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A GIS-based habitat suitability model for commercial yield estimation of *Tapes philippinarum* in a Mediterranean coastal lagoon (Sacca di Goro, Italy)

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Abstract

Habitat suitability models have been extensively used by conservation planners to estimate the likelihood of occurrence and abundance of threatened wildlife species in terrestrial ecosystems, but they have been rarely applied to aquatic environment. In this study a GIS-based habitat suitability (HS) model has been developed to identify suitable sites for Manila clam (*Tapes philippinarum*) farming in the Sacca di Goro lagoon and to estimate the expected commercial yield. Habitat suitability and the assessment of potential yield for each specific site of the lagoon are derived on the basis of information on six exogenous parameters, namely sediment type, dissolved oxygen, salinity, hydrodynamism, water depth and chlorophyll "a". For each of them, a parameter-specific non-linear suitability function has been used to transform parameter values into a quality index normalized between zero (i.e., habitat non suitable to clam rearing) and 1 (habitat best suitable with respect to that specific parameter). Habitat suitability of a specific site within the lagoon is then computed as a weighted geometric mean of the quality indices corresponding to the six measured parameters. Weight has been set according to expert knowledge. Finally, a scaling function derived from field observations is used to transform HS values into estimates of annual potential yield (kg m^{-2} $year^{-1}$). The model has been applied to the Sacca di Goro lagoon where data on actual yield and the main biogeochemical and hydrodynamic parameters have been gathered in 15 sampling sites. These point data have been interpolated by Kriging so as to derive full maps of each biochemical parameter for the whole lagoon. The HS model has been then applied to derive the thematic maps of suitable sites for clam rearing and the corresponding expected yield. In order to assess the sensitivity of model predictions to errors in weights estimation, we performed a MonteCarlo analysis considering three different assumptions on ranges of variation of weights values. The model has proved to provide managers with sound estimates on yield potential of the different sites of Goro lagoon where *T. philippinarum* is commercially exploited. We thus claim that this reasonably rapid and cost-effective approach poses the basis for a fair partition of harvesting concessions among competitive users and for a remarkable improvement of transparency in the decision-making process.

Keywords: Habitat suitability model; *Tapes philippinarum*; Clam yield; Mollusc farming; Geographic information system

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1. Introduction

The management of wetlands is a complex task that requires to face multiple-conflicting goals, like the conservation of the natural environment (Charlier and Lonhienne, 1996; Mitsch and Gosselink, 2000), the preservation of irreplaceable ecological functions and services (Vives, 1996) and, at the same time, the environmental and economic sustainability of industries based on commercial harvesting of lagoon natural resources, such as fish species (e.g. finfish and shrimp) (Chopin et al., 2001) and bivalves (typically oysters, mussels and clams) (Kaiser et al., 1998). According to Naylor et al. (2001) the commercial global aquaculture production more than doubled its volume during the last decade, becoming one of the most dynamic segments of the world food economy. In Europe the suitability of many coastal lagoons for fisheries and mollusc farming allowed the development of flourishing activities of exploitation and farming, particularly in France, England, Portugal, Spain and Italy.

To preserve sustainability of extensive aquaculture, it's of the utmost importance to design and implement adaptive management systems policies (De Leo and Levin, 1997) able to avoid the well-known ecological and economic consequences of over-exploitation of open-access fisheries (Clark, 1983) and to acknowledge the complexity of wetland ecosystem and services. In practice, this means that regulations and protocols are needed to limit the number of competitive fishermen, to set up harvesting quotas for each of them, to avoid illegal harvesting and to control exploitation effort and harvesting techniques, and to set suitable thresholds for the commercial size of the targeted species. In particular, in wetland management where extensive mollusc farming is performed, the assessment of clam yield potential of different lagoon sites is the foremost task to improve economic efficiency (Arnold et al., 2000), to insure an equitable share of exploitable areas in the presence of multiple competing subjects and to foster transparency in the decision-making process.

Particularly meaningful in this context is the commercial exploitation of *Tapes philippinarum* (Adam and Reeve, 1850) in the Sacca di Goro coastal lagoon (Fig. 1), one of the most important and most studied aquacultural systems in Italy (Castaldelli et al., 2003; Fano et al., 2003; Giordani et al., 1997; Viaroli et al., 2001). About 10 of the 26 km^2 of the lagoon are heavily exploited for farming of *T. philippinarum*, with an annual production of about 1000 t and an average annual revenue around 50,000,000 € (Cellina et al., 2003) distributed among more than 3000 people (Paesanti and Pellizzato, 2000). The Manila clam *T. philippinarum*, which is of Indo-Pacific origin, was first introduced in the lagoon in 1984 (Rossi, 1989) as a culture species and quickly found favorable environmental conditions for growth and reproduction, replacing the native species *Tapes decussatus* (Paesanti and Pellizzato, 2000). A management system defined as “culture-based fishery” has been operating for some years in Goro lagoon, that is, harvestable areas are divided by the regulatory agency among a number of concessions, each managed by local clam fishermen under a strict set of rules on access limitation and exploitation effort.

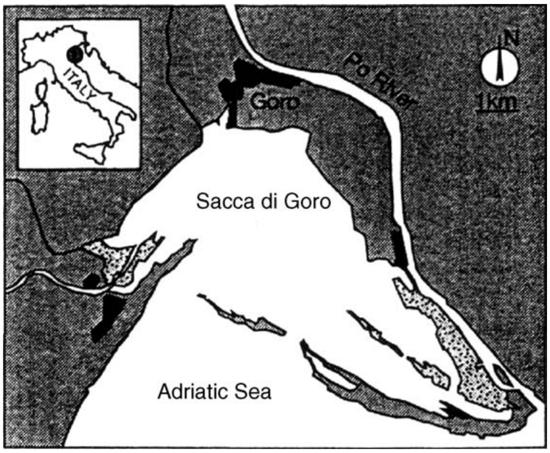

Fig. 1. The Sacca di Goro lagoon and its position in Northern Italy.

To improve the clam concession regime, the assessment of potential productivity of different sites in the lagoon is mandatory. The aim of the present study is to define a simple methodology to identify areas of different clam yield potential within the Sacca di Goro lagoon by using a GIS-based habitat suitability (HS) model that explores the relationship between occurrence and abundance of Manila clam and key biogeochemical and hydrodynamic properties for its survival and growth that can be sampled or estimated at a fairly low-cost. We intend to show how simple information and widely accepted field-knowledge on the parameters affecting the commercial yield of *T. philippinarum* can be used in a rigorous and objective framework to identify sites with different suitability.

