This is a preprint (pre-peer reviewed) version of the following paper: “Chiara Venier, Stefano Menegon, Hugh P. Possingham, Elena Gissi, Andrea Zanella, Daniel Depellegrin, Alessandro Sarretta, Andrea Barbanti, Jennifer McGowan, Multi-objective zoning for aquaculture and biodiversity”, in Science of the Total Environment, Volume 785 (2021) 146997 <https://doi.org/10.1016/j.scitotenv.2021.146997>.

Multi-objective zoning for aquaculture and biodiversity

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Graphical Abstract

Abstract

Aquaculture is the fastest growing food production industry in the world yet research and guidance demonstrating strategic multi-objective zoning for sector expansion is scarce. Quantifying and mitigating conflicts and impact on sensitive coastal environments through jointly-optimized objectives for aquaculture and biodiversity simultaneously has not been tested yet.

We here develop and evaluate six alternative planning scenarios for one of the European Union's highest priority mussel aquaculture areas, the Emilia-Romagna Region in Italy. We i) develop an aquaculture profitability surface as a function of the distance from main ports, and in parallel build a fine-scale aquaculture suitability distribution surface for important commercial species using multi-criteria analysis; ii) prioritize protected areas for biodiversity while testing how different considerations of human impacts influence priorities; iii) simultaneously plan for aquaculture and biodiversity while minimizing impacts on other maritime activities. We compare results from different scenarios according to how well they capture suitable aquaculture habitats and minimize impacts. We introduce a new evaluation method for scenario comparison in spatial optimization using a nearest-neighbour analysis for spatial pattern similarities.

41 Lastly, we test the “value of information” provided by our investment in developing the fine-scale
42 suitability surface to improve efficiencies.

43 We find that an integrated multi-objective zoning approach, which simultaneously optimizes for
44 biodiversity and aquaculture, supports more efficient planning than traditional sector specific growth
45 strategies. We also discovered that the fine-scale suitability model delivered an 8% more efficient solution
46 than the simple distance function, highlighting the role of proxy surfaces and diminished returns from
47 investing in comprehensive habitat suitability analysis in regions without much variation in key
48 parameters.

49 We offer evidence of improved efficiency and practical guidance for integrated planning in Blue Growth
50 agendas. Our analysis can be applied in any context where multiple objectives occur for aquaculture sector
51 growth and biodiversity conservation.

52
53 **Keywords:** *Biodiversity Conservation, Maritime Spatial Planning, Marxan and Marxan with Zones, Multi-*
54 *objective Zoning, Sustainable Aquaculture Development, Value of Information.*

1 Introduction

Aquaculture is the fastest growing form of food production on the planet, growing at an annual rate of 6% per year (FAO 2015; Froelich et al. 2018, O'Shea et al. 2019). Significant expansion of aquaculture in the Mediterranean is a primary component of the European Union's Blue Growth Initiative (Blue Growth Initiative, DG MARE 2012), of the Adriatic and Ionian Macro-regional strategy (EC 2014a) and of the Maritime Spatial Planning (MSP) Directive 2014/89/EU (EC 2014b). The coastal waters of the northern Adriatic Ionian Region of Italy, in particular the Emilia-Romagna region, are a priority for aquaculture development (EC 2008; Barbanti et al. 2018). This region produces 45% of the national production of clams (*Tapes philippinarum*) and mussels (*Mytilus galloprovincialis*) - approximately 40,000 tons/year (Mipaaf 2015). National planning requires the identification of proposed areas of interest for the development and expansion of the aquaculture sector based on their environmental suitability, conflicts and synergies with other uses, as well as proximity to port infrastructure (Barbanti et al. 2018).

Biodiversity protection is also a fundamental component of the EU-MSP Directive and the Adriatic Ionian Sea is recognized as an Ecologically and Biologically Significant Marine Area (EBSA) (Johnson et al. 2018, Giakoumi et al. 2013). Coastal waters contain valuable Essential Fish Habitats that provide resources and nursery grounds to both vulnerable species, such as the Atlantic horse mackerel, and commercially important species such as anchovies (e.g., *Engraulis encrasicolus*) and sole (*Solea solea*) (Grati et al. 2013). Additionally, these waters host bottlenose dolphin (*Tursiops truncatus*) and provide one of the most important feeding grounds in the Mediterranean for the endangered Loggerhead sea turtle (*Caretta caretta*).

