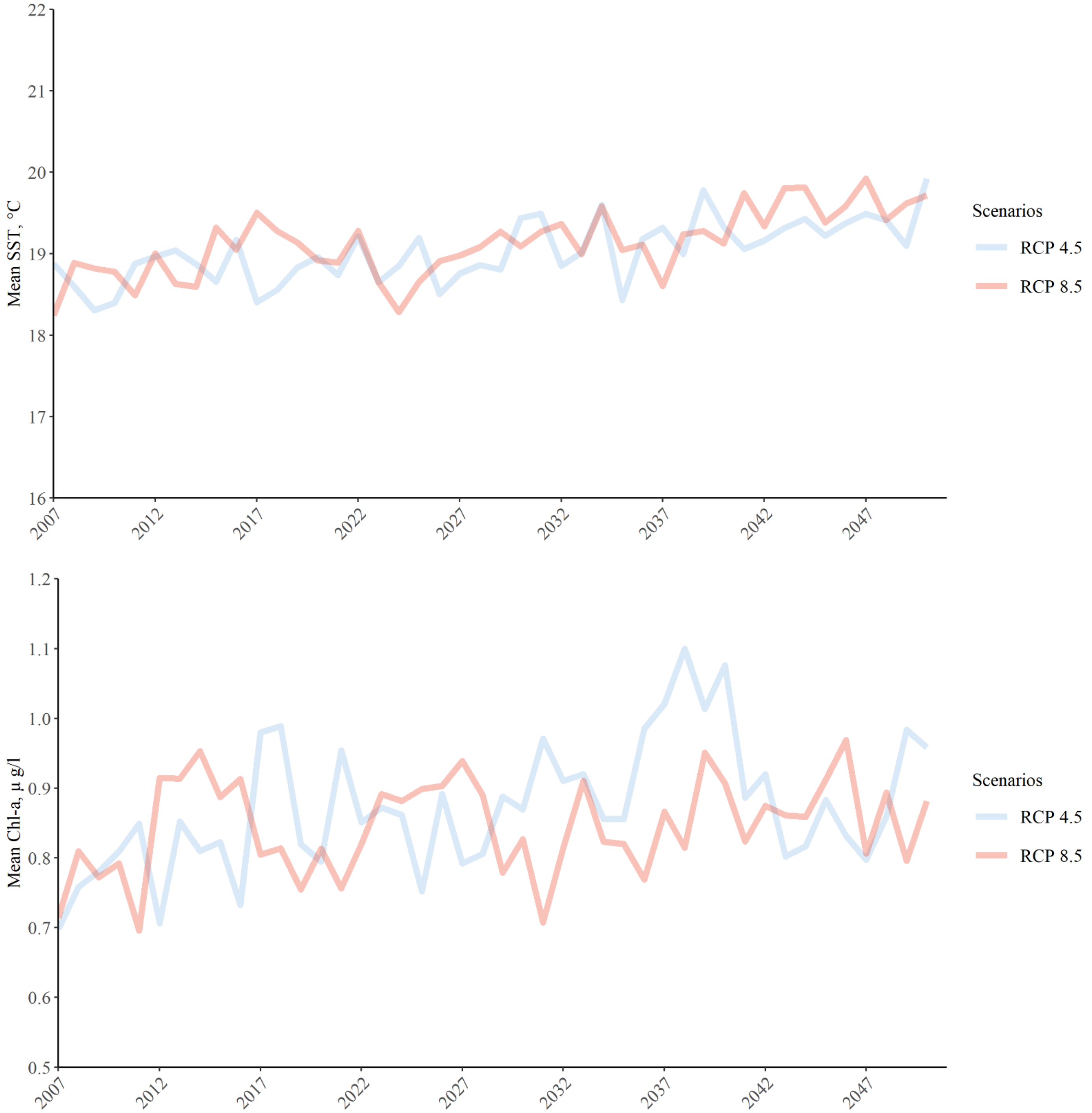
