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Making space for shellfish farming along the Adriatic coast

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This work focuses on the selection of new areas for shellfish farming along the coast of the Northern Adriatic Sea (Italy). Shellfish site suitability was assessed by means of a methodology based on Spatial Multi-Criteria Evaluation (SMCE), which provided the framework to combine mathematical models and operational oceanography products. Intermediate level criteria considered in the analysis included optimal growth conditions, environmental interactions, and socio-economic evaluation (*e.g.* organic carbon deposition; distance to harbour). Results showed that the whole coastal area comprised within 0 and 3 nm is highly suitable for farming of mussel, while the area comprised between 3 and 12 nm is divided between a highly suitable northern part, and a less suitable southern one. Seven different scenarios of development of shellfish aquaculture industry were explored. The introduction of a new species, and the assessment of the exposure to storm events are specific aspects taken into account in development scenarios. Results show that the degree of suitability for shellfish aquaculture in this area would not change dramatically with the introduction of oyster farming. Furthermore, results highlight that: (i) the growth potential in this area is high; (ii) the space with suitability index >0.5 increases when prioritizing the optimal growth condition criteria, and (iii) the socio-economic is the most restrictive Intermediate Level Criteria. Results were discussed by deriving general lessons concerning the use of SMCE in aquaculture space allocation, from the specific application in the Northern Adriatic Sea. Challenges and opportunities related to the proposed methodological framework, with particular reference to the use of resources provided by remote sensing and operational oceanography by means of mathematical models, were also discussed. Results can support a science-based identification of allocated zones for aquaculture in order to avoid conflicts, and promote sustainable aquaculture in the Mediterranean Sea, where the space for these activities is becoming increasingly limited.

Keywords: Adriatic Sea, mathematical models, operational oceanography, remote sensing, shellfish aquaculture, site selection.

Introduction

The selection of areas allocated to aquaculture plays a key role in supporting the sustainable development of this industry (EATIP, 2012). Space selection should take into account both the production, ecological and social carrying capacity of a given area (McKindsey *et al.*, 2006), and the conflicting uses of marine space (Douvere, 2008). Furthermore, aquaculture planning involves stakeholders in order to lead to more realistic and effective policies and spatial plans but, at the same time, stakeholders have diverse objectives leading to space competition and affecting the consultative process (Sevaly, 2000). In the EU, the «Blue Growth Strategy» (EC, 2012), includes aquaculture as one of its pillar. However, within this region, the shellfish industry has to comply with Directives aimed at preventing further deterioration of marine ecosystems, and regulating human uses of the sea («Marine Strategy Framework Directive - MSFD» 2008/56/CE, European Community, 2008; «Maritime Spatial Planning - MSP» 2014/89/EU, European Community, 2014). Available space for aquaculture activities is becoming increasingly limited and a proper design of Allocated Zones to Aquaculture (AZAs) is necessary in order to avoid conflict, to promote a sustainable mariculture (Sanchez-Jerez *et al.*, 2016) avoiding environmental degradation and negative interaction with other marine activities.

The designation of new AZA should be considered in a context of Ecosystem Approach for Aquaculture (EAA), promoting sustainable development, equity and resilience of the social-ecological system (Soto *et al.*, 2008). According to the report FAO (2015), the selection of sites/areas allocated to aquaculture plays a key role in supporting the sustainable development of aquaculture farming within the framework of the EAA. To this regard, the identification of AZA, the selection of individual sites and the design of Aquaculture Management Areas (AMAs) are three complex and key issues, which has to be dealt within the framework of a comprehensive spatial planning (FAO, 2013).

Different studies presented applications of Spatial Multi-Criteria Evaluation (SMCE) to aquaculture site selection, as these methodologies allow one to deal with complex spatial problems (*e.g.* Pérez *et al.*, 2005; Longdill *et al.*, 2008; Radiarta *et al.*, 2008, 2011; Hossain *et al.*, 2009; Silva *et al.*, 2011; Liu *et al.*, 2014; Nayak *et al.*, 2014; Brigolin *et al.*, 2015; Dapueto *et al.*, 2015). SMCE techniques are used to aggregate different spatial factors, such as existing marine use and biotic variables, into a spatial Suitability Index (SI) providing a comprehensive assessment for the decision-makers of suitability of the aquaculture activity (Longdill *et al.*, 2008; Silva *et al.*, 2011).

The present paper focuses on the selection of areas to be allocated to off-shore shellfish culture along the coast of the Emilia-Romagna Italian region (Northern Adriatic Sea). Longline farming of Mediterranean mussel (*Mytilus galloprovincialis*) along this coast started in the 90s (Prioli and Moretti, 2000; Prioli, 2004), and now represents an important source of product for the national market (21.6×10^3 metric tons in 2013, ∼33.6% of the national production (MiPAAF, 2014)). The product is sold both at the local and the national level. Most farms are located within 3 nm from the coast, at a depth of ∼10 m (Adriatic Atlas); in 2015, they were managed by 29 companies. The Legislative Decree n. 201/2016 has recently set the framework for the MSP implementation in the Italian Seas. The regulators are represented by a Committee lead by the Italian Ministry of Infrastructure and Transports, and including 1 delegate of Italian region for each reference maritime area and 4 Ministries: (i) Environment, Land and Seas; (ii) Agriculture and Forestry; (iii) Economic Development; (iv) Cultural Heritage and Activities and Tourism.

Information concerning current issues and perspectives of the activity was collected at a stakeholder workshop, held in Chioggia (Italy) on 7th November 2015 in the framework of the EU H2020 project "Aquaspace". The workshop involved representatives from shellfish farmers associations, research organizations, and regulators, who identified the three main issues listed below:

(i) the establishing of new farms in deeper areas, beyond the 3 nm limit, would be beneficial to the activity, as it could allow the introduction of a new longline technology, *i.e.* the Japanese longline system;

(ii) the introduction of new, more profitable, species, such as Pacific oyster (*Crassostrea gigas*) (Gennari *et al.*, 2014);

(iii) the need of assessing the risks for a farm because of storm events, in particular in less sheltered off-shore areas.

Taking into consideration these issues, our aim in the present work is twofold:

- to develop a framework combining mathematical models and operational oceanography products to assess shellfish site suitability;
- to explore the sensitivity of suitability maps to species diversification and different prioritization of the criteria.