Reconciling the need for biodiversity protection alongside economic growth from aquaculture in Emilia-Romagna must also consider human uses co-occurring in the region. These include coastal and maritime tourism, which is the primary economic activity, as well as port activities, shipping of goods and passengers, commercial and recreational fisheries, energy and communication infrastructure, military uses, sand extraction, underwater cultural heritage sites, and offshore gas and oil platforms (the region alone contributes roughly 50% of the national gas supply (Assomineraia, 2015). Thus, developing marine spatial planning strategies that can identify suitable sites for aquaculture expansion, while not compromising important areas for biodiversity and other socio-economic uses in the region, is a complex but essential priority (Gissi et al. 2018; Mazor et al. 2014; Farella et al. 2020; Henriques et al. 2017; Fernandes et al. 2018).

There are many examples of multi-objective marine spatial planning approaches (Beger et al. 2015) that balance biodiversity with industry and other human activities (Klein et al. 2008; Jumin et al. 2018; Yates et al. 2015; Grantham et al. 2013) but these typically focus on developing zoning plans that retain existing fishing grounds. Currently, there is limited guidance for planning the expansion of aquaculture in coastal habitats while balancing the needs of biodiversity and managing conflicts with other uses. We fill this gap by proposing a comprehensive analysis that develops and tests six planning scenarios in the Emilia-Romagna region of Italy. These scenarios increase in complexity from traditional approaches that prioritize biodiversity alone, while minimizing impacts on human activities, through to multi-objective prioritization for both biodiversity and aquaculture.

Prioritizing new locations for aquaculture requires an understanding of the environmental, biophysical and economic constraints influencing suitability. Thus, we conduct a comprehensive suitability analysis for the target aquaculture species (Stelzenmüller et al. 2017), but also test the value of this information

to inform priorities against a profitability assessment driven by distance to the coastline (Mazor et al. 2016; Jumin et al. 2018). We use the decision support tool Marxan (Ball and Possingham 2000), as well as its advanced version, Marxan with Zones (Watts et al. 2009), to identify priority areas for aquaculture and/or conservation. We evaluate our results in two ways. Firstly, we look at the aquaculture area prioritized across all scenarios and zoning configurations. Secondly, we develop a new comparative method to examine the similarities of the spatial configurations of zoning solutions in addition to their levels of priority. This method calculates pairwise similarity between scenarios and randomly generates solutions in order to quantify observable differences in spatial priorities. Given the important and increasing role aquaculture will play in global food production (Gentry et al. 2017), our aim is to provide the first practical exploration of how to conduct and evaluate multi-objective prioritization for aquaculture and biodiversity using a systematic planning approach.

Figure 1: Study Area boundaries (a) and their location in the Adriatic Sea (b) and in the Mediterranean Sea (c) context.

2 Material and Methods

2.1 Study Area and Design

The planning area spans on the Emilia-Romagna marine waters (5256 km²), from the coast (approximately 120 km in length) up to the limit of Italian jurisdictional waters, including the territorial sea and high seas up to the midline (approximately 70 km), which is the international waters limit (see Figure 1). The planning area was divided into 5,256 square planning units of 1km x 1km size.

Our study design consists of three main steps performed consecutively (Appendix S.1 in the Supporting Information). Firstly, we organize and develop the three classes of spatial data layers required to underpin the analyses, which include: i) relevant conservation features (e.g. habitats and species); ii) aquaculture suitability and profitability surfaces; and iii) distributions of human activities and industries. Secondly, we construct six planning scenarios using different treatments of the three classes of data to identify priorities in either single objective plans using Marxan, or multi-objective plans using Marxan with Zones. Lastly, we conduct *post-hoc* evaluations across all scenarios using suitability analysis and a spatial similarity analysis based on a new analytic method.