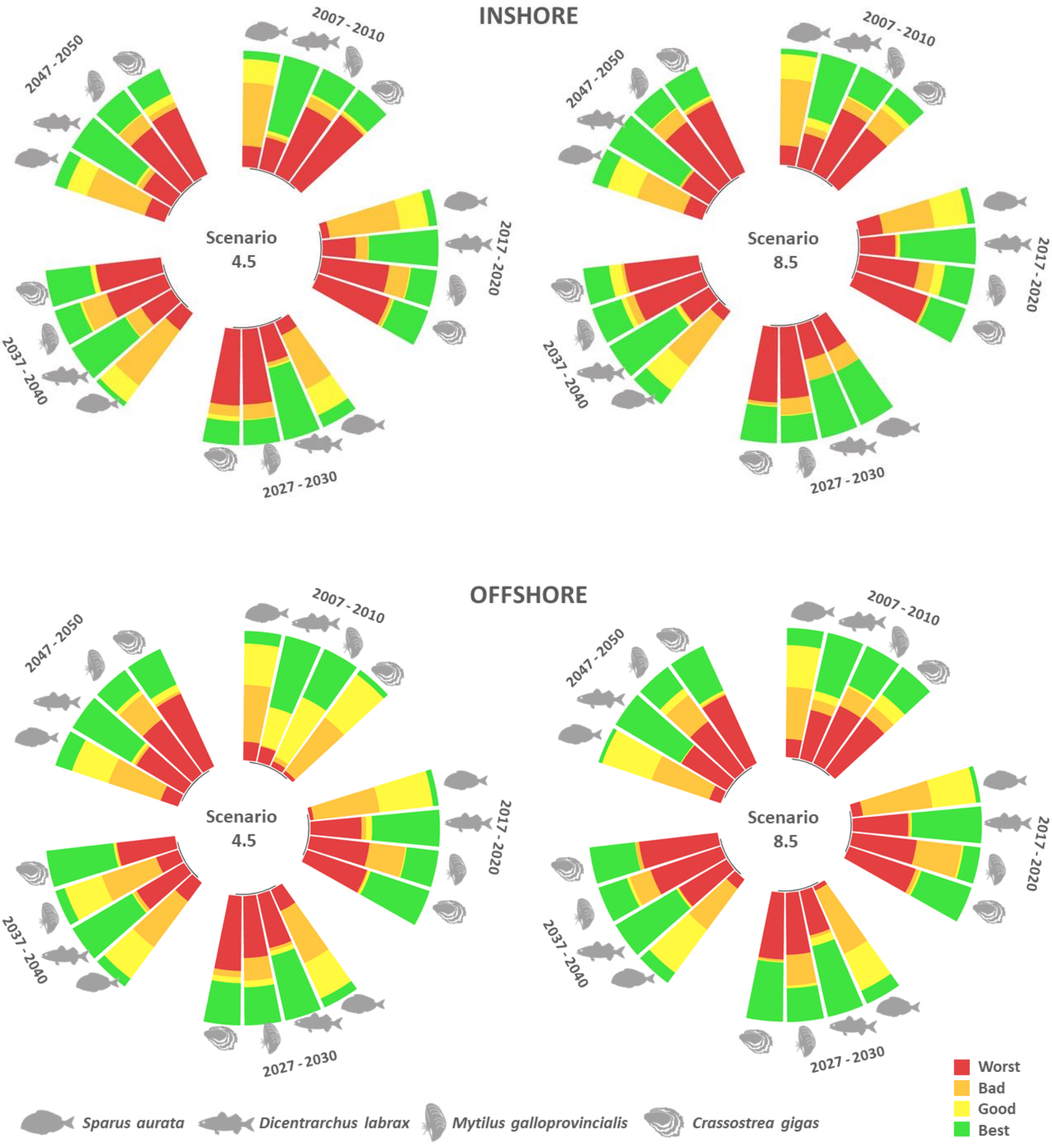