Material and methods

SMCE (Malczewski, 2006) is the general framework in which analysis was carried out. SMCE application to aquaculture site selection has been described elsewhere (see *e.g.* Pérez *et al.*, 2005; Longdill *et al.*, 2008; Radiarta *et al.*, 2008; Hossain *et al.*, 2009; Silva *et al.*, 2011; Liu *et al.*, 2014; Nayak *et al.*, 2014; Brigolin *et al.*, 2015; Dapueto *et al.*, 2015). This section provides a brief introduction on SMCE and, subsequently, a detailed description of the criteria that were mapped in order to deal with our case study.

This approach was used to investigate future perspectives of shellfish culture in an area of the Adriatic Sea, in the nearby of the Emilia-Romagna coasts (Figure 1). The area of the continental shelf comprised between 3 and 12 nm was selected. This portion of sea has an overall extension of 1561 km^2. Mussels are farmed with longline systems, and the sea farms are placed between 1.5 and 3 nm (Prioli, 2008). In the next future this activity is expected to increase, expanding outside the 3 nm and up to 12 nm, and introducing *Crassostrea gigas* as new farmed species (Gennari *et al.*, 2014).

Spatial Multi-Criteria Evaluation

The foundation of SMCE is the analytic hierarchical process developed by Saaty (1980), which is used to develop a set of relative weights for each criterion selected. SMCE allows dealing with complex spatial decision problems, through the combination of different criteria, once they are grouped, standardized, and weighted. In our study, SMCE was carried out in three steps: (i) the normalization of criteria; (ii) the assignment of a weight to each one of them; (iii) the aggregation of criteria in order to obtain the SI. Each criterion was normalized by linearly re-scaling each value in the range 0–1, by subtracting the minimum value and dividing by the range of the raw data (Eastman, 1999). In this way, the values of criteria were reclassified by means of a new numerical scale. Normalization is done in the way that high normalized values match with a better suitability for shellfish culture.

In accordance with Radiarta *et al.* (2008), the criteria were grouped in macro-categories, called "Intermediate Level Criteria" (ILC). In this study three ILC were considered (see Figure 2): (i) optimal growth conditions (OG); (ii) environmental interactions (EI); (iii) socio-economic evaluation (SE). Different criteria were considered for each ILC: time to reach the market size for mussels (OG); time to reach the market size for oysters (OG); area subjected to elevated organic deposition (EI); distance from ports and highways (SE); significant wave height (SE)—considered as an indicator of farm exposure to storm events. A uniform grid with a 4-km resolution was used to represent the SMCE spatial domain—this resulted from a compromise of the scales of the different data used. Details are provided in the section "Mathematical models".

The SI was calculated by applying the weighted linear combination. The normalized criteria were combined linearly by using relative weight as coefficients. This allowed us to obtain a SI ranging from 0 to 1, where values close to 1 indicate the highest suitability. We divided the SI in 5 classes of suitability: 0–0.25, very low suitability; 0.25–0.35, low suitability; 0.35–0.50, medium suitability; 0.50–0.75, high suitability; >0.75, very high suitability. Constraints because of the presence of other activities were superimposed in the final suitability map by using a Boolean classification scheme (suitable areas 1, unsuitable areas 0) (Falconer *et al*., 2013).

The analysis considered the reference situation and the seven different scenarios were summarized in Table 1. Each scenario resulted from a combination of aquaculture production, and weighting assignment (of ILC):

(1) two productions were considered: (i) only mussels; (ii) mussels and oysters;

(2) four priorities for Intermediate Level Criteria (Table 1).

Values for OG and EI were calculated as described in the section "Mathematical models". For OG scenarios 1–4 we considered only the criterion "time to reach the market size for mussels", while for scenarios 5–8 we included also the "time to reach the market size for oysters" one. The two criteria were combined by assuming a 0.5/0.5 weights combination. Values for SE in scenarios 1–4 combined the "significant wave height" and the "distance from ports criteria" (0.5/0.5), while the 5–8 scenarios combined the "significant wave height" and the "distance from highways criteria" (0.5/0.5). Then the combination criteria were normalized to a [0,1] scale (Table 1). Data analyses were performed using free open software R 3.2.3, R packages raster, ncdf4 and maptools (R Core Team, 2015), and QGIS 2.10.1 Pisa (Quantum GIS Development Team, 2015).