2.2 Spatial data

2.2.1 Conservation Features

We included 33 conservation features (Appendix S.2) based on regional spatial data provided in the Tools4MSP Geoplatform - the primary platform developed to support marine spatial planning in the

Adriatic Sea (data.tools4msp.eu) (Menegon et al. 2018). The features include seabed habitats (maerl bed, infralittoral fine sands, circalittoral fine sands, circalittoral sandy mud, circalittoral fine mud) (European Environmental Agency 2017), and data for important species including: bottlenose dolphin (*Tursiops truncatus*), seabirds and loggerhead sea turtles (*Caretta caretta*) species distributions, and nursery and spawning areas of commercially important fish species (*Engraulis encrasicolus*, *Mullus barbatus*, *Pagellus erythrinus*, *Sardina pilchardus*, *Scomber colias*, *Scomber scombrus*, *Solea solea*, *Trachurus mediterraneus*, *Trachurus trachurus*).

2.2.2 Aquaculture suitability

Developing a spatial understanding of where conditions are most suitable for the three most commercially important species of mussels, *Crassostrea gigas*, *Mytilus galloprovincialis*, and *Ostrea edulis*, is required before priority areas for aquaculture expansion can be identified. To do so, we followed the methods outlined in existing literature to derive aquaculture suitability scores (Valentini et al. 2016; Davaasuren et al. 2010; Andersen et al. 2013), which we then vetted with national aquaculture experts. This process defines eleven important indicators related to three criteria: environmental quality, optimal mussel growth conditions and socio-economic considerations (Appendix S.3). We assume suitability scores of 0.6 or higher reflect sufficient environmental quality for mussel growth (Arpae, 2017; Dapuerto et al., 2015).

Weights for all criteria (Appendix S.3) were assigned according to previous work by Dapuerto et al. (2015). The suitability (S) for each planning unit (i) was calculated according to the following equation (Appendix S.4.a):

$$S_i = \sum_j w_j c_{ij} \quad , \quad (\text{Eq. 1})$$

167

168 where:

169 i = i -th planning unit,

170 j = criteria (environmental quality, optimal mussel conditions and socio-economic aspects),

171 w_j = weight of the j -th-criteria, and

172 c_{ij} = scores of the indicators.

173

174 The primary socio-economic factor considered was the distance of a planning unit to any port, as we
175 assume aquaculture zones placed further away from shore will decrease net profits due to the operational
176 costs of travel (Mazor et al. 2014). To calculate the value, we used the following equation to build the
177 proxy profitability surface:

178

179
$$P = \max (1 - \alpha d, 0)$$
 , (Eq. 2)

180

181 where the proxy profitability (P) of a planning unit is determined by the parameter α which reflects how
182 fast profitability declines as the facility moves from the coast. Coastal areas near ports have a shorter
183 distance to travel, thus the management cost for the industry (e.g. fuel, vessel maintenance, etc) is
184 considered marginal closer to the coast and increases with distance. We assume aquaculture would no
185 longer be profitable in the area outside of 12 nm (Appendix S.4b).

186

187 2.2.3 Human Use layer

188 To generate a cost surface reflective of human uses, we follow the method of Gissi et al. 2018, which used
189 the number of maritime industries occurring in each planning unit as a proxy for the transaction costs of

negotiating biodiversity protection in each unit (e.g., the more industries, the higher the cost to conserve) (Appendices S.5 and S.6). We included the distributions of 12 industrial sectors and activities, as mapped by Tools4MSP Geoplatform (Menegon et al. 2018): aquaculture, coastal and maritime tourism, coastal defence works, dumping area for dredging, maritime transport, military areas, naval-based activities, off-shore sand deposit, oil and gas extraction, oil and gas research, small-scale fisheries, and commercial fishery (Appendix S.5a). We assumed that all maritime industries have equal standing in the negotiation process and thus did not add an arbitrary weighting to the aggregate values. We also created a variation of this cost surface that included a total of 7 uses considered to be in conflict with aquaculture, specifically (Appendix S.5b).

2.3 Scenarios and Prioritization

Reconciliation of competing human uses lay at the center of marine spatial planning challenges in the Adriatic Sea (Gissi et al. 2018). Therefore, we were primarily interested in understanding how priorities for biodiversity and aquaculture changed depending on the treatment of human uses and industries used in the prioritization analysis. We used the spatial decision-support tools Marxan (Ball and Possingham 2000) and Marxan with Zones (Watts et al. 2009), which use a simulated annealing algorithm to meet predetermined targets for conservation features whilst minimizing impacts (also termed "costs") to industries. We used different combinations of objectives, targets, Marxan softwares, and costs to develop six planning scenarios (Table 2). To make our comparisons as objective as possible, we did not apply the boundary length modifier in our analyses to preference compactness.