22
21
20
19
18
17
16
Mean SST, °C
2007
2012
2017
2022
2027
2032
2037
2042
2047
Scenarios
RCP 4.5
RCP 8.5
1.2
1.1
1.0
0.9
0.8
0.7
0.6
0.5
Mean Chl-a, µ g/l
2007
2012
2017
2022
2027
2032
2037
2042
2047
Scenarios
RCP 4.5
RCP 8.5

Figure 2.



INSHORE
Scenario
4.5
Scenario
8.5
OFFSHORE
2007 - 2010
2017 - 2020
2027 - 2030
2037 - 2040
2047 - 2050
Worst
Bad
Good
Best
Sparus aurata
Dicentrarchus labrax
Mytilus galloprovincialis
Crassostrea gigas

Figure 3.

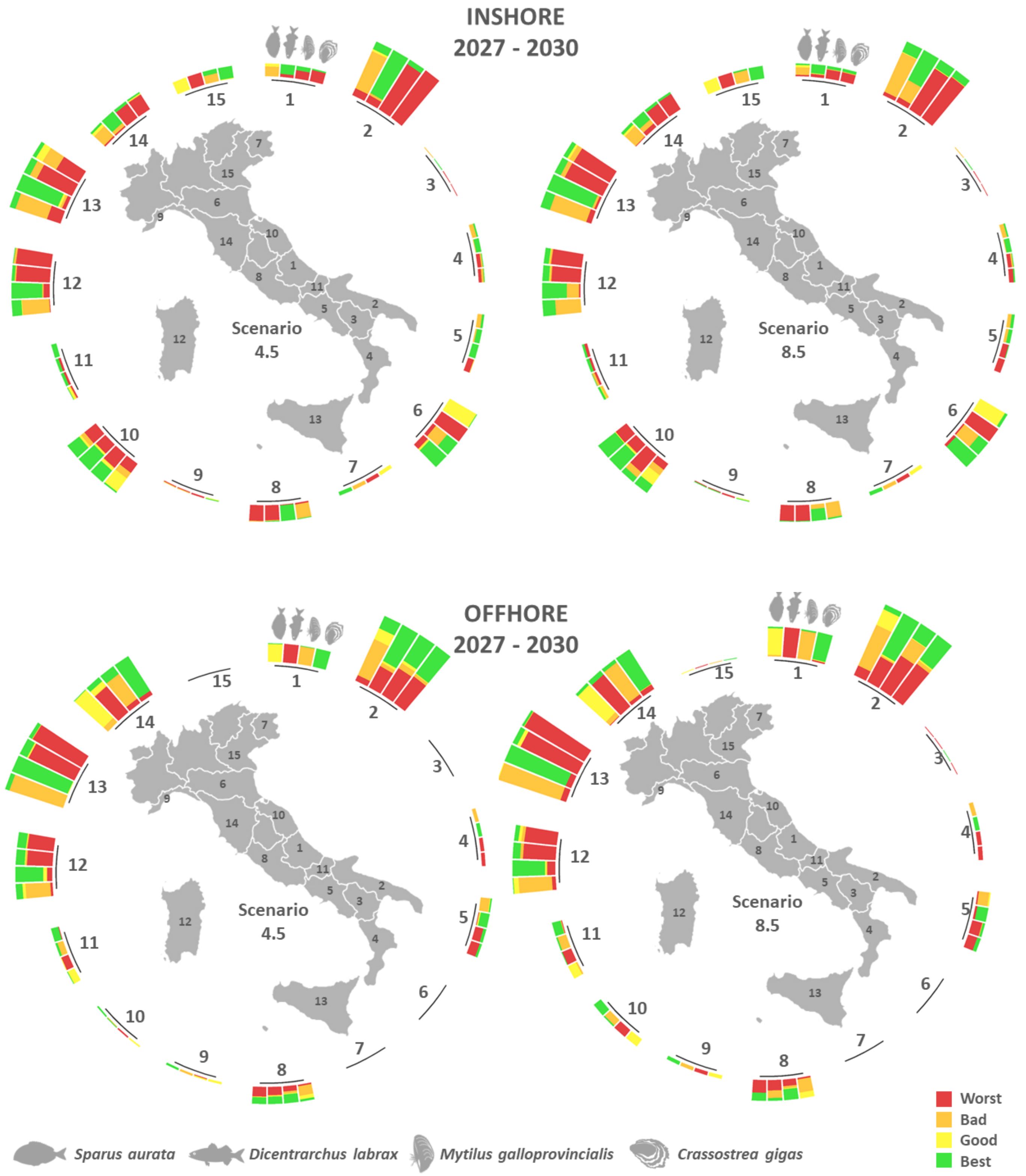
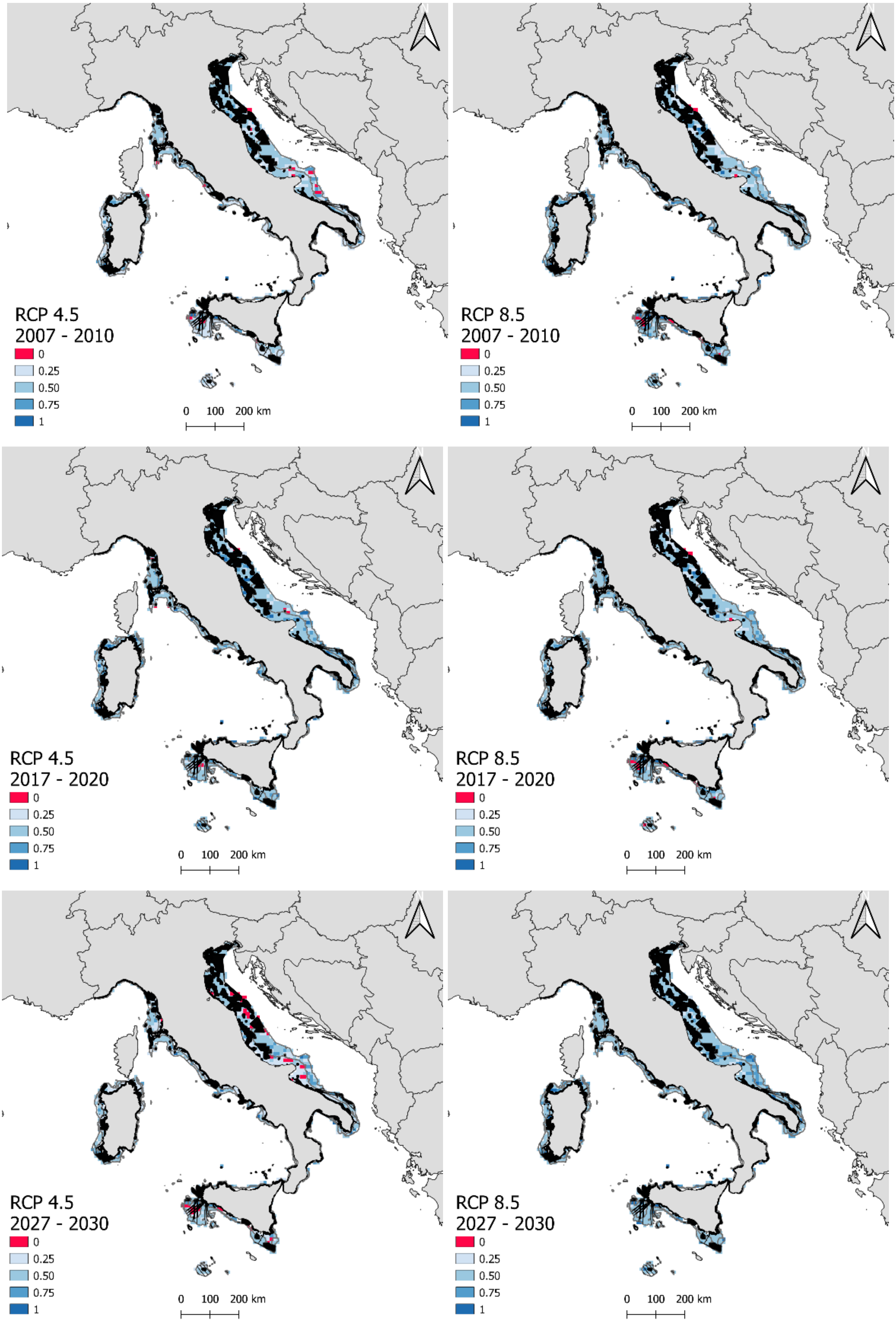