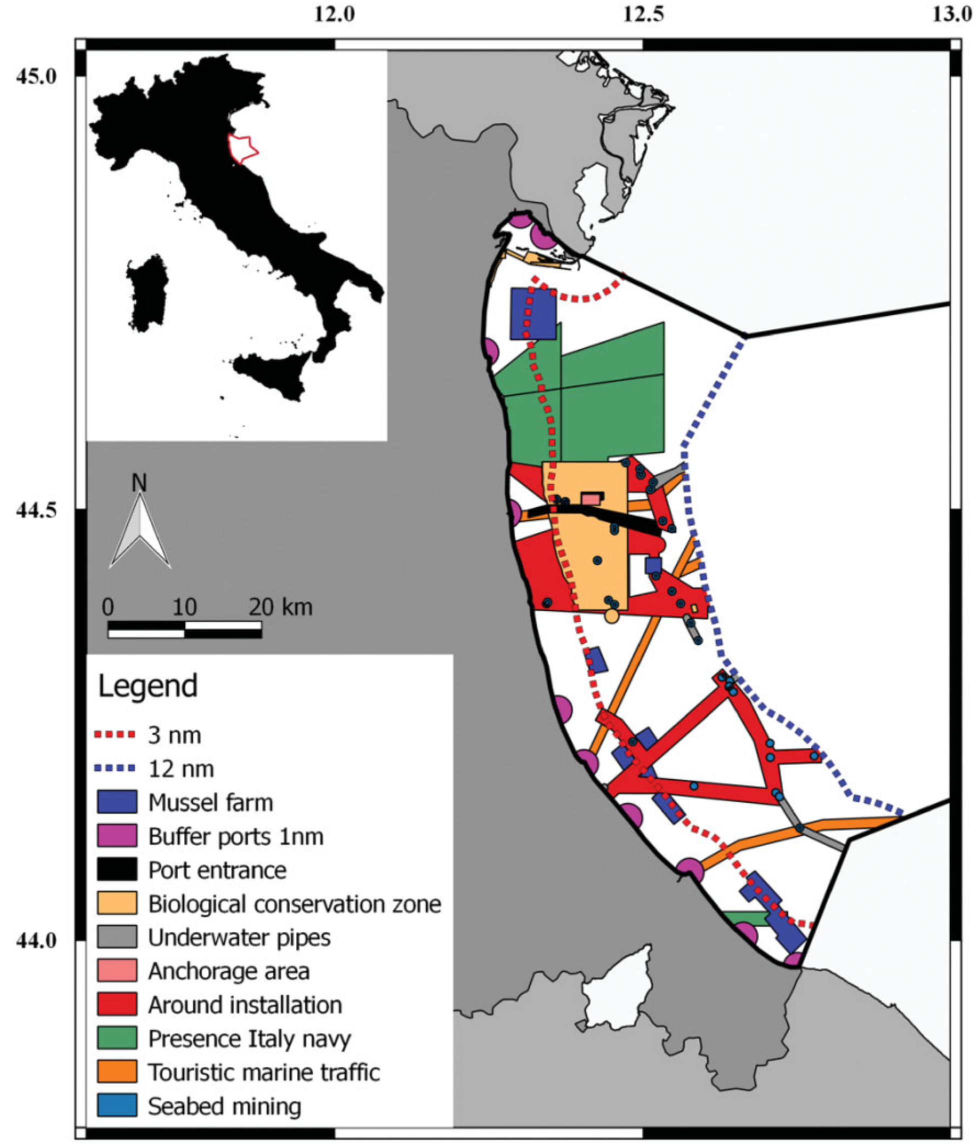

Figure 1. Study site: the portion of sea considered along the entire coast of Emilia-Romagna and constraints, imposed by current uses which cannot coexist with shellfish farms.

Mathematical models

0D individual-based population dynamic models for the farmed species and 3D Lagrangian models of farm organic matter deposition were applied at each cell of the 4 km grid. Model description and simulations set-up are provided below. Model inputs–outputs are set within the overall SMCE framework in Figure 2.

Individual models

Two species-specific bioenergetic models were applied for Pacific oysters (Pouvreau *et al.*, 2006) and Mediterranean mussel (Brigolin *et al.*, 2009). These individual models are, respectively, based on a Dynamic Energy Budget (DEB) (Pouvreau *et al.*, 2006), and on a Scope for Growth (SfG) (Brigolin *et al.*, 2009) formulation. The Mediterranean mussel model was previously validated for the northern Adriatic (see Brigolin *et al.*, 2009), while the Pacific oyster model validation, presented in Pouvreau *et al.* (2006), allowed one to simulate the energy budget in the Pacific oyster in various environments with the same set of parameters. Further details on individual models caveats and limitations are provided in the discussion. These models allow one to explicitly take into account the influence of water temperature and food availability on individual growth and metabolism. In this respect, environmental forcing required in input are: chlorophyll-*a* concentration and sea water temperature.

These data were obtained from Earth Observation, as described in "Integration of remote sensing, operational oceanography and cartographic data", thus enabling us to map the OG criterion "time to reach the market size" for both *M. galloprovincialis* and *C. gigas*, which was estimated on the basis of the simulated shell length, taking into account mussel, 5 cm, and oysters, 6 cm, minimum market sizes. In order to obtain robust estimates we simulated the evolution of lengths throughout a typical grow-out cycle at all grid points assuming that mussels are stocked in September, using input data concerning the years 2003–2012 and then averaging the outputs. Furthermore, individual models allow one to compute daily faeces and pseudofaeces production rates: these

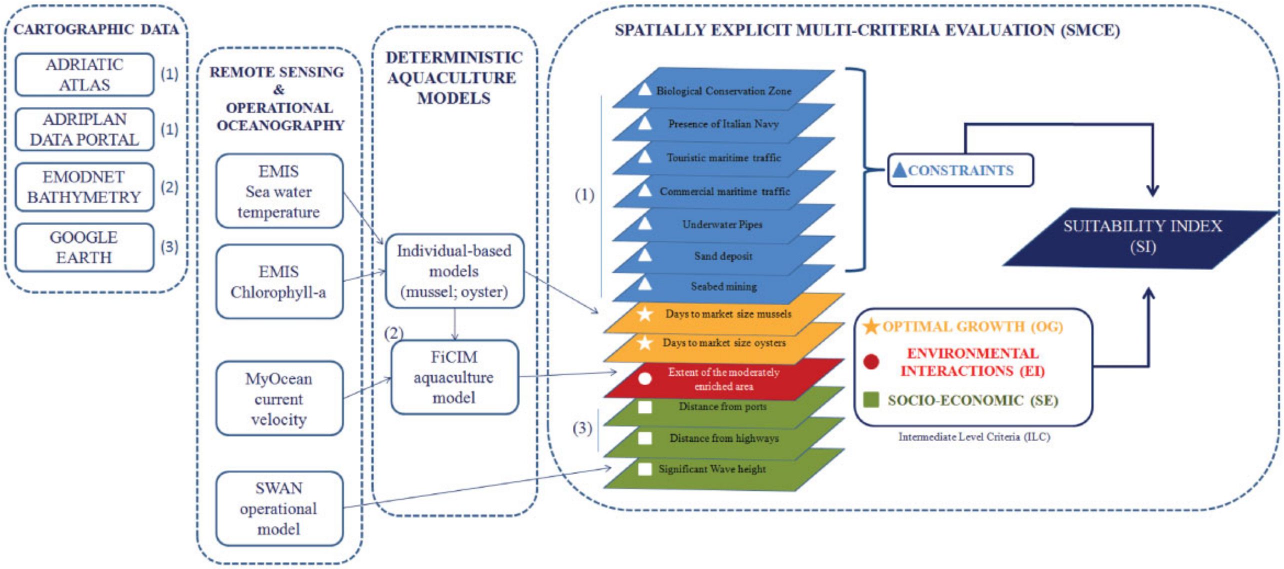

Figure 2. Information flow, and framework adopted in the SMCE. Colours mark the different Intermediate Level Criteria (ILC): i) "optimal growth" (orange,★); ii) "environmental interactions" (red,●); iii) "socio-economic evaluation" (green,🟩). Constraints are shown in blue (▲).

Table 1. Scenarios considered by the SMCE, the weights assigned to each criterion and, between parentheses, the weights assigned to each variable.

Product	Market	Priority	Scenario number	Weights		
				Growth (mussel/Oyster)	Environment	Socio-economic (wave/ports/highways)
Mussels	**Domestic**	**No priority**	**1 (REF)**	**0.33 (1/0)**	**0.33**	**0.33 (0.5/0.5/0)**
		Optimal growth	2	**0.50 (1/0)**	**0.25**	**0.25 (0.5/0.5/0)**
		Environment interactions	3	**0.25 (1/0)**	**0.50**	**0.25 (0.5/0.5/0)**
		Socio-economic	4	**0.25 (1/0)**	**0.25**	**0.50 (0.5/0.5/0)**
Mussels and oysters	International	No priority	5	**0.33 (0.5/0.5)**	**0.33**	**0.33 (0.5/0/0.5)**
		Optimal growth	6	**0.50 (0.5/0.5)**	**0.25**	**0.25 (0.5/0/0.5)**
		Environment interactions	7	**0.25 (0.5/0.5)**	**0.50**	**0.25 (0.5/0/0.5)**
		Socio-economic	8	**0.25 (0.5/0.5)**	**0.25**	**0.50 (0.5/0/0.5)**

REF corresponds to an expansion of the current situation in the 3 – 12 nm area – no priority to a specific ILC is given.

were used as inputs for the deposition model, see below. Individual-based growth models were coded in Matlab. The ordinary differential equations were numerically solved by means of a fourth-order Runge Kutta scheme.