Table 2: Scenario construction describing how objectives, tools, targets, and costs vary across the six analyses.

Objective	Scenario	Conservation Features and Targets	Cost Used
Biodiversity Prioritization (Marxan)	S1	<ul style="list-style-type: none"> Seabed habitats (30%) Nursery and spawning areas (30%) Species distribution (10%) 	Area
	S2		Aquaculture profitability
	S3		Number of human uses
	S4		Aquaculture suitability
Biodiversity and Aquaculture Prioritization (Marxan with Zones)	S5	Biodiversity zone (S5Z1) <ul style="list-style-type: none"> Seabed habitats (30%) Nursery and spawning areas (30%) Species distribution (10%) 	Number of human uses
		Aquaculture zone (S5Z2) <ul style="list-style-type: none"> Aquaculture profitability (40%) 	Number of uses in conflict with aquaculture
		Multiple-Use (S5Z3) <ul style="list-style-type: none"> No targets set 	Number of human uses
	S6	Biodiversity zone (S6Z1) <ul style="list-style-type: none"> Seabed habitats (30%) Nursery and spawning areas (30%) Species distribution (10%) 	Number of human uses

		Aquaculture zone (S6Z2) <ul style="list-style-type: none"> • Aquaculture suitability (40%) 	Number of uses in conflict with aquaculture
		Multiple-Use zone (S6Z3) <ul style="list-style-type: none"> • No targets set 	Number of human uses

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214

215 2.3.1 Single-objective scenarios using Marxan

216 Important conservation features were assigned a 30% target in accordance with the world's oceans target
 217 established at the IUCN World Conservation Congress in Hawaii (2016). We also set 10% targets for broad
 218 ranging species distributions in line with Aichi 11 Target under the Convention on Biological Diversity
 219 (2010). For the first four scenarios, we kept these targets consistent while we varied the way in which the
 220 cost of a planning unit was calculated. The costs for the four scenarios were: S1) area of the planning unit
 221 - a baseline approach to set equal costs across the planning region so that priorities are solely determined
 222 by the conservation features, S2) aquaculture profitability based on the distance to port function, S3)
 223 human uses based on the number of maritime activities found in a planning unit and S4) the aquaculture
 224 suitability surface.

225

226 2.3.2 Multi-objective scenarios using Marxan with Zones

227 We then developed two additional multi-objective prioritization scenarios (S5 and S6) aimed at
 228 simultaneously meeting targets for biodiversity and aquaculture whilst minimizing costs to maritime

industries. Marxan with Zones allows for more sophisticated planning problems than standard Marxan, allowing users to make specific allocations of features, targets and costs to different more than just one kind of zone (Watts et al. 2009; Klein et al. 2010). We organized this analysis around three zones: Biodiversity (Zone 1) with the aim of conserving our biodiversity features; Aquaculture (Zone 2) with the aim of capturing suitable sites for aquaculture; and Multiple-Use (Zone 3) where any activity can take place, but which has no biodiversity or aquaculture targets set. We kept the biodiversity targets consistent with the single objective scenarios for the biodiversity zone, set targets for 40% for the Aquaculture Zone, applied to the profitability surface used in Scenario 5 (S5Z2) and the suitability surface used in Scenario 6 (S6Z2). We also applied two different treatments of the human use cost surfaces, using all human uses in the Biodiversity and Multiple-Use Zones and human uses deemed incompatible with aquaculture in the Aquaculture Zone (Table 2).

2.4 Scenario Comparisons

Marxan returns two major outputs: the individual solutions from each run (total of 100 runs per scenario in this analysis), from which one is determined the “best solution” by achieving the lowest Marxan score; and the “selection frequency” - the frequency with which any planning unit is selected from 100 good solutions. A selection frequency of 100 means a planning unit was in all 100 good solutions and is deemed irreplaceable in order to achieve your objectives (Smith et al. 2019).