INSHORE
2027 - 2030
Scenario
4.5
Scenario
8.5
OFFHORE
2027 - 2030
Scenario
4.5
Scenario
8.5
Sparus aurata
Dicentrarchus labrax
Mytilus galloprovincialis
Crassostrea gigas
Worst
Bad
Good
Best

Figure 4.


RCP 4.5
2007 - 2010
0
0.25
0.50
0.75
1
0 100 200 km
RCP 8.5
2007 - 2010
0
0.25
0.50
0.75
1
0 100 200 km
RCP 4.5
2017 - 2020
0
0.25
0.50
0.75
1
0 100 200 km
RCP 8.5
2017 - 2020
0
0.25
0.50
0.75
1
0 100 200 km
RCP 4.5
2027 - 2030
0
0.25
0.50
0.75
1
0 100 200 km
RCP 8.5
2027 - 2030
0
0.25
0.50
0.75
1
0 100 200 km

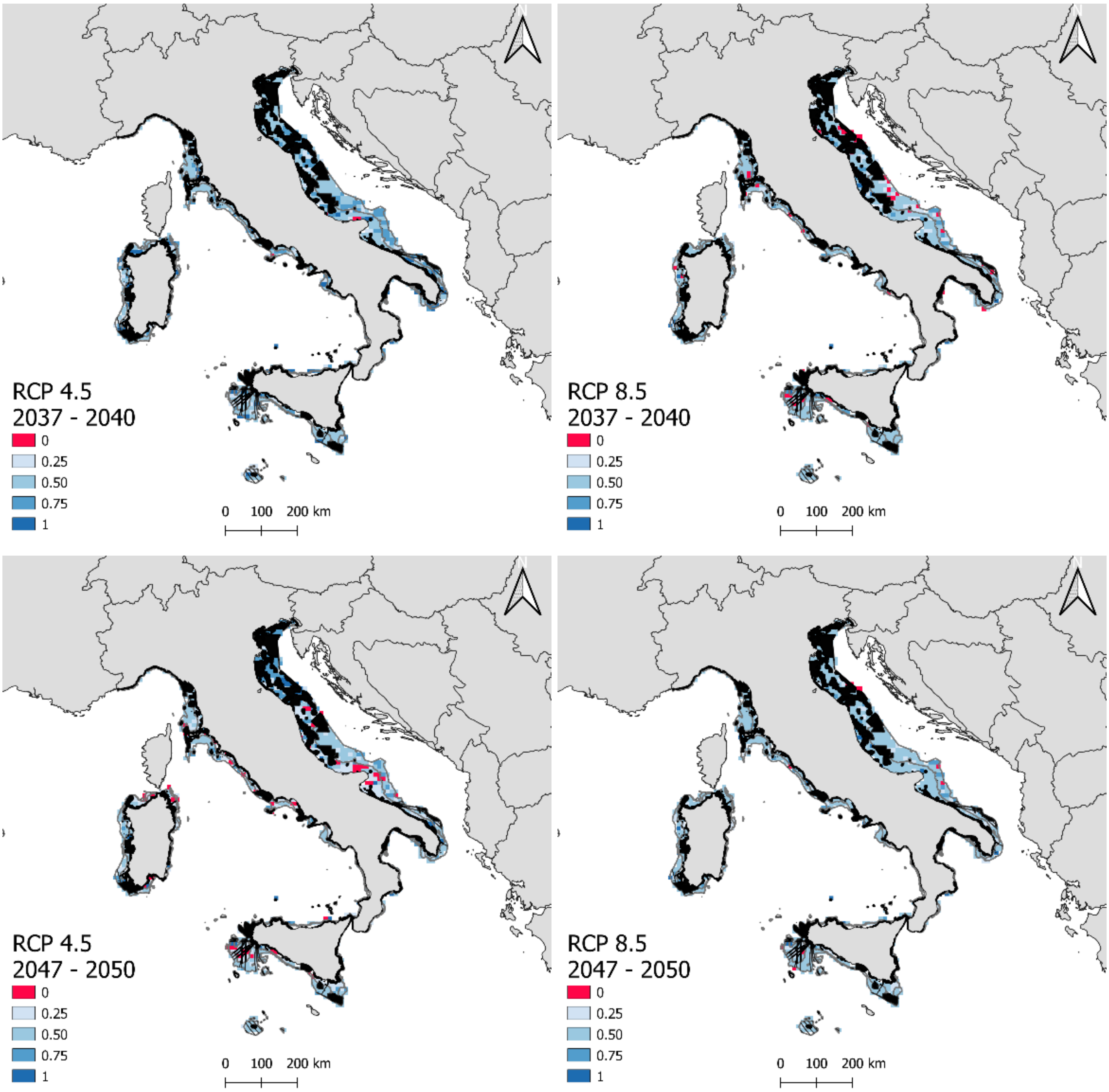

RCP 4.5
2037 - 2040
0
0.25
0.50
0.75
1
0 100 200 km
RCP 8.5
2037 - 2040
0
0.25
0.50
0.75
1
0 100 200 km
RCP 4.5
2047 - 2050
0
0.25
0.50
0.75
1
0 100 200 km
RCP 8.5
2047 - 2050
0
0.25
0.50
0.75
1
0 100 200 km

Figure 5.