Population models

In the simulated growth-out cycle, shellfish are stocked in September and harvested after 11–12 months (for mussels see Brigolin *et al.*, 2009). The same cycle was hypothesized for oysters, which are not yet cultivated in the area. Individual mussels are seeded at 4.0 cm length (according to data collected in Brigolin *et al.*, 2009), and oysters are seeded at 2.5 cm length (Gennari *et al.*, 2014). An idealized farming cycle was considered, assuming a recruitment completely controlled by the farmers, and a fixed mortality rate, here set at 10% year^{-1} (Gangnery *et al.*, 2004). A typical Adriatic longline farm, covering an area of 2 km^2, and producing ∼600 t year^{-1} was represented. Mussels and oysters were seeded at a density of 15 ind m^{-2}. The individual model was up-scaled to the population level by means of a set of Monte Carlo simulations, which were used for estimating the size structure of the population (the virtual population was made up of 5000 individuals; for additional details see Brigolin *et al.*, 2009). In accordance with Bacher and Gangnery (2006) such differences were accounted for by assigning to each specimen a different maximum clearance rate, reflecting variability in individual phenotypes as well as differences in the localization of specimens within the farm.

Table 2. Factors for site selection in Emilia-Romagna, data used for the analysis and spatial resolution.

Spatial data	Spatial resolution
Input data	
Sea surface temperature	4 km
Chlorophyll-*a* concentration	4 km
Current velocity	8 km
Wave height derived from SWAN model	1 km
Bathymetry	200 m
Optimal growth (OG)—individual-based models output	
Days to commercial size for *Mytilus galloprovincialis*	4 km
Days to commercial size for *Crassostrea gigas*	4 km
Environmental Interactions (EI)—deposition model output	
Enriched area, >0.1 g C m^{-2} d^{-1}	20 m
Socio-economic evaluation (SE)	
Distance between nodes and the nearest port	–
Distance between nodes and the nearest highways on-ramp	–

Deposition models

The mapping of the EI criterion requires the estimation of the organic enrichment of surface sediment because of the presence of a shellfish farm. In order to achieve this goal, the transport and deposition on the seabed of the organic matter released by shellfish was simulated using the integrated model Fish Cage Integrated Model (FiCIM), described by Brigolin *et al.* (2014). The model combines three generic modules, respectively accounting for: (i) individual growth and dynamics of the farmed population; (ii)

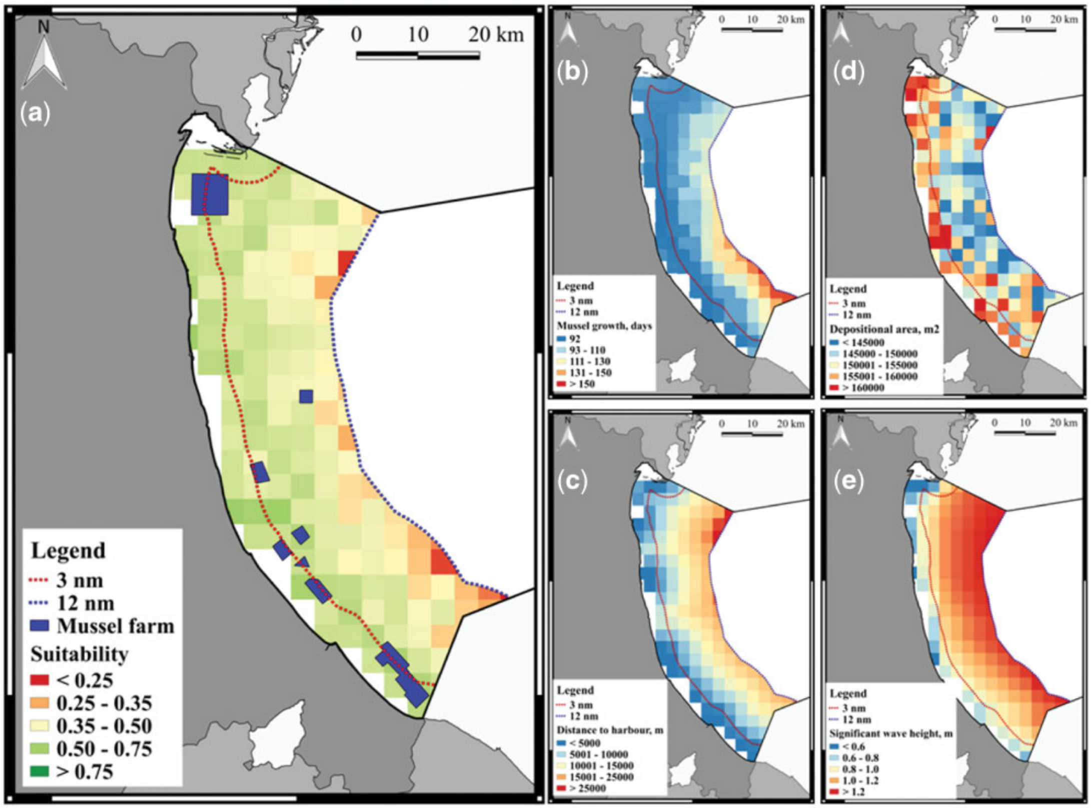

Figure 3. SMCE results for the reference condition (REF, see Table 1): (a) SI considering the existing leases for shellfish farming; (b), (c), (d) and (e) criteria considered in this scenario (normalized values are reported in Supplementary Appendix).

organic particle tracking and deposition; (iii) benthic degradation (early diagenesis). For a validation of the particle tracking model the reader is remanded to the original work by Jusup *et al.* (2009). The integrated model was tested at a fish farm located in the Southern Adriatic Sea (Brigolin *et al.*, 2014). Subsequently, the population module for farmed shellfish was introduced, and the model was tested at a mussel farm located in the Northern Adriatic (Brigolin, pers. comm.). The deposition was modelled considering the typical farm and the farming cycle presented (see "Population models"). Mussels are grown on ropes $\sim$4 m long, which are suspended on cables, and placed at depths between 2 and 4 m. Lines are positioned parallel to the coast, along the principal current direction at a distance of 40 m between each other. Length of each line is $\sim$2 km. The farmed area was assumed to be characterized by a flat bathymetry, with depths depending on the location of the site, and set according to site-specific cartographic data described in the section "Integration of remote sensing, operational oceanography and cartographic data".