To compare scenarios, we were interested in understanding how the different cost surfaces (e.g. area, profitability, suitability and human uses) performed at minimizing impacts to the most suitable areas for aquaculture expansion, particularly within the 12 nm limit where aquaculture industries can operate. To analyze this, we took the portfolio of solutions for each scenario, assigned the aquaculture suitability value

to the selected planning units and evaluated the mean of such values. We refer to this as the “suitability footprint” of the solution (Appendix S.7). Boxplots and histograms of the suitability footprints for scenarios allow us to understand how our decisions on cost considerations impact our planning results.

Examining how the best solution or selection frequency changes from scenario to scenario is a common way to evaluate differences across scenarios. This is often done graphically by identifying where planning unit selection diverges or remains the same between two scenarios. Another method is to use statistical analyses such as calculating the Jaccard statistic (Real and Vargas 1996) or performing hierarchical clustering (Harris et al. 2014). One limitation of these approaches is that they do not provide insight into how similar the spatial configuration of selected planning units may be. Thus, two solutions may have very similar prioritization patterns in a region, but if the selected planning units are slightly shifted in space, the similarity analysis results can be misleadingly low. In order to overcome this limitation, we developed a method to evaluate the patterns of spatial priorities, in addition to standard comparison methods, for every pairwise scenario, for all 15 comparisons.

We adapted the Nearest Neighbor Analysis approach (Ebdon, 1991), normally used for single scenario analysis, to investigate the similarity in the spatial configuration across scenarios.

The best solution outputs from each scenario have been used to compute the *Nearest Neighbour ratio index* (Eq.3), testing the performance of this approach, according to the following steps:

- Firstly, we compute the average of the minimum distance distributions between the centroid of a selected planning unit of one scenario and the centroid of the closest selected planning unit of the other scenario, $NN(S_x, S_y)$, where x and y denote two separate solutions (plans).

- considering that nearest neighbour distance is asymmetric, in most cases $nn(Sx, Sy)$ (forward) is not equal to $nn(Sy, Sx)$ (backward), we define the Nearest Neighbor distance (NN) as the maximum over these distances (forward and backward).
- Finally, the NN ratio is calculated as the observed NN distance divided by the expected NN based on the hypothetical randomized solutions of both scenarios with the same number of selected planning units (NN).

$$NNratio_{xy} = \frac{NN(Sx, Sy)}{NN(Sxr, Syr)}, \quad (Eq. 3)$$

with

$$NN(Sx, Sy) = \max\{nn(Sx, Sy), nn(Sy, Sx)\}$$

and

$$nn(Sx, Sy) = \frac{\sum_{i \in Sx} \min_{j \in Sy} d_{i,j}}{n}, \quad nn(Sy, Sx) = \frac{\sum_{j \in Sy} \min_{i \in Sx} d_{i,j}}{m},$$

where:

n = total number of selected planning units for scenario Sx,

m = total number of selected planning units for scenario Sy, and

$d_{i,j}$ = distance between planning unit i of scenario Sx and planning unit j of scenario Sy.

If the index is less than 1, the two scenarios exhibit more similarity in their patterns than random. If the index is greater than 1, the patterns are more dissimilar than random.

To evaluate this new Nearest Neighbor method, we also calculated the Jaccard distance (0 (full similarity) to 1 (no similarities)) for each pairwise scenario, defined as the ratio of the size of the symmetric difference between scenarios to their union (Real and Vargas 1996). We compute (see Eq.4) how many times the

planning units have been selected in just one of two scenarios compared and divided this value by the total number of selected units (excluding the combination 0-0) to derive the *Jaccard ratio*:

$$Jaccard\ ratio_{xy} = \frac{J(Sx,Sy)}{\underline{J}(Sx,Sy)} \quad (Eq. 4)$$

where Jaccard distance (J) is divided by the expected Jaccard mean distance given from random patterns ($\underline{J}$) for two scenarios.

We plot the NN ratio and Jaccard ratio for each pairwise comparison in order to explain the similarity and dissimilarity between their spatial patterns. For this method, the lower the NN and Jaccard ratios, the more similar the two solutions are.