The analysis of species–environment relationship has been thoroughly studied in conservation biology in recent years (Guisan and Zimmermann, 2000; Laymon and Barrett, 1994) when the availability of low-cost and user-friendly geographical information systems has allowed ecologists and decision-makers to quickly process, represent and manage huge amount of spatial information. Habitat suitability models are often used to predict the likelihood of occurrence and abundance of a species using habitat attributes considered important for its survival, growth and reproduction (Gibson et al., 2004; Kliskey et al., 1999; Pereira and Itami, 1991; Store and Kangas, 2001). As Morrison et al. (1992) pointed out, HS models should be seen as hypotheses of species–habitat relationship rather than definitive statement of cause and effect relations. Habitat suitability models have been used extensively in conservation planning (Gibson et al., 2004) on the assumption that size and spatial arrangement of suitable habitat can influence the long-term retention and persistence of faunal species (Gibson et al., 2004; Lindenmayer and Possingham, 1996).

Most of the applications of HS-GIS models have regarded terrestrial ecosystems, with particular reference to charismatic wildlife species (Clevenger et al., 2002; Corsi et al., 1999; Mace et al., 1999; Pearce and Ferrier, 2001), even though, more recently, GIS-based approaches have also been used for identifying appropriate sites for mollusc farming in various regions of the world (e.g. Nath et al., 2000), especially in North-America and Mexico (e.g. Aguilar-Manjarrez and Ross, 1995; Kapetsky et al., 1988) as well as in other North Adriatic lagoons. Yet, applications such as that presented by Arnold et al. (2000) provide a simple binary classification of habitat, in terms of sites suitable or non-suitable to clam rearing, with no further information on differential levels of suitability or potential productivity. On the contrary, the HS-GIS methodology we present in this work allows us to discriminate among different levels of suitability of lagoon areas for mollusc extensive farming and, moreover, to provide quantitative estimates of the corresponding expected annual yield (in $\text{kg m}^{-2}\,\text{year}^{-1}$) on the basis of simple information of sediment type and other physical and biochemical parameters.

The present work is organized as follows: after a brief description of the study area and available data, we summarize the main factors regulating clam growth and survival and illustrate the different components of our HS model for *T. philippinarum* and how it is used to assess the potential commercial yield. Then, we apply the model to the Goro lagoon to identify areas of different potential yield and present a sensitivity analysis of the results with respect to the uncertainty in the definition of key parameters of the model. Finally, in the last section, we briefly discuss the relevant features, limitations and future developments of HS-GIS models for clam yield estimation.

2. Study area

Sacca di Goro is a shallow lagoon (surface 26 km^2, average depth 1.5 m) approximately triangular in shape, located in the southern area of the Po river delta (44.78–44.83°N, 2.25–12.33°E). The lagoon has four freshwater inlets (Po di Goro and Po di Volano rivers and Bianco and Giralda channels) and is separated from the Adriatico Sea by a narrow sandy barrier with two mouths of about 0.9 km each regulating saltwater exchanges. The production of *T. philippinarum* reached a peak of 16,000 t in 1991 (Rossi and Paesanti, 1992), but recently a decline in productivity – possibly due to extensive algal blooms – has become evident. At present, the regulatory agency allows aquaculture practices approximately in only one-third of the lagoon, with annual production of about 10,000 t.

Goro lagoon is directly influenced by tide regime, the flow and organic load of tributaries, and rain patterns. As a consequence, the dynamics of nutrients and of the main biogeochemical variables affecting clam growth and survival, such as hydrodynamism and sand–silt ratio in the sediment (Rossi, 1996), are characterized by significant stochastic fluctuations.

3. Main environmental factors affecting clam growth and survival

Although *T. philippinarum* actively reproduces in North Adriatic coastal lagoons, the effect of commercial seeding in farmed areas is far larger than natural settlement. The identification of the most suitable areas for clam farming is thus important for a successful and sustainable business. According to Paesanti and Pellizzato (2000), *T. philippinarum* is quite tolerant to mid-high variations of relevant habitat variables typical of coastal lagoons, such as temperature, salinity, dissolved oxygen, turbidity etc. To avoid noxious algal blooms (*Ulva*, *Enteromorpha*, *Gracilaria*) lagoon bottom must be cleared of vegetation, as the consequent anoxic episodes may lead to massive clam mortality (Cellina et al., 2003). Optimal sites for clam farming are usually characterized by weak water currents that allow for nutrient circulation. In the case of anoxic crises, moreover, intermediate hydrodynamism allows also for a faster water reoxygenation with respect to areas of still-water, where only oxygen diffusion processes occur through the water column. Because of sanitary reasons, *T. philippinarum* farming sites have to be located far from pollution sources and from areas susceptible to toxic phytoplankton blooms. Water temperature is another important factor regulating clam growth (Goulletquer et al., 1989; Mann, 1979; Melià et al., 2004). Water temperature between 16 and 23 °C is considered optimal for clam growth in the Sacca di Goro lagoon (Paesanti and Pellizzato, 2000). Seasonal fluctuations of temperature are also important for the determination of the optimal timing of the year for clams seeding and harvesting, as shown in Solidoro et al. (2003) and Melià et al. (2004). Mean annual temperature is likely to be important to explain (along with other factors such as organic load, as shown by Pastres et al. (2001) and Solidoro et al. (2003)) differences in the mean annual yield between colder ocean coastal lagoons (such as Le Ferret and Les Jacquets in the Bassin d'Arcachon, West France, as described in Robert et al. (1993)) and warmer North Adriatic lagoons, such as Goro (Melià et al., 2004).

Finally, analysis by Rossi (1996) and Melià et al. (2004) show that rearing sites with high sand content are definitely better for clam farming than muddy bottom in terms of both growth speed, maximum attainable size and success of juvenile settlement.

4. Data and sampling campaign

Due to its characteristics and its geographic importance, the Sacca di Goro lagoon has received a considerable attentions by the public administration and the local fishermen cooperatives; as a consequences, several studies and sampling campaigns have been performed in recent years to gather information on sediment, primary productivity, water quality, etc., and hence some long-term data series are available (Castaldelli et al., 2003; Fano et al., 2003; Giordani et al., 1997; Viaroli et al., 2001). Two data sets (from the Dipartimento di Biologia of the University of Ferrara and the Amministrazione Provinciale of Ferrara) were used in the first phase of the research to acquire information on key variables, in particular the historical series of clam abundance from 1989 to 1999 and the historical series of hydrological parameters from 1986 to 1999. A sampling campaign has been performed in 2000, with particular attention to obtain data related to lagoon areas not explored in previous studies and not exploited for farming. The main features of the sampling campaign relevant to the present study are described here below.

