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Estimating clam yield potential in the Sacca di Goro lagoon (Italy) by using a two-part conditional model

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Abstract

The assessment of clam yield potential and the identification of suitable sites for clam rearing are a necessary step to improve the economic and environmental sustainability of the exploitation activities in a regulated fishery. We discuss the development, validation and application of a method for estimating the clam yield potential of a northern Adriatic lagoon (Sacca di Goro, Italy) by combining logistic and ordinary regression. Clam yield potential was derived on the basis of six environmental parameters, namely sediment type, dissolved oxygen, salinity, hydrodynamism, water depth and chlorophyll “a”. Density data were positively skewed and contained a substantial proportion of zero values due to the patchy-distribution of *Tapes philippinarum*. The original data set was divided in two parts: one indicating if *T. philippinarum* was present or not and the other indicating the abundance of the species when it was present. The presence data was modelled by using logistic regression and the abundance data was separately modelled by using ordinary regression. The two models were then combined to identify suitable sites, to compute the expected clam yield potential in the Goro lagoon and to define the role of each environmental parameter in determining clam presence and abundance. The two-part model was then validated on a further data set ($R^2=0.87$). Data on environmental parameters gathered in 15 sampling sites were interpolated *via* a nearest neighbour algorithm so as to derive maps of each environmental parameter for the whole lagoon. Finally, the two-part model was applied to derive the thematic maps of suitable sites for clam rearing and the corresponding yield potential.

We claim that this reasonably rapid and cost-effective approach provides a rigorous framework for a fair partition of harvesting concessions among competitive users and for a substantial improvement of transparency in the decision-making process.

Keywords: Conditional model; *Tapes philippinarum*; Clam yield; Sacca di Goro; Habitat suitability

1. Introduction

The achievement of highly productive harvesting activities compatible with the long term conservation of the natural environment is generally considered a central goal of wetland management where extensive mollusc farming is performed. In areas where clam fishing is not regulated, such as the lagoon of Venice

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(Italy), the use of illegal fishing tools, overfishing and the exploitation of polluted sites (Pastres et al., 2001; Solidoro et al., 2003) put a serious threat on the sustainability of the whole fishery. An effective management policy to prevent unlimited access to the resource and the consequent overexploitation of the fisheries requires the design of a rationale concession regime regulating the harvesting activities. Protocols limiting the harvesting days, Total Available Catch (TAC) and setting individual harvestable quotas and/or minimum clam size can be implemented to sustain the exploitation activities in the long run. In this context, a rigorous identification of the harvestable ground and an accurate assessment of the commercial yield potential are necessary to guarantee a sustainable fishery, to improve economic efficiency and to foster transparency in the decision-making process aimed at planning the exploitation activities. This is what needs to be done in the Sacca di Goro coastal lagoon in North Adriatic (Fig. 1), one of the most important aquaculture systems in Italy for the commercial exploitation of the Manila clam *Tapes philippinarum*. The farming of Manila clam, an exotic clam of Indo-Pacific origin first introduced in the lagoon in 1984 (Rossi, 1989) as a culture species, provides in Goro an average annual production of about 10,000–15,000 t that guarantees an annual revenue of about 50 million euros (Cellina et al., 2003) distributed among more than 3000 people (Paesanti and Pellizzato, 2000). At present, only 10 of the 26 km^2 of the Goro lagoon are actually exploited and the harvestable areas has been divided by the public regulatory agency into a number of concessions (site licences) — each managed by local clam fishermen — whose potential yield is estimated on the basis of past experience and expert knowledge. The competition among fishermen for the assignment of the most productive patches within the lagoon forced the regulatory agency to explore more objective and rigorous methods to assess the potential productivity of different sites within the Sacca di Goro. On one hand, fairly complex models of nutrient dynamics and/or clam demography and population structure have been developed by Pastres et al. (2001), Solidoro et al. (2003) for the Venice lagoon and by Melià et al. (2003, 2004) and by Melià and Gatto (2005) for the Sacca di Goro. On the other hand, Vincenzi et al. (2006) developed a conceptually simple and cost-effective GIS-based Habitat Suitability (HS) model to associate occurrence and abundance of *T. philippinarum* in Goro to site-specific biogeochemical and hydrodynamic parameters, namely: share of sand in the sediment, salinity, oxygen concentration, average water current, chlorophyll “a” and water depth. For each environmental parameter, a specific suitability function was derived on the basis of practical experience, expert knowledge and grey literature (Paesanti and Pellizzato, 2000); the parameter-specific suitability functions evaluate the suitability — defined on an arbitrary scale between 0 and 1 — of a given site with respect to each biogeochemical and hydrodynamic parameter. The parameter-specific suitabilities were then aggregated by Vincenzi et al. (2006) through a weighted geometric mean to derive an integrated assessment of site-specific habitat suitability. Finally, a scaling function derived from field observations was used to transform habitat suitability values into estimates of potential yield. Unfortunately, weights were assigned only on the basis of experts opinion. As a consequence, even though the HS model was based on objective data and consolidate practical knowledge of clam rearing in north Adriatic lagoons, the overall methodology was affected by a high level of uncertainty in the relative importance of the different environmental factors in predicting clam presence and abundance.