3. Results

3.1 Scenarios analysis

Across the biodiversity prioritization scenarios (Figure 2; S1-4; Table 2), the areas identified for protection were heavily influenced by the spatial distributions of the cost surfaces. When we used area as a cost (S1), priorities for protection were uniformly distributed across the region because solutions are not bound by variations in the cost surface and biodiversity targets could easily be met throughout the planning region. More definitive priorities emerge in Scenarios S2-S4 with the introduction of spatial variation in costs. Aggregations of high priority areas near the city of Ravenna and along the 12nm boundary emerge where impacts to aquaculture profitability (S2) and suitability (S4) are minimized. Consideration of human activities (S3) constrains the pelagic areas outside of 12nm, evidenced by the clear avoidance of linear shipping lanes in the southwest region. In all cases, targets for both important nearshore habitats and more broadly distributed pelagic features can be met with a high level of flexibility across the region (Appendix S.8) and the area needed to meet these targets covers around 30% of the planning region.

Figure 2: Results from scenarios 1-4 showing the best solutions (top row) and selection frequencies (bottom row) where the cost surface changes.

Figure 3: Top row - Best Solution results for a) scenario 5 and b) scenario 6. Bottom row - Selection Frequency (SF) results for c) scenario 5 and d) scenario 6, where: Mostly biodiversity (dark green), when SF biodiversity $\geq 70\%$; Frequently biodiversity (light green), when SF biodiversity between 50% and 70%; Mostly aquaculture (dark blue), when SF aquaculture $\geq 70\%$; Frequently aquaculture (light blue), when SF aquaculture between 50% and 70%; Mostly multi-use (dark grey), when SF multi-use $\geq 70\%$; Frequently multi-uses (light grey), when SF multi-use between 50% and 70%; Flexible (white), when the difference

among the three zones is less than 15%.

Best solutions from the multi-objective scenarios (Figure 3; S5-S6) show the nearshore coastline as the most preferred placement for aquaculture, with biodiversity objectives needing to be met throughout.

3.2 Scenario comparisons using the suitability footprint

Projecting the aquaculture suitability footprint onto the solutions prioritized for biodiversity shows that, in general, locations identified for biodiversity conservation in the basic Marxan approach occupy more of the suitable aquaculture areas relative to the multi-objective Marxan with Zones-based approach. For example, the aquaculture suitability footprint of the solutions (Appendix S.7) ranged from 0.25 to 0.27 for the single-objective scenarios (S1-S4) but was reduced to 0.21 when biodiversity and aquaculture were simultaneously prioritized (S5-S6) (Appendix S.9). When we prioritized for both objectives simultaneously, the average suitability footprint in the aquaculture zones ranged from 0.55 (S5) to 0.58 (S6) (Appendix S.9).

Histograms of the best solutions for each scenario show the number of planning units prioritized for biodiversity and their corresponding aquaculture suitability values within the 12nm coastal area (Figure 4). We found the scenarios that used the aquaculture-related cost surfaces for profitability (S2) and suitability (S4) met biodiversity priorities by selecting more planning units in the 6-12nm area, where aquaculture suitability is lower, than scenarios that used the non-aquaculture related costs: area (S1) and human impacts (S3). The biodiversity zones in the multi-objective prioritizations were the most efficient at avoiding suitable aquaculture habitat, using less overall area to meet biodiversity priorities in the

coastal area, in terms of the number of planning units, but also in terms of selecting fewer highly suitable places for aquaculture than any of the single objective scenarios.

Figure 4: Histograms of the number of selected planning as a function of suitability values within 12 nm from the coast taken from the best solutions. Colours represent the distance of the planning unit from the coast. (a) Best solutions of the four Marxan scenarios. (b) Best solutions of the two Marxan with Zones

scenarios. Biodiversity (Z1) and Aquaculture (Z2) zones are reported for both scenarios.

3.3 Scenario comparisons using the spatial pattern analysis

The scatterplot (Figure 5) between NN ratio and the Jaccard ratios for all pairwise comparisons shows that the most similar patterns for prioritized biodiversity are between Scenarios 5 and 6 (scenarios using respectively profitability and suitability surfaces as conservation features) according to the J ratio (0.87) and between Scenarios 2 and 4 (scenarios using respectively profitability and suitability surfaces as costs) according to the NN ratio (0.87). The most dissimilar scenarios are represented by the comparison between S2-S6 (J ratio = 0.99 and NN ratio = 1.34).

We found significant NN distances ($p < 0.05$) between all pairwise scenarios except for S1 - S2 ($p = 0.14$). Differently, Jaccard distances are all significant except for S1 - S6 ($p = 0.05$) and S2 - S6 ($p = 0.05$) (see Figure 5 and Appendix S.10).