4.1. Tapes philippinarum population density

Density samples were acquired in the year 2000 by local expert fishermen (Università degli Studi di Ferrara, 2000) by means of a gear locally called "*rasca*" which consists of an iron cage with two sledges preventing it from sinking into the sediment, and a net bag where clams are collected. The *rasca* is similar to the gear used in North Carolina to harvest bivalve *Mercenaria mercenaria* using the so-called "clam kicking" method (Peterson et al., 1987). In order to sample clams of all size, *rasca* with 6 mm fine mesh net bags were used in the harvesting process.

4.2. Physical–chemical parameters

Data on salinity, dissolved oxygen and chlorophyll "a" were gathered in 1998 in 15 different stations inside the lagoon perimeter by using a multi-parametric probe (IDRONAUT OCEAN SEVEN 301M). The probe was programmed to sample every 30 cm from surface to lagoon bottom, recording both parameter values and water depth. To account for seasonal variations, sampling campaign were repeated in spring, summer, autumn and winter. For each season, samplings were replicated from 1 to 11 times (as shown in Table 1) and observed values were then averaged to compute the seasonal mean. Data on bathymetry were gathered

Table 1
Mean ± standard deviation and number of replicates in brackets for three model parameters (salinity, chlorophyll "a" and dissolved oxygen) as measured in each season in 15 sampling stations

Station	Salinity (‰)			
	Winter	Spring	Summer	Autumn
1	28.66 ± 0.88 (3)	23.07 ± 3.13 (3)	23.72 ± 1.92 (3)	24.49 ± 0.35 (2)
2	26.51 ± 3.03 (2)	18.31 ± 5.60 (4)	21.56 ± 1.43 (9)	23.30 (1)
3	27.38 ± 1.81 (9)	21.22 ± 4.60 (6)	25.18 ± 3.76 (8)	25.01 ± 4.82 (5)
4	25.78 ± 1.52 (4)	16.16 ± 3.93 (7)	24.99 ± 2.88 (6)	28.18 ± 3.67 (3)
5	26.88 ± 2.99 (3)	22.90 ± 5.06 (7)	27.54 ± 4.12 (10)	29.51 ± 3.56 (5)
6	26.28 ± 2.31 (4)	18.51 ± 4.30 (6)	24.87 ± 0.84 (2)	–
7	27.98 ± 3.07 (3)	18.96 ± 5.78 (8)	22.65 ± 2.83 (3)	26.62 ± 3.37 (4)
8	28.15 ± 2.49 (5)	19.37 ± 4.18 (11)	22.97 ± 4.52 (11)	24.76 ± 3.14 (3)
9	27.54 ± 2.37 (4)	17.99 ± 5.38 (8)	22.66 ± 3.93 (8)	24.90 ± 5.81 (2)
10	27.16 ± 0.23 (3)	14.90 ± 0.32 (2)	23.28 ± 4.85 (6)	2.72 (1)
11	26.02 ± 1.17 (3)	12.04 (1)	22.26 ± 22.72 (2)	–
12	25.81 ± 1.70 (7)	21.00 ± 4.75 (4)	24.39 ± 2.12 (5)	28.91 ± 2.58 (2)
13	31.32 (1)	23.35 ± 5.07 (4)	30.18 ± 1.42 (2)	24.26 (1)
14	34.52 ± 0.93 (2)	29.88 ± 5.43 (9)	31.78 ± 2.79 (10)	32.28 ± 1.00 (7)
15	27.50 ± 0.90 (2)	29.40 ± 5.19 (7)	31.87 ± 2.82 (10)	31.16 ± 2.53 (7)

Station	Chlorophyll "a" (mg l^{-1})			
	Winter	Spring	Summer	Autumn
1	1.67 ± 0.22 (3)	8.61 ± 7.24 (3)	8.41 ± 3.12 (3)	18.78 ± 13.39 (2)
2	3.97 ± 2.09 (2)	12.16 ± 7.63 (4)	17.00 ± 14.47 (9)	20.30 (1)
3	3.67 ± 3.11 (9)	7.38 ± 4.46 (6)	3.90 ± 2.79 (8)	13.90 ± 8.18 (5)
4	2.51 ± 1.46 (4)	3.99 ± 4.29 (7)	7.29 ± 5.73 (6)	3.64 ± 2.60 (3)
5	3.33 ± 0.45 (3)	5.03 ± 2.98 (7)	2.80 ± 2.60 (10)	2.29 ± 1.45 (5)
6	3.03 ± 1.10 (4)	3.85 ± 2.24 (6)	9.20 ± 3.09 (2)	–
7	4.27 ± 3.40 (3)	6.11 ± 5.00 (8)	16.47 ± 16.61 (3)	5.80 ± 4.34 (4)
8	1.31 ± 0.19 (5)	1.74 ± 1.05 (11)	10.92 ± 6.34 (11)	12.12 ± 8.08 (3)
9	1.86 ± 0.52 (4)	1.70 ± 1.90 (8)	8.28 ± 5.09 (8)	16.55 ± 1.93 (2)
10	1.03 ± 0.86 (3)	4.21 ± 3.07 (2)	4.86 ± 4.94 (6)	4.24 (1)
11	2.01 ± 0.79 (3)	1.01 (1)	16.26 (1)	–
12	2.77 ± 2.13 (7)	1.54 ± 0.74 (4)	8.93 ± 7.03 (5)	3.51 ± 3.80 (2)
13	11.34 (1)	10.98 ± 15.42 (4)	5.10 ± 2.32 (2)	2.78 (1)
14	3.55 ± 3.52 (2)	4.92 ± 4.60 (9)	4.01 ± 3.89 (8)	10.23 ± 8.64 (7)
15	10.20 ± 10.11 (2)	16.30 ± 24.19 (7)	2.28 ± 2.86 (10)	2.74 ± 7.22 (7)