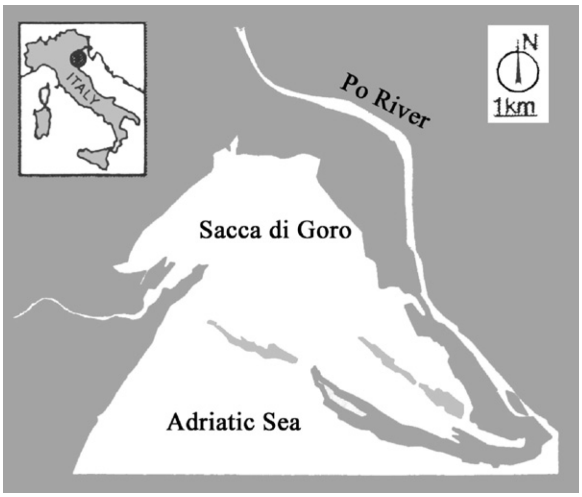

Fig. 1. The Sacca di Goro coastal lagoon and its position in Northern Italy.

Aim of the present work is the assessment of commercial clam yield potential in the Sacca di Goro lagoon by using a more robust, data-driven modelling approach, namely by calibrating and validating a two-part conditional model on field data.

In many ecological studies, abundance or density data often exhibit a substantial proportion of zero values. This is also the case of *T. philippinarum* in the Sacca di Goro lagoon, where the presence of zero inflation is clearly linked to the patchy-distribution of the organism reflecting differences in suitability on different sites within the lagoon. The presence of zero inflation due to excess zeros is a special case of overdispersion (McCullagh and Nelder, 1989; Hinde and Demetrio, 1998; Poortema, 1999): when the number of zeros is so large that the response variable cannot be fit by using standard distributions (i.e., normal, Poisson, binomial, negative binomial, beta and gamma) the data set is considered "zero inflated" (Heilbron, 1994; Tu, 2002). The term can be applied either when zero inflation is the result of a large number of zero observations caused by the ecological effect under study ("true zeros") and when excess zeros are caused by sampling or observer errors during data collection ("false zeros"). As noted by Martin et al. (2005), zero-inflated models have been recently applied in a broad range of ecological scenarios, including data sets in which zero inflation was determined either by true zero (e.g. Podlich et al., 2002; Kunhert et al., 2005) or by false zero observations (e.g. Tyre et al., 2003; Wintle et al., in press). Basically, two approaches have been proposed to model count data when the number of zero is too high for the response variable to be fit by a standard distribution (Fletcher et al., 2005; Martin et al., 2005): the mixture model approach and the two-part modelling approach. In the mixture model approach, the response is assumed to have a mixture distribution: with probability p it is equal to zero and with probability $1-p$ it has a Poisson or negative binomial distribution (Lambert, 1992). A key feature of the mixture model approach is that it allows zero to be part of either component (Lambert, 1992). In the two-part modelling approach, also known in the literature as conditional model approach, the occurrence of zero observations and the positive abundances are separately modelled, whereby the first part is a binary outcome logistic-type model and the second part is a truncated count model (Welsh et al., 1996) calibrated on available data. For this second part, a range of available distributions have been employed, typically the Poisson or negative binomial for discrete counts and the Gamma or log-normal for continuous data. As noted by Fletcher et al. (2005) and Martin et al. (2005), the two-part modelling approach has two major advantages: first, presence and abundance can be modelled separately gaining insights into whether they are influenced by the covariates in different ways and second, the analysis is simpler than with the mixture model approach, as the set of parameters for the two models can be estimated and