The present work made use of a model version developed for screening purposes, in which the final output considered is the area (m^2) in which the average organic carbon flux along the farming cycle (Φ_C) > 0.1 g C m^{-2} d^{-1}. Φ_C was selected, being considered as a major driver of sediment biogeochemical transformation (see Hargrave *et al.*, 2008; Hargrave, 2010). The threshold value was set on the basis of work by Cromey *et al.* (1998), who classified "moderate organic enrichment" >0.1 g C m^{-2} d^{-1}. This fixed threshold value assumes that sediment texture does not change significantly over the study area, in accordance with the findings presented in Giordani *et al.* (2002), who observed mud contents ranging between 98 and 99% at their stations (S1, E11, S2, and S3), which can be regarded as representative of a large part of the study area. Furthermore, the oxic–anoxic ratio in benthic biogeochemical processes is mostly controlled by differences in organic matter grain size and composition (this assumption was discussed for this area in Brigolin *et al.*, 2011). The areas >0.1 g C m^{-2} d^{-1} were determined on a 2D map of resolution 20 m × 20 m, and providing the average flux of C towards the sea bed (g C m^{-2} d^{-1}) along the farming cycle. The deposition model was run at each cell over the 4 km × 4 km spatial grid, *i.e.* assuming to install a farm within each cell of the domain. Parameters used in the deposition model, values and their references are reported in Supplementary Table SA1 (Supplementary Appendix). Organic matter deposition was simulated by means of a Lagrangian technique (Jusup *et al.*, 2007). A detailed description of the particle tracking algorithm and of the details of coupling between population and deposition models is provided by Brigolin *et al.* (2014). The settling velocity of each particle was randomly selected from a normal distribution (faeces $\mu = 1.0$; $\sigma = 0.1$ cm s^{-1}; pseudofaeces $\mu = 0.1$; $\sigma = 0.01$ cm s^{-1}; see Weise *et al.*, 2009). The model required in input time series of water

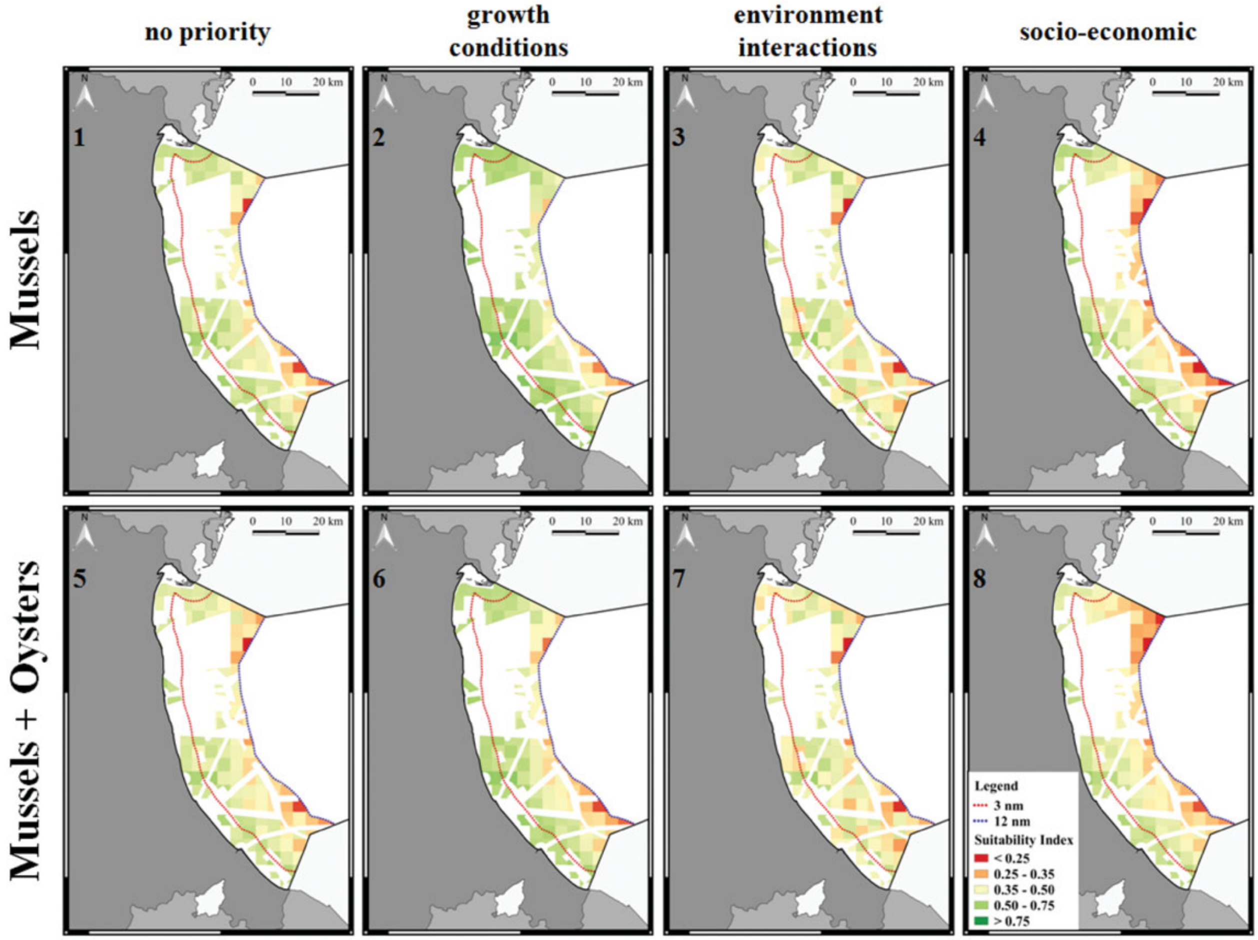

Figure 4. Scenarios produced by the SMCE. Details of each scenario are provided in Table 1.

velocity at an hourly time step. The integrated model was coded in FORTRAN while the Lagrangian equation for the deposition model was solved following Jusup *et al.* (2007). FiCIM model runs were performed on SCSCF (www.dais.unive.it/scscf), a multiprocessor cluster system owned by Ca' Foscari University of Venice running under GNU/Linux.