Station	Dissolved oxygen (% of saturation)			
	Winter	Spring	Summer	Autumn
1	88.24 ± 4.92 (3)	97.38 ± 11.53 (3)	74.00 ± 40.97 (3)	48.22 ± 5.00 (2)
2	88.72 ± 1.59 (2)	96.10 ± 24.41 (4)	79.05 ± 39.62 (9)	106.53 (1)
3	86.22 ± 14.21 (9)	98.86 ± 17.42 (6)	64.19 ± 19.66 (8)	49.70 ± 33.15 (5)
4	90.30 ± 8.82 (4)	133.02 ± 30.3 (7)	61.81 ± 65.57 (6)	69.49 ± 26.61 (3)
5	86.72 ± 9.01 (3)	80.52 ± 27.83 (7)	64.67 ± 27.51 (10)	61.76 ± 16.54 (5)
6	87.42 ± 11.76 (4)	123.0 ± 37.57 (6)	101.6 ± 103.9 (2)	–
7	85.55 ± 5.34 (3)	91.31 ± 25.95 (8)	108.9 ± 46.54 (3)	71.41 ± 10.24 (4)
8	80.6 ± 23.58 (5)	144.8 ± 44.0 (11)	84.44 ± 44.65 (11)	81.90 ± 19.98 (3)
9	84.84 ± 15.27 (4)	119.0 ± 42.86 (8)	72.35 ± 50.65 (8)	88.81 ± 19.70 (2)
10	83.61 ± 7.97 (3)	104.0 ± 54.01 (2)	55.59 ± 31.02 (6)	26.39 (1)
11	76.68 ± 23.63 (3)	106.24 (1)	27.04 ± 38.09 (2)	–
12	87.69 ± 22.83 (7)	111.3 ± 26.16 (4)	33.77 ± 37.39 (5)	39.67 ± 21.61 (2)
13	100.26 (1)	67.45 ± 49.64 (4)	59.71 ± 27.61 (2)	52.67 (1)
14	56.19 ± 9.23 (2)	79.79 ± 22.57 (9)	66.70 ± 29.86 (10)	86.26 ± 28.69 (7)
15	81.77 ± 36.50 (2)	97.40 ± 25.56 (7)	81.00 ± 29.78 (10)	104.6 ± 33.95 (7)

in the year 2000 by using an Eco-Sounder (248,000 total points).

4.3. Sediments and hydrodynamism

Sediment sampling was carried out by the Dipartimento di Geologia of the University of Ferrara (Simeoni et al., 2000) in order to derive the fraction of sand in the sediment, as *T. philippinarum* performs better in sandy sediment rather than in muddy sediment (Barillari et al., 1990; Paesanti and Pellizzato, 2000; Rossi, 1996). Data on sand content of the sediment have been classified in six categories (less than 20%, between 20 and 30%; between 30 and 50%; between 50 and 70%; between 70 and 95% and more than 95%).

Information on water flow dynamics in the Sacca di Goro lagoon were acquired from Brath et al. (2000) who calculated flow fields and flow capacity values ($m^3\,s^{-1}\,m^{-1}$) by implementing the computer program MIKE21 (DHI, 1993), which solves the vertically integrated equations of continuity and conservation of momentum in two horizontal dimension (the third dimension is implicitly integrated in the equations by considering a system vertically homogeneous). Hydrodynamism has been estimated in all the lagoon for four different conditions: low tide, high tide, intermediate decreasing tide, intermediate increasing tide and the average value has been used in the present work.

4.4. Data interpolation and thematic maps

Point data have been interpolated via Kriging over a grid of 100×88 points by using SURFER^{TM} of Golden Software Inc., ver. 7.02, in order to produce thematic maps of the Goro lagoon for each of the measured parameter. The mesh size identifies sites with area of approximately 1 ha. Results are shown in Fig. 2 for mean summer concentration of oxygen; mean summer salinity; mean summer concentration of chlorophyll “a”; type of sediment.

5. Model formulation

Estimates of habitat suitability for clam farming of Goro lagoon and the correspondent yield are computed

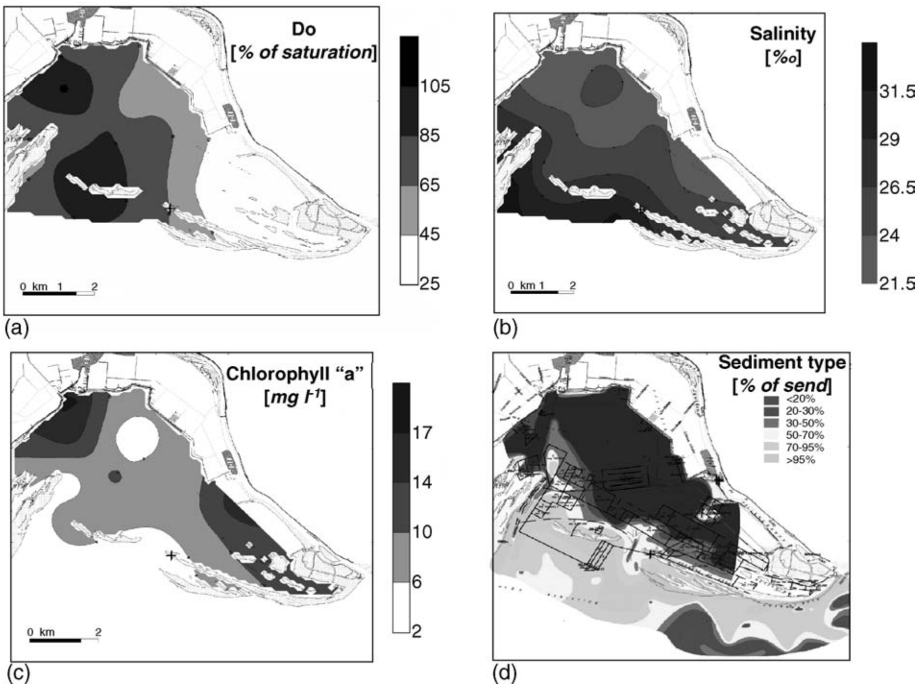

Fig. 2. GIS maps representing: (a) mean summer concentration of dissolved oxygen (% of saturation); (b) mean summer concentration of salinity (‰); (c) mean summer concentration of chlorophyll “a” ($mg\,l^{-1}$); (d) sediment type (% of sand).

in five steps:

- first, the main biogeochemical, hydrodynamics and morphological parameters affecting clam yield are identified;
- second, a parameter-specific suitability functions (PSSF) is defined to assess the suitability of a given site with respect to each parameter (Pedrotti and Preatoni, 1995; Ranci Ortigosa et al., 2000);
- third, the PSSFs are aggregated though a weighed geometric mean to derive an integrated assessment of site-specific habitat suitability HS;
- then, a function is defined to related HS values with expected yield $E(Y)$ (kg m^{-2} year^{-1});
- finally, the model is fed with the spatial data gathered for the Goro lagoon, so as to identify the most suitable sites and the corresponding yield.

Each of these steps is described in detail in the following.