Figure 5 shows that NN distances and Jaccard distances are not perfectly correlated so they reflect real differences in similarities. The J ratio is always less than 1 which means all the plans are more similar than random. Jaccard alone is not sufficient to study the comparison among scenarios, NN alone provides a better understanding, the combination of both gives a more solid analysis.

According to the NN ratio, three scenario combinations (S2-S4, S5-S6, S1-S4) are more similar than random (NN ratio < 1). Interestingly, analysing similarity relationships on S1, S2, S4, it emerges that scenario S4 is positioned “between” S1 and S2 (S2-S4 = 0.87, S1-S4 = 0.95, S1-S2=0.91). This is confirmed by the spatial

distributions (Figure 2), where S1 is quite similar to a random distribution and S2 shows a more defined clustered pattern, with higher aggregation along the coast, as already mentioned. S4 shows an intermediate clustering pattern between the two. So, using the NN ratio, we infer that profitability and suitability surfaces produce similar scenario patterns and thus similar results. Furthermore, no significant similarity is shown between Marxan and Marxan with Zones scenario combinations. However, scenarios S3 and S5, as well as S3 and S6, which use the same cost surface for the biodiversity zone, show a “lower dissimilarity”.

Figure 5: Scatter plot of NN and J ratios. No confidence interval is shown (grey areas) for a significance level of 0.05.

4. Discussion

Marine aquaculture is an increasingly important industry for blue economic growth and food security worldwide (FAO 2015). Yet guidance on how to help countries expand and prioritize zoning for the aquaculture industry alongside biodiversity conservation and other human uses of the sea remains limited. We tested a systematic conservation planning approach for Italy's most economically important mussel farming region, the Emilia-Romagna. We were particularly interested in how variations in the socio-economic data used, and how they were considered (e.g. either as costs to be minimized (Marxan) or features to prioritize (Marxan with Zones)), influenced spatial zoning priorities. We found that planning for both biodiversity and aquaculture simultaneously resulted in more efficient conservation zones placed in areas less likely to generate conflict with other human uses, including aquaculture. Additionally, higher quality suitable habitat was retained for aquaculture zoning compared to when biodiversity alone was prioritized in an effort to minimize conflict with industries. Thus, we advocate for the integration of multi-objective seascape zoning to improve efficiency and minimize conflicts when industry and conservation are both considered parts of blue economic growth strategies. Further, embedding multi-objective optimization and decision-support tools into blue economy frameworks will help planners and stakeholders better understand the trade-offs between objectives that need to reconcile critical biodiversity protection, food production and economic growth.

In the Emilia-Romagna region, we found there is ample space to grow the aquaculture sector without compromising biodiversity objectives for habitats and the pelagic species in the region. Minimizing impacts with other industries should also be feasible as the majority of industries in direct conflict with mussel aquaculture tend to be spatially discrete and distributed further offshore from where the most suitable coastal conditions are for mussel farms (Appendix S5.b). We suggest using the results from

Scenario 6 as the foundation for discussions with stakeholders to further determine the most appropriate and cost-effective placement of mussel farms and MPAs within the broader zones identified.

We did not quantify the potential negative impacts from bivalve farms on the surrounding biodiversity as part of this study. However, these impacts can be accommodated in the multi-objective zoning approach using Marxan with Zones. This will be particularly important for integrated zoning for aquaculture species that are known for causing more substantial environmental impacts (e.g. carnivorous crustaceans and marine fish (Primavera 2006)).

An important part of our analysis was developing a fine-scale suitability surface for the target aquaculture species. It takes a long time and substantial resources to gather the environmental and biophysical characteristics of the region, as well as validating weightings with regional experts on the ecological and socio-economic parameters affecting suitability (Dapuerto et al. 2015). Given the investment in time and resources required to generate this suitability surface (S6), approximately 3 months FTE for 3 scientists (analysis simple from a computational point of view, timing mainly due to literature analysis and data processing, most of the data already available, but not all, no timing from expert considered, since we rely on Dapuerto et al. 2015), we also wanted to retrospectively understand the value of that information to inform the optimization compared to the proxy distance surface computed in less than 1 hour in a Geographic Information System - the profitability surface (S5). Value of information theory frames the investments scientists make in data collection in terms of its ability to help managers make better decisions (McGowan et al. 2017). In spatial planning, value of information can help us direct limited resources towards collected data where it will reduce key uncertainties in our knowledge of marine ecosystem processes, and subsequently, impact or change what emerges as priority areas (Mazor et al. 2016).