Integration of remote sensing, operational oceanography and cartographic data

Information flow within SMCE analysis is summarized in Figure 2, and spatial resolution of each class of data used in the analysis is reported in Table 2. The final resolution of the SI maps is 4 km × 4 km. Time series of monthly Sea Surface Temperature (SST) and concentration of Chlorophyll-*a* were extracted from the EMIS (http://emis.jrc.ec.europa.eu/) database for the years 2003–2012 by means of the R package EMISR v0.1 (R version 3.0.3). Chlorophyll-*a* and SST data were derived from the sensor Modis (Moderate Resolution Imaging Spectroradiometer) Aqua and Terra, respectively, with a spatial resolution of 4 km (see Table 2). This resolution was preferred to the higher spatial resolution of 2 km for the lower degree of missing days (because of cloud coverage). Maps showing average SST and Chlorophyll-*a* concentration in the study area within the whole time period are provided in Supplementary Appendix.

Bi-hourly 2D current velocity data were provided by the European MyOcean project (Copernicus Marine Service—Ocean monitoring and forecasting service; http://www.myocean.eu/) produced by means of NEMO ocean model version 3.1 (Madec, 2008) on a regular grid with a spatial resolution of 8 km. Data of eastward (u) and northward (v) current velocity ($\mathrm{m\ s^{-1}}$) were downloaded for the period comprised between 1st September 2014 and 31st August 2015, covering 1 year (the choice of this restricted time window was imposed by data availability). Subsequently, data for each grid point were extracted and linearly interpolated to produce hourly time series, which were provided as an input to the FiCIM model (see *Deposition models*). Depth for simulations was rescaled and set at each grid point, based on the Emodnet bathymetry data and downloaded from the dedicated website portal (http://www.emodnet-hydrography.eu/), with a native spatial resolution of 0.0021 degrees (≈200 m).

Additionally, wave height, distance from ports and highways were considered as important criteria for the development of aquaculture activities. Significant wave height was calculated by means of the SWAN (Simulating WAves Nearshore) model run operationally by the Hydro-Meteorological Service of the Regional Environment Protection Agency of Emilia-Romagna for the wave forecasting of the Emilia-Romagna coast, with a computational resolution of ∼1 km. This model is implemented on a regular grid (1 km × 1 km), combining data derived from the WAM (Wave Model), WaveWatch III and SWAN model itself. Hourly data used in SMCE covered a time window of more than 9 years, from October 2006 until February 2016, corresponding to the entire dataset published by the agency. Over this timeframe, the 90th percentile for the significant wave height was computed for each grid point of the SMCE domain (4 km × 4 km). Furthermore, the distance of each grid cell from ports and highways was derived through the Nearest Neighbour Analysis. In particular, for each cell, using QGIS, we estimated the distance to the nearest port and consequently the distance from the port to the nearest highway ramp, taking advantage of Google Maps.

Conflicting uses of the sea in the area were mapped based on a recent initiative providing access to cartographic data through WebGIS services, Shape (http://atlas.shape-ipaproject.eu/). These constraints to the development of shellfish farm aquaculture are mapped in Figure 1. Spatial resolutions of input data used for the analysis are provided in Table 2, all data were re-scaled to the 4 km resolution, the same spatial resolution of the input data of the mathematical models.

Results

SI for shellfish culture

Figure 3a shows the SI, for the baseline scenario (current situation) taking into account the current distribution of shellfish farms. The whole coastal area comprised within the 3 nm was found to be suitable for mussel farming, with SI values comprised between 0.53 and 0.76, and a mean of 0.65. This is not the case for the area comprised between 3 and 12 nm, in which SI shows a clear spatial pattern decreasing going southwards and eastwards (at increasing distance from the coast). The total available area comprised within 3 and 12 nm is 1561 km^2. This is reduced to 824 km^2 after accounting for constraints imposed by existing uses. Within this space, the portion with SI >0.5 is 580 km^2. Interestingly, all the mussel farms currently in place, marked in blue in Figure 3a, are located in zones characterized by relatively high suitability (average SI of pixels in which farms are located is >0.65).

Figure 3b–e shows the non-normalized results obtained for each criterion. These include days to reach the commercial size (Figure 3b) for which values are comprised within the 92 days up to 3.5 nm, along the whole coastline, exceeding the 150 days only

Table 3. Extension of the available space in km^2 (percentage of the total area): results were aggregated in five suitability classes (each class is defined by a SI interval).

SI	N	Scenarios	Low suitability 0–0.25	→ 0.25–0.35	→ 0.35–0.5	→ 0.50–0.75	High suitability 0.75–1
Scenario number	1	REF	0.6 (0.07%)	26.8 (3.25%)	217.4 (26.37%)	570.2 (69.17%)	9.4 (1.14%)
	2	OG	0.6 (0.07%)	17.2 (2.09%)	144.8 (17.56%)	624.3 (75.73%)	37.5 (4.55%)
	3	EI	8.9 (1.08%)	36.3 (4.40%)	206.5 (25.06%)	563.2 (68.32%)	9.4 (1.14%)
	4	SE	20.5 (2.49%)	53.9 (6.54%)	364.5 (44.22%)	385.4 (46.75%)	0.0 (0.00%)
	5	No priority	8.4 (1.02%)	30.8 (3.74%)	315.1 (38.22%)	470.1 (57.02%)	0.0 (0.00%)
	6	OG	0.5 (0.06%)	25.6 (3.11%)	256.6 (31.14%)	530.6 (64.36%)	11.0 (1.33%)
	7	EI	8.4 (1.02%)	45.0 (5.46%)	266.5 (32.32%)	504.5 (61.20%)	0.0 (0.00%)
	8	SE	8.4 (1.02%)	77.9 (9.45%)	401.9 (48.76%)	336.1 (40.77%)	0.0 (0.00%)

The reference situation and the seven scenarios presented in Table 1 have been considered.

in the south eastern portion of the studied domain. The distance to harbour is represented in Figure 3c, where it is possible to detect equally distributed values that increase going offshore, with, in general, lower distances in the southernmost portion of the area. The depositional area >0.1 g C m^{-2} d^{-1} (Figure 3d) appears to be patchly distributed with highest values recorded at lower depths, close to the coastline, and lowest values in the central part of the domain. With respect to significant wave height (Figure 3e) values >1.0 m, are present in the whole area comprised between 3 and 12 nm, with values progressively declining while approaching the coast, and going below the 0.8 m within the 3 nm.