5.1. Model variables

Information on species–habitat relationships and species life history are the basic ingredients to develop habitat suitability models. United States Fish and Wildlife Service (1981) identifies input variable of HS models as the habitat features that, if modified, "would be expected to affect the capability of the habitat to support the evaluation species". Input variables also need to be practical to measure at reasonably low-cost (Kliskey et al., 1999). Candidate variables for habitat assessment include chemical, physical and biological habitat features that can be measured under existing conditions and possibly predicted under future conditions (United States Fish and Wildlife Service, 1981). According to these principles, to the available data and to the reference manual by Barillari et al. (1990) and the studies conducted by Paesanti and Pellizzato (2000) and Melià et al. (2004) for *T. philippinarum*, we have chosen the following set of six biogeochemical and hydrodynamic parameters as input variables for the HS model, namely: share of sand in the sediment (%), dissolved oxygen (% of saturation), salinity (‰), hydrodynamism (m s^{-1}), water depth (m), chlorophyll "a" (mg l^{-1}). As for mean annual temperature, a crucial determinant of clam growth, data sampled in 2003 in three different stations show that differences in average annual temperature within the Goro lagoon (Station-1 = 20.63 ± 7.33, n = 3128; Station-2 = 20.49 ± 7.20, n = 3921; Station-3 = 22.00 ± 7.63, n = 2665) are statistically not significant (ANOVA, $p \gg 0.05$) and unlikely to explain variations in the mean annual commercial yield of *Tapes* with respect to parameters such as mean hydrodynamism and sediment type, as these parameters exhibit a much more remarkable spatial gradient within Goro than temperature. As a consequence, data on temperature has not been explicitly included in the model to identify differences in yield potential within the lagoon.

5.2. Parameter-specific suitability functions (PSSF)

Parameter-specific suitability functions (PSSF) have been defined to assess the suitability of a given site with respect to biogeochemical and physical parameter (Pedrotti and Preatoni, 1995; Ranci Ortigosa et al., 2000). For each specific biogeochemical parameter, suitability is expressed in terms of a Suitability Index defined on an arbitrary scale between 0 and 1, where 0 denotes a non suitable habitat, while 1 a habitat most suitable (United States Fish and Wildlife Service, 1981). PSSF can be a non-linear function as shown in Fig. 3. The PSSFs used in this work are those presented in the widely known reference manuals for clam rearing in extensive environment by Barillari et al. (1990) and Paesanti and Pellizzato (2000), as briefly illustrated hereafter.

5.2.1. Sediment (Fig. 3a)

Lagoon substrate has a great importance in clam culture. Rocky sediments are unsuitable for clam farming while optimal substrate is characterized by a high sand percentage and the remaining fraction made up of silt and clay (20–30%).

5.2.2. Dissolved oxygen (Fig. 3b)

Viable conditions for *T. philippinarum* growth require a percentage of dissolved oxygen saturation varying from 40 to 110%. Absence or strong reduction of dissolved oxygen may be found in summer months.

5.2.3. Salinity (Fig. 3c)

Water salinity affects survival and growth of all life stages of *T. philippinarum*. For optimal growth

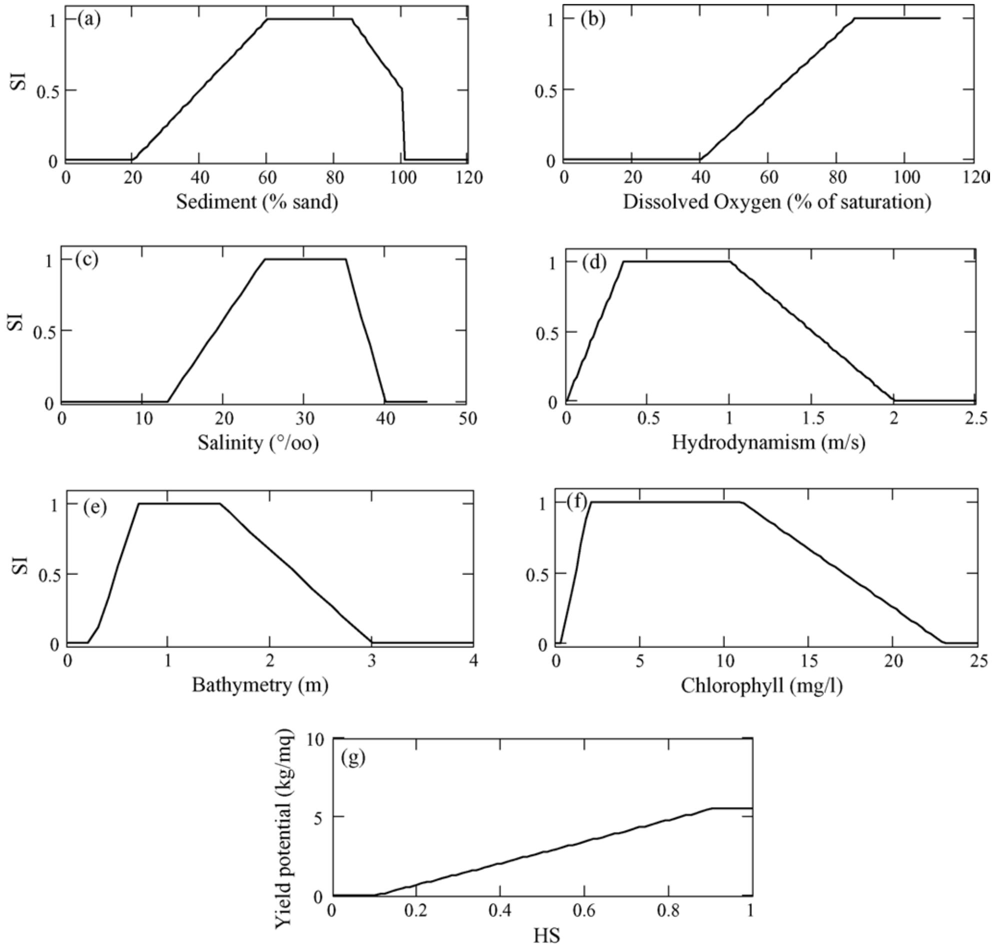

Fig. 3. The PSSF relationships between model variables and suitability for clam rearing. (a) Sediments; (b) dissolved oxygen; (c) salinity; (d) hydrodynamism; (e) bathymetry; (f) chlorophyll "a"; (g) relationship between habitat suitability HS and clam yield potential.

T. philippinarum requires water salinity in the range 25–35‰.

5.2.4. Hydrodynamism (Fig. 3d)

Optimal water flow for *T. philippinarum* culture has been found in the range 0.3–1 m s^{-1}. Flow velocities under 0.3 m s^{-1} do not allow sufficient nutrient circulation while velocities over 1 m s^{-1} could destabilize intertidal areas.

5.2.5. Bathymetry (Fig. 3e)

Optimal sites for the Manila clam *T. philippinarum* farming are located in water depths less than 2 m for easy harvesting and because the clams grow faster in shallower water. On the contrary, shallower water may impair *T. philippinarum* growth by exposing clams directly to air when tide is low.