451
452 In this instance, the value of fine scale suitability information (S6) resulted in an 8% increase in efficiency
453 for the areas prioritized for aquaculture compared to the simpler profitability surface (S5). These two
454 scenarios, which prioritized aquaculture alongside biodiversity in the multi-objective zoning approach,
455 also produced the most similar spatial solutions than any pairwise comparison (Figure 5). We conclude
456 that the return on investment for the time and resources to generate the more realistic suitability surface
457 was significant but marginal (Appendix S4a-b), highlighting that when multi-criteria approaches to define
458 suitability include socio-economic factors or other operational constraints (e.g. distance to coastlines or
459 port) with high weightings assigned to them, a proxy surface may provide sufficient information to
460 properly inform the optimization and save valuable time and resources. However, we recognize that this
461 finding is also dependent on the fact that the ecological parameters did not vary widely across our
462 planning region - we anticipate the value of fine-scale suitability modelling to alter the priorities in places
463 with higher oceanographic and water quality variability.

464
465 The comparative statistical methods we apply (projection of the suitability onto different scenarios,
466 histograms distributions, Jaccard, Nearest Neighbors) are consistent in demonstrating significant
467 similarity between two pairs of scenarios: S5 and S6, S2 and S4, where S5 and S6 are multi-objectives
468 scenarios respectively with aquaculture profitability and suitability as conservation features, while S2 and
469 S4 are biodiversity prioritization scenarios respectively with aquaculture profitability and suitability as
470 costs.

471 According to our statistical analysis (histograms and ratios), the S5 and S6 spatial plans are very similar. In
472 these scenarios, the introduction of an aquaculture zone, allows us to obtain better results in terms of the
473 trade-off between aquaculture and biodiversity (statistics show good capacity to avoid areas of high
474 suitability).

Plans S2 and S4 were expected to be similar because the aquaculture suitability has been built with strong emphasis on socio-economics. However statistical analysis reveals that plan S4 is preferable because of the more detailed socio-economic modelling.

However, the difference in using profitability and suitability is less marked in S5 and S6 in line with crossplot output and also consistent with the distance between S5 and S6, which is lower than that one between S2 and S4.

5 Conclusion

We provide practical guidance on how to conduct and evaluate multi-objective spatial prioritization for aquaculture and biodiversity using a systematic planning approach. We believe our overall approach can be adopted to any study where society needs to make trade-offs between biodiversity, aquaculture and other industries. This work is a first step in helping bring aquaculture zoning into the planning dialogue that is taking shape around the world but has yet to see the development of long-term growth strategies (Froelich et al. 2020).

Author's Contributions

C.V., S.M., H.P., E.G., A.S., A.B. and J.M.C conceived the initial ideas for this work; C.V., S.M., H.P. and J.M.C. developed the methodology; C.V. and A.Z. data acquisition and curation; C.V. initial analysis; C.V. and S.M. formal analysis; C.V. and S.M. maps and visualization; C.V. wrote the first draft of the manuscript; H.P. and J.M.C provide major contributions to the analysis and to drafting the text; H.P. and J.M.C supervision; H.P., J.M.C, A.S., A.B, and E.G. funding acquisition; H.P., E.G., D.D., A.S., A.B., and J.M.C. review. All authors contributed critically to the drafts and gave final approval for publication.

Acknowledgements

This research is funded by: RITMARE Flagship Project of the National Research Programmes funded by the Italian Ministry of University and Research (2012–2016); Short Term Mobility (STM) Grants funded by the National Research Council of Italy (2016); Research Grant Program of The Ministry of Research and Higher Education of Indonesia in academic year 2017/2018 and by the Erasmus Mundus Master Course on Maritime Spatial Planning of the Education, Audiovisual and Culture Executive Agency (EACEA) (GA 2016-1889 and 2017-1725).

Data Availability

Data available from the Zenodo Repository <https://doi.org/10.5281/zenodo.4279386> (Venier et al., 2020).

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