Comparing scenarios of shellfish aquaculture development in Emilia-Romagna

Figure 4 compares the SI under REF with the 7 explored scenarios of development of shellfish aquaculture industry in Emilia-Romagna. The SI maps produced under the different scenarios show slight differences, which can be further assessed by comparing the extension of the areas by suitability class, which are reported in Table 3. Suitable space (SI >0.5) for developing the shellfish aquaculture industry reaches the lowest value under S_8 (mussels and oysters; socio-economic priority), which presents 488 km^2, 59% of the total space, with SI below 0.5. On the other hand, S_2 presents 38 km^2, $>5\%$ of the total space, ranked as highly suitable (SI >0.75). With respect to ILC priority, higher SI scores are obtained when prioritizing OG, while SE scenarios present the lowest scores. Remarkable changes in the spatial patterns of SI are visible when changing the market (see Figure 4 S4 *vs.* S_8).

Discussion

The synergistic capabilities of GIS and SMCE allow one to obtain information for decision-making, providing evident benefits to the applied research (Malczewski, 2006). The Emilia-Romagna coastal zone is intensively used by multiple actors with various purpose and involving different stakeholders. The activities range from maritime transport to fishing, aquaculture, offshore platforms and sand extraction (Policy Research Cooperation, 2011). The multiple maritime uses need a spatial planning that combine different layers and in our study SMCE allowed us to combine satellite data, operational oceanography products and cartographic (WebGIS) data. The key step for the combination of these information sources was the application of mathematical models of individual growth and aquaculture–environment interactions. We recommend that future work on MSP implementation in the region will consider the pure suitability evaluation for shellfish aquaculture, not taking existing uses into account—in this regard, all the maps produced within this work are povided in Supplementary Appendix without the mask of Figure 1.

Expanding shellfish farming along the Emilia-Romagna coast

Results suggest that the space for shellfish aquaculture would present comparable suitability (SI value) in presence of the single activity of mussel farming, and of mussel and oyster faming practiced in parallel—we recall here that oyster farming is currently not present in this area. More specifically, under scenario 1, the area above 0.5 SI is 70% of the available space between 3 and 12 nm (net of other existing uses), which reduces to 57% under scenario 5.

The scenario analysis carried out by assigning priorities to the different ILC highlighted the following characteristics of the area: (i) the growth potential is high—space with SI >0.5 increases when prioritizing OG; (ii) the socio-economic is the most restrictive ILC.

The first aspect is closely related with production carrying capacity. Former local studies investigated this issue at the farm scale in the past in the Gulf of Trieste (Martincic, 1998) and for a typical Adriatic longline farm (Brigolin *et al.*, 2008), evidencing that farm geometry can have an effect on the production carrying capacity. However, the Western Northern Adriatic (WNA) is regarded as a highly productive portion of sea, ranging from mesotrophic to eutrophic conditions, according to the specific area and season (Zoppini *et al.*, 1995; Zavatarelli *et al.*, 1998; Solidoro *et al.*, 2009). The Emilia-Romagna portion of coast, studied in this work, is considered as the most productive area in WNA, being under the direct influence of Po river (loads from Po were estimated by Cozzi and Giani (2011) around 1 10^5 tons N $year^{-1}$ DIN and 2.5 10^3 tons P $year^{-1}$ PO4 for the 1995–2007 period). The river plume extends southwards, originating a strong coastal current (Western Adriatic Current) (Cushman-Roisin *et al.*, 2001). A formal estimation of shellfish production carrying capacity has not been performed for the area. However, mussels, the only cultivated species, have been reported to complete their growth-out cycle within a time of 10–12 months (Prioli *et al.*, 2003, 2004; Pastres *et al.*, 2009). An indication of the growth potential of this area is provided by the time required to reach the commercial size of 5 cm, which within the 3 nm is around 90 days (starting from an initial length of 3.5 cm), as reported in Figure 3b. This is in agreement with mussel biometric data by Brigolin *et al.* (2009), who reported a growth from 3 to 4 cm achieved in 3.5 months, and one rearing cycle completed in 11 months, when mussel shell reach a length of 6 cm. OG show a decreasing spatial gradient going south-east, which is primarily related to the average seasonal spatial gradient in phytoplankton concentrations, controlled by the Po river plume (Zavatarelli *et al.*, 1998; Solidoro *et al.*, 2009). OG for oyster presents slightly lower values, as one can see from comparing Figures 4–2 and 4–6. A possible explanation of this feature is related with the use of the model by Pouvreau *et al.* (2006), which was tested on field data from the Thau lagoon (Western Mediterranean Sea, France). We suggest that future work should include further model testing with *in situ* data from the Adriatic Sea, to confirm our model predictions. This will imply the set-up of oyster farms pilot prototypes. Distance from harbours (Figure 3c) and significant wave height (Figure 3e) determined the performance with respect to SE (Socio-Economic) ILC. In both cases, at a first glance, maps show quite homogeneous land-sea gradients. Eight harbours are disseminated within this highly inhabited portion of coast, with a higher density towards its southern part (see Figure 2). The average distance to cover from a hypothetical new farm located on the bathymetric of 15 m would be of 12.6 km. Differently, significant wave height, the second SE of the ILC considered, presents on top of the coast-sea gradient, also a north south decrease, indicating that most suitable areas, with respect to this specific feature are in the southern part of the region. The result is of interest, because it shows to farmers venturing on new investments a trade-off between the growth potential and the possible risk associated with rough sea conditions, possibly affecting the longlines. Environment Interactions (EI) ILC is also presenting a land-sea gradient, but reversed, with more intense deposition predicted closer to the coastline, at low bathymetries. The spatial gradient of EI is less clear, primarily depending on the spatial and temporal variability of currents in the area, which quantification is probably influenced by the coarse resolution (8 km) of the operational hydrodynamic model (with respect to this point see the additional discussion in the section "Making use of resources provided by remote sensing and operational oceanography in site selection").

With respect to the EI criteria, mussel farming is expected to have very limited effects on the benthic system, because only 6–9% of the farming area is affected by deposition fluxes that we considered to potentially have effects on benthic communities, $>0.1\,\mathrm{g\ C\ m^{-2}\ d^{-1}}$ based on the ranges reported by Cromey *et al.* (1998). This limited impact is in line with previous knowledge on organic deposition in well flushed conditions, such as the ones characterizing long-line farms in the Northern Adriatic Sea (Rampazzo *et al.*, 2013). The idea of assessing environmental interactions links to the need of preservation of the good state of the marine environment in presence of human activities, as required by the Marine Strategy Framework Directive (European Community, 2008). This has already been considered in the work by Longdill *et al.* (2008), who studied the space allocation of *Perna canaliculus* in the Bay of Plenty (New Zealand), and linked potential impacts on the environment to the long term sustainability of the activity. However, areas with a limited degree of deposition, such as the ones originated by mussel farms in Emilia-Romagna, may also have a positive interaction with the surrounding ecosystem, locally enhancing the diversity of benthic habitats, and thus having a positive return in terms of services provided to the ecosystem itself (see the review by McKindsey *et al.*, 2011).