5.2.6. Chlorophyll "a" (Fig. 3f)

Here, according to Barillari et al. (1990), we have assumed that concentration varying from 2 to 11 mg l^{-1} of chlorophyll "a" are considered optimal for clam farming.

5.3. Habitat suitability model

After PSSFs have been defined for each parameter, they need to be aggregated into a habitat suitability

Table 2
Mean value and range of variation of the weights w_i used in Eq. (1) to compute habitat suitability under three different assumptions on uncertainty in weights estimation

Parameter	Mean value $\bar{w}$	Range of variation		
		±20% (min, max)	±30% (min, max)	Asymmetric range (min, max)
Sediment	5.0	4.0, 6.0	3.5, 6.5	4.0, 6.0
Hydrodynamism	10.0	8.0, 12.0	7.0, 13.0	8.0, 12.0
Bathymetry	2.0	1.6, 2.4	1.4, 2.6	1.0, 3.0
Salinity	1.0	0.8, 1.2	0.7, 1.3	0.5, 2.0
Oxygen	1.0	0.8, 1.2	0.7, 1.3	0.5, 2.0
Chlorophyll "a"	1.0	0.8, 1.2	0.7, 1.3	0.5, 2.0

index, $HS_{x,y}$ to produce a comprehensive assessment of the overall suitability of a given site within the lagoon located at latitude x and longitude y (coordinates x and y are identified by Gauss Boaga system). HS (we skip the subscript x, y from now on to simplify notation) is then computed as a weighted geometric mean of the PSSFs as described here below:

$$\mathrm{HS} = \left(\prod_{i=1}^{6} \mathrm{PSSF}_i^{w_i}\right)^{1/\sum_{i=1,\ldots,6} w_i} \quad (1)$$

where PSSF_i are the parameter-specific suitability functions transforming the biogeochemical parameters of a given site into suitability levels; w_i, the weights corresponding to the importance of each PSSFs; $i = 1, \ldots, 6$ is an index identifying the corresponding six input biochemical parameters of the model.

HS is bounded between 0 and 1. Weights w_i indicate the relative importance of one variable with respect to the others and have been defined according to expert knowledge (Edoardo Turolla, personal communication) as reported in Table 2.

Therefore, according also to findings by Melià et al. (2004), the maximum weight has been assigned to the hydrodynamic regime, as it plays a key role in determining growth processes of filter-feeder organism by influencing nutrient circulation and dissolved oxygen. A relevant, though smaller, weight is attained by the fraction of sand in the bottom sediment, and further smaller weights have been set for the PSSF of the other parameters.

With respect to additive models, the use of geometric mean implies that, if a site is unsuitable with respect to one parameter only (that is, $\mathrm{PSSF}_j = 0$), the overall habitat suitability index HS of the site is zero regardless the value of the other $\mathrm{PSSF}_{i \neq j}$.

5.4. Relationship between habitat suitability and expected yield

The relationship between the actual HS value of a specific site in the lagoon and the expected mean annual commercial yield (kg m^{-2} year^{-1}) of clams having commercial size (>25 mm) in the same site, under traditional aquaculture practices, has been derived by observing that, according to expert judgment (Edoardo Turolla, personal communication) and field observations, the maximum attainable yield of the most suitable sites in the lagoon (those with HS ≥ 0.9) attains about 5 kg m^{-2} year^{-1}, a figure a little lower than the estimates (6 kg m^{-2} year^{-1}) presented by Rossi (1996) and Melià et al. (2004). On the contrary, we assume that areas with HS below 0.1 are not harvested in practice because of they low productivity, and thus we assume that the associated yield is negligible. As a consequence, the expected annual yield $E(Y)$ can be computed by linearly scaling the habitat suitability index between HS = 0.1 and 0.9 as follows (Fig. 3g):

$$E(Y) = \begin{cases} 0 & \text{if HSI} \leq 0.1 \\ 6.25\mathrm{HSI} - 0.625 & \text{if } 0.1 < \mathrm{HSI} < 0.9 \\ 5 & \text{if HSI} \geq 0.9 \end{cases} \quad (2)$$

5.5. Model implementation

The model here derived has been applied to the Sacca di Goro lagoon in order to identify most suitable sites for Manila clam farming and to estimate clam yield potential. While some habitat parameters, such as bathymetry and sediment type, can be considered fairly constant in time, other parameters can exhibit remarkable seasonal or daily variations, such as salinity, dissolved oxygen and chlorophyll “a”. As for hydrodynamism we have simply used the mean of the four water speeds (m s^{-1}) corresponding to the minimum tide, maximum tide, increasing tide and decreasing tide. As we are interested in the estimation of mean annual potential yield of the Goro lagoon, we have averaged seasonal data for salinity, dissolved oxygen and chlorophyll “a” for each sampling site, interpolated the data in order to derive maps of each parameter for the whole lagoon, and then applied the PSSFs on these maps so as to compute HS and $E(Y)$ on the averaged data. Finally, model predictions on expected yield have been contrasted with field data sampled in the lagoon in 10 different sites.

6. Results

The HS model provides an estimated of expected yield of about 25,700 t year^{-1} for the whole lagoon on a suitable area of 1345 ha with an average productivity of 2 kg m^{-2} year^{-1}. The distribution of areas with different expected productivity is reported in Fig. 4.

6.1. Suitability classes

We have then computed the surface area [in ha] of Goro lagoon corresponding to six different classes of expected yield (kg m^{-2} year^{-1}), as shown in Table 3, ranging from the least productive (less than 0.5 kg m^{-2} year^{-1}), to the most commercially valuable (more than 4.5 kg m^{-2} year^{-1}).

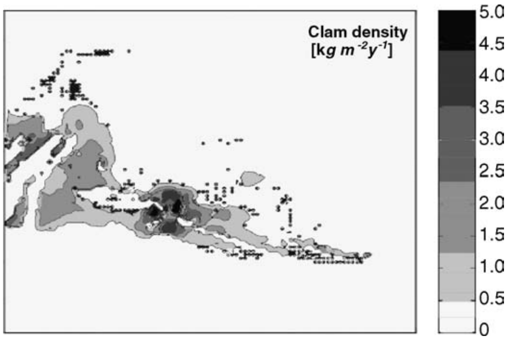

Fig. 4. Annual commercial yield (kg m^{-2} year^{-1}) of *T. philippinarum* as estimated by the HS model in the Goro lagoon. The black dots represent the sites where the coefficient of variation of the expected yield is larger than 20% under the assumption of a ±30% error in the estimation of model parameters w_i (see text for details).

Table 3
Surface area (ha) of the lagoon as a function of expected yield as estimated by the HS model

Expected yield classes (kg m^{-2} year^{-1})	Area (ha)
$0 \le E(Y) < 0.5$	42
$0.5 \le E(Y) < 1.5$	401
$1.5 \le E(Y) < 2.5$	640
$2.5 \le E(Y) < 3.5$	196
$3.5 \le E(Y) < 4.5$	44
$E(Y) \ge 4.5$	22

Table 4
Comparison of field data against clam yield potential obtained from model implementation

Site #	Field observations (kg m^{-2} year^{-1})	Model predictions (kg m^{-2} year^{-1})
1	1.3	2.6
2	3.8	4.9
3	3.8	3.8
4	1.3	1.3
5	2.5	1.2
6	3.8	2.6
7	2.5	2.4
8	1.3	1.3
9	1.3	1.3
10	3.8	3.8

6.2. Confronting model predictions with field data

The expected yields of 10 sites obtained with the HS model were contrasted against field data (Table 4). For 3 out of 10 sites the model overestimates (site #1) or underestimates (sites #5 and #6) considerably the clam yield potential (±50–150%). In six sites the model provides accurate figures of clam yield potential according to field data (sites #3, 4, 7, 8, 9, 10) and in one site the model overestimate by ≈20% the harvest by fishermen.

7. Sensitivity analysis

The determination of parameter weights w_i used in Eq. (1) is probably the most critical step of the analysis. Even if the weights w_i proposed on the basis of field experience by the clam biologist of Goro fishery

(Edoardo Turolla, personal communication) have been partially confirmed by findings of Melià et al. (2004) with specific reference to the sediment type, we were not able to implement a rigorous calibration procedure to minimize the deviation between the observed commercial production and the potential yield provided by the model, as in only 10 sites within the lagoon all the six parameters have been sampled along with clam density. As a consequence, it is interesting to evaluate how the expected yield potential provided by the model changes with respect to errors in the estimation of the weights w_i. We have thus performed a sensitivity analysis by using a MonteCarlo approach, as described in the following:

(1) we have identified with the biologist of the Goro fishery (Edoardo Turolla, personal communication) a reasonable range of variation $[w_i^{\min}, w_i^{\max}]$ around the central value $\bar{w}_i$ of the six weight used in the HS model, as shown in Table 2. The larger the range $[w_i^{\min}, w_i^{\max}]$, the higher the uncertainty associated with that parameter;
(2) for every weight we have defined a truncated probability distribution function *beta*[*a*, *b*] ranging between $w_i^{\min}$ and $w_i^{\max}$ and with expected value equal to $\bar{w}_i$;
(3) we then draw a random value $\hat{w}_i$ from the *beta*[*a*, *b*] function of every weight w_i;
(4) the set of six weights $\hat{w}_i$ drawn from their respective *beta* distribution has been used to derive a habitat suitability map and the expected yield;
(5) we replicated steps (3) and (4) 1000 times, so as to derive each time a different suitability map with the specific set of weights drawn from their respective beta distribution;
(6) we used the 1000 replications to derive the principal statistics for every site inside the lagoon, in particular the average, standard deviation and coefficient of variation (CV).

The use of a truncated distribution function is particularly convenient for the sensitivity analysis: in fact, while the normal distribution is defined over the range $(-\infty, +\infty)$ and the logarithmic distribution between 0 and $+\infty$, the distribution *beta*[*a*, *b*] is defined only in the desired range between $w_i^{\min}$ and $w_i^{\max}$. The shape parameters *a* and *b* of the *beta* distribution have been both set equal to 1.5 to account for a sufficient degree of variability within the range $[w_i^{\min}, w_i^{\max}]$, as shown in Fig. 5. As for the ranges of variation $[w_i^{\min}, w_i^{\max}]$, we have performed the sensitivity analysis under three different assumptions on uncertainty on weights estimation, that is: (i) a ±20% of variation, for all the six parameters, with respect to the central value $\bar{w}_i$; (ii) a ±30% of variation with respect to the central value $\bar{w}_i$; (iii) a range of variation $[w_i^{\min}, w_i^{\max}]$ different and in some cases asymmetric for each of the six weights, as reported in the last column of Table 2.

For each of the three cases, we have computed the coefficient of variation CV of the expected yield in each site of the lagoon as the ratio between the standard

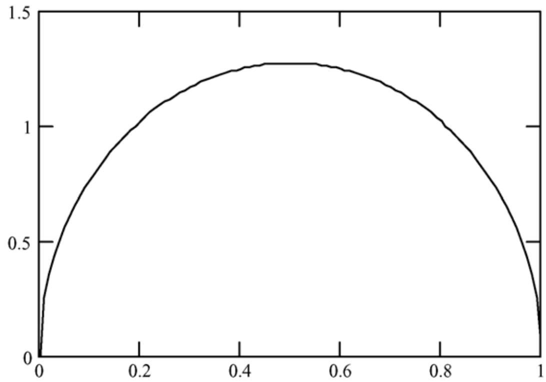

Fig. 5. Probability distribution function beta normalized between 0 and 1 with shape parameters *a* and *b* equal to 1.5.

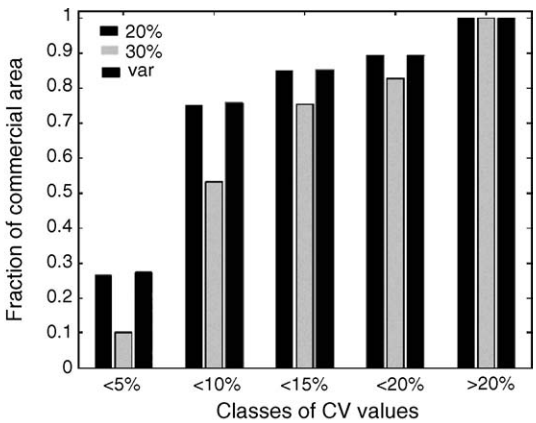

Fig. 6. Cumulated distribution of the coefficient of variations of the expected yield as estimated by the HS model for the productive area of the Goro lagoon by means of a MonteCarlo analysis under three different scenarios of uncertainty in parameter estimation as reported in Table 2.

deviation of the 1000 replicates of potential yield and the mean value of the 1000 replicates. Results are reported in Fig. 6 as the fraction of the overall lagoon area in each class of CV. It is worth noting that, in all the three cases of uncertainty considered in the sensitivity analysis, the larger part of Goro lagoon (from 80 to 90% of the area) is characterized by CV values under 20%. Further analyses show that there is a negative correlation between expected yield and its coefficient of variation ($r = -0.63$, $p < 0.01$): this means that the highest CV values (>20%) are associated with lagoon sites with low productivity (<*0.5* kg m^{-2} year^{-1}), that is, in marginal areas of low commercial interest, as shown in Fig. 4.