Making use of resources provided by remote sensing and operational oceanography in site selection

The interest on the applicability of tools for aquaculture science-based management has increased remarkably in the last two decades, in relation to the need of implementing the EAA (Soto *et al.*, 2008). Ferreira *et al.* (2012) reviewed possible combinations of geospatial data and mathematical models—collectively termed "virtual technologies"—for the sustainable management of aquaculture activities. A major roadblock to a further increase in the use of virtual technologies for aquaculture management was identified in the scarcity of data for model application (see conclusions by Ferreira *et al.*, 2012). The spatial explicit analysis proposed in the present work demonstrates how this limitation can be partially overcome by using information obtained from remote sensing and operational oceanography. Saitoh *et al.* (2011) recently reviewed operational uses of satellite remote sensing and marine GIS for a sustainable management of aquaculture. Previous works successfully applied SMCE to site selection for shellfish (Buitrago *et al.*, 2005; Longdill *et al.*, 2008; Radiarta *et al.*, 2008). The use of individual-based growth models and particle tracking models in the framework of SMCE represents, to our knowledge, an element of novelty of the present work with respect to previous applications. In the works cited, the scoring system used to evaluate environmental parameters and quantify biophysical criteria was not anchored deterministically to species-specific physiological processes. This represents a major obstacle for model transferability to areas other than the calibration one. Dynamic models used in the present work are integrated with a daily time step and provide a final indicator of growth performance at the end of the cycle, allowing to combine instantaneously the non-linear effects of the different environmental parameters (*i.e.* water temperature, chlorophyll-*a* concentration), and integrate these effects along the time of the farming cycle. The use of deterministic growth models also allowed us to link water temperature and chlorophyll-*a* concentrations to the assessment of environmental interactions through the quantifications of faeces and pseudofaeces production rates. The adoption of two different frameworks for modelling individual growth (DEB and SfG), suggests that this tool can be transferred to sites in which individual-based models of different types have been previously calibrated/validated—*e.g.* a DEB model for *M. galloprovincialis* was recently applied by Sarà *et al.* (2012) in Southern Mediterranean conditions. Although beyond the scope of the present work, we believe that this framework presents the capabilities for including in the planning of aquaculture also the forecasted long-term trends in environmental parameters induced by climate changes, as this will represent a mandatory step for a sound science-based management (Cochrane *et al.*, 2009). In order to increase the robustness of our predictions, future work on this line must provide a comprehensive assessment of the uncertainty of SI results, carried out in the global mode (Saltelli *et al.*, 2008), extended to all modelling components, and taking into account both parameters and forcing functions as sources of variability. We underline that this analysis should include an evaluation of the effects of potential spatial inconsistencies of remote sensing products—nearshore and off-shore Chlorophyll-*a* remote sensing require different post-processing (Barale *et al.*, 2010). This analysis may also include a specific assessment of how the weights of each attribute can affect the results. Finally, it is worth remarking here that the assumption made by using a spatially uniform threshold for defining the area influenced by organic deposition could be limited by variability in sediment nature, and therefore should be carefully verified when transferring this model framework in different environments.

In the Mediterranean Sea operational oceanography presented an increasing development during the last decade (for a review see Pinardi and Coppini, 2010), and can be reasonably perceived as the backbone of future coastal management applications. In the Adriatic Sea, such as in other sub-regional areas, a numerical ocean forecasting system is available, assimilating all the available data in real time, and a set of forecasting oceanographic models are running (Pinardi and Coppini, 2010). With respect to the use of these predictions as primary data for SMCE applications it is worth highlighting two potential limitations: (i) the availability of models at the sub-regional scale is not equally distributed in all the areas of the Mediterranean; (ii) the coarse spatial scale of current velocity predictions represent a potential issue. With respect to point (i), a good example is provided by the use of high resolution wave models, which implementation is not routinely provided for all Mediterranean sub-regions. The lack of this data could hinder the capability of assessing exposure to waves, which links to an aspect of primary interest for farmers planning their investment, such as the potential damages and losses of capital because of ruptures of lines. For a portion of coast in Algeria, Brigolin *et al.* (2015) recently based their evaluation of wave height for fish farm exposure on the *ad hoc* implementation of the SWAN model. With respect to point (ii), we remark that in the present work the final spatial resolution represented a compromise between the finest 1 km resolution of wave height data and the coarser 8 km one of current velocities. In this latter case, we remark that the availability of higher resolution hydrodynamic models purposely designed for the area, could improve the accuracy of final predictions. This kind of models would also allow one to consider the effects of inter-annual variability of hydrodynamic conditions on the patterns of organic matter deposition, which in the current application was limited by the availability of a single year of data.

Conclusions

This work shows the potential of SMCE for assessing site suitability for shellfish farming. The work does not provide a formal validation of the SMCE framework, however, all the adopted models were validated independently in previous works. The overall SMCE validation for this area will require the installation of prototype farms within the 3–12 nm area, including oyster farms, which are not present in this area at the moment. With respect to this latter point, we suggest that future work will include further testing of the oyster model with *in situ* data from the Adriatic Sea. A novel aspect of our approach is represented by the inclusion within the SMCE framework of simple 0D individual-based mathematical models, and of more complex integrated biogeochemical models of the farm, which provided useful resources for processing data obtained from remote sensing and operational oceanography, and producing maps relative to each specific criteria. This goes in the direction of overcoming limitations imposed by scarcity of data for SMCE applications. With respect to the specific area of study, the Western Northern Adriatic, we remark the importance of taking into account the results of this sector-specific evaluation within the future MSP implementation, also considering the early stage of the implementation in the Italian country. Suitability maps not including constraints are provided in supplementary materials for this purpose (Supplementary Appendix). Results show that the degree of suitability for shellfish aquaculture in this area would not change dramatically with the introduction of oyster farming. Values obtained for the SI under the different scenarios considered confirm that the growth potential in this area is high, and that the Socio-Economic is the most restrictive Intermediate Level Criteria. Results also show a trade-off between the growth potential and the possible risk associated with rough sea conditions, potentially of interest for farmers venturing on new investments. We advocate for further work in assessing the positive interaction of mussel farming with the surrounding ecosystem, and for improving the accuracy of model predictions by means of higher resolution hydrodynamic models.

Supplementary data

Supplementary material is available at the *ICESJMS* online version of the manuscript.

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