8. Discussion and conclusions

When multiple competing users of a renewable resource operate in the same lagoon, it is important that the regulating agency makes use of an objective methodology and if available, of rigorous and quantitative instruments for assessing the potential yield of different lagoon sites, so as to reduce or eliminate the perception of subjective bias or unstated assumptions. In this work, we have shown that the application of a GIS-based habitat suitability model provides an effective methodology for identifying and quantifying optimal sites for the exploitation of aquacultural species. Potential yield estimated by the model for the whole Goro lagoon is about twice as much that reported by the fishery. This is due to the fact that only about one-third of the 2600 ha lagoon area is actually exploited for clam harvesting, while our model provides estimates also for areas outside of the farming areas.

The methodological approach to the identification of suitable sites and the estimation of expected yield can be possibly applied to Manila clam farming in other lagoons of North Adriatic, as well as to other molluscs species of commercial interests subject to extensive farming in natural or semi-natural environment. Information must be available in order to identify a set of biogeochemical parameters affecting body-size growth and habitat carrying capacity and the corresponding parameter-specific suitability functions.

As for the application of our HS model to *T. philippinarum* in other coastal lagoons, we expect that, according to Paesanti and Pellizzato (2000), the PSSFs can be likely considered valid also in other North Adriatic coast lagoons. Anyway, as the trophic state of the lagoon is very important in determining the actual clam productivity (Pastres et al., 2001), it is likely that the scaling function to transform HS values into estimates of expected yield should be adjusted to match the actual maximum yield of the lagoon, since productivity depends on other site-specific factors not explicitly accounted for in our model, such as mean annual water temperature, length of day light, nutrient load and cycle, etc. In order to apply our approach to other bivalve species of commercial interest, a rigorous statistical investigation, field campaign and laboratory analysis might be required in order to identify the relevant factors affecting mollusc yield and to calibrate the actual PSSFs. In general, the following criteria should be followed in order to choose appropriate input variables for the HS model, namely: (1) the morphological and biochemical variables must related to habitat carrying capacity and/or survival and growth rate of the species commercially exploited; (2) there is sufficient understanding of the relationship between the variables and the habitat; (3) the variables can be gathered or measured or sampled in a practical and cost-effective way.

Different approaches to analyse optimal management strategies or to identify suitable rearing sites for *T. philippinarum* were used by Pastres et al. (2001), Solidoro et al. (2003) and Melià et al. (2003, 2004). Models by Solidoro et al. (2003) and Melià et al. (2003, 2004) are actually physiological or management models rather than tools for designing the concession regime and, consequently, they have been derived for purposes different than planning, that is: to simulate the population dynamics of clams along the year, to explicitly describe the relationship between seasonal fluctuations of temperature and clam growth rate, to assess the effect of different seeding density of the final yield, and to identify the optimal timing for seeding and for harvesting, to maximize the economic value of rearing activities, etc. In our case, on the contrary, the goal was to identify areas with different degree of suitability to harvesting under the assumption that the proper day-to-day management practices are carried on.

The multi-criteria approach proposed by Pastres et al. (2001) aims at identifying suitable areas for commercial rearing of *T. philippinarum* by combining spatial information on water quality and bathymetry with the results of a 3D hydraulic model coupled to a complex trophic model made up by 14 state-variable and 52 parameters to simulate the dynamics of nutrients, primary production and clams growth and survival. With respect to Pastres et al. (2001), we have chosen a simpler approach that does not make use of complex trophic models explicitly derived for the studied area: in fact, these models, though very detailed and realistic, are usually costly to design, to calibrate, to validate and also to run. In our formulation, information on lagoon trophism has been summarized in suitability functions for dissolved oxygen, chlorophyll "a", salinity and hydrodynamis. Needless to say, there is no doubt that, if a carefully calibrated, spatially explicit, complex trophic/dynamical model were already available for Goro, it would provide very useful insights on nutrient cycling and would allow for a finer analysis of potential clam productivity. Yet, with the information usually retrievable or available for many North Adriatic lagoons and, specifically, in Goro – where, to our knowledge, there is still nothing available even close to the model for the Venice lagoon used in Pastres et al. (2001) and developed elsewhere in more than 10 years of work (Dejak et al., 1987, 1998; Pastres et al., 1995) – we feel that our approach is able to provide useful information for designing the concession regime in a very simple and cost-effective way.

Of course, our model is not exempt from criticism. In the first place, it might well be that other exogenous or endogenous factors remarkably influence clam growth and carrying capacity, such as nutrient availability, wave height, time of permanence outside the water, sediment in suspension, water temperature, bottom slope, water pH, pathogens, predators and competitors and other form of natural or anthropogenic disturbance (Paesanti and Pellizzato, 2000). Moreover, some of the parameters used in the model might be quite variable in time and space, and thus sampling should be accurately designed in order to elucidate conditions experienced by clams during the year. Of course, error in data sampling will affect the robustness of model predictions. Also, our model does not say anything about long-term sustainability of different concession regimes and management practices, it simply identifies areas with different potential for commercial harvesting under present conditions. For addressing issues such as long-term sustainability or risk of dystrophic crises, of algal blooms, and of catastrophic collapse of clam biomass, an approach such as that used by Cellina et al. (2003), Melià et al. (2003), Pastres et al. (2001) or Solidoro et al. (2003) would be more appropriate.

Finally, even though the weights here used have been determined through expert knowledge and are considered acceptable by clam biologists of the Goro fishery, we believe that there is space for a quantitative calibration of the HS model by using an optimization algorithm to search the best set of weights that minimizes the difference between predicted and observed yield. For this reason, we intend to perform a new sampling campaign to derive a suitable set of field data for a robust calibration of the model. Anyway, the use of PSSFs from Paesanti and Pellizzato (2000) and weights from experts' judgment might also be seen as a strong, rather than a weak aspect of the present methodology, as these weights are representative of the shared knowledge of the fishermen operating in the lagoon, and, as a consequence, are actually widely accepted. In this sense, this approach contributes to define a common basis to assess yield potential of the lagoon and thus help to create consensus through a more participated planning process of lagoon aquaculture activities. Moreover, the average productivity in kg m^{-2} year^{-1} provided by the model is comparable with findings of Pastres et al. (2001) and Solidoro et al. (2003) for *T. philippinarum* rearing in the lagoon of Venice. Even though far from a scientific validation, the managers of the Goro lagoon believe that there is a reasonable congruence between model predictions and their knowledge of commercial rearing in the Goro lagoon.

We are thus confident that the approach here described can indeed help to increase the transparency of the decision-making process and can be considered as a valid screening methodology to plan and design clam concessions in a fairly objective and equitable way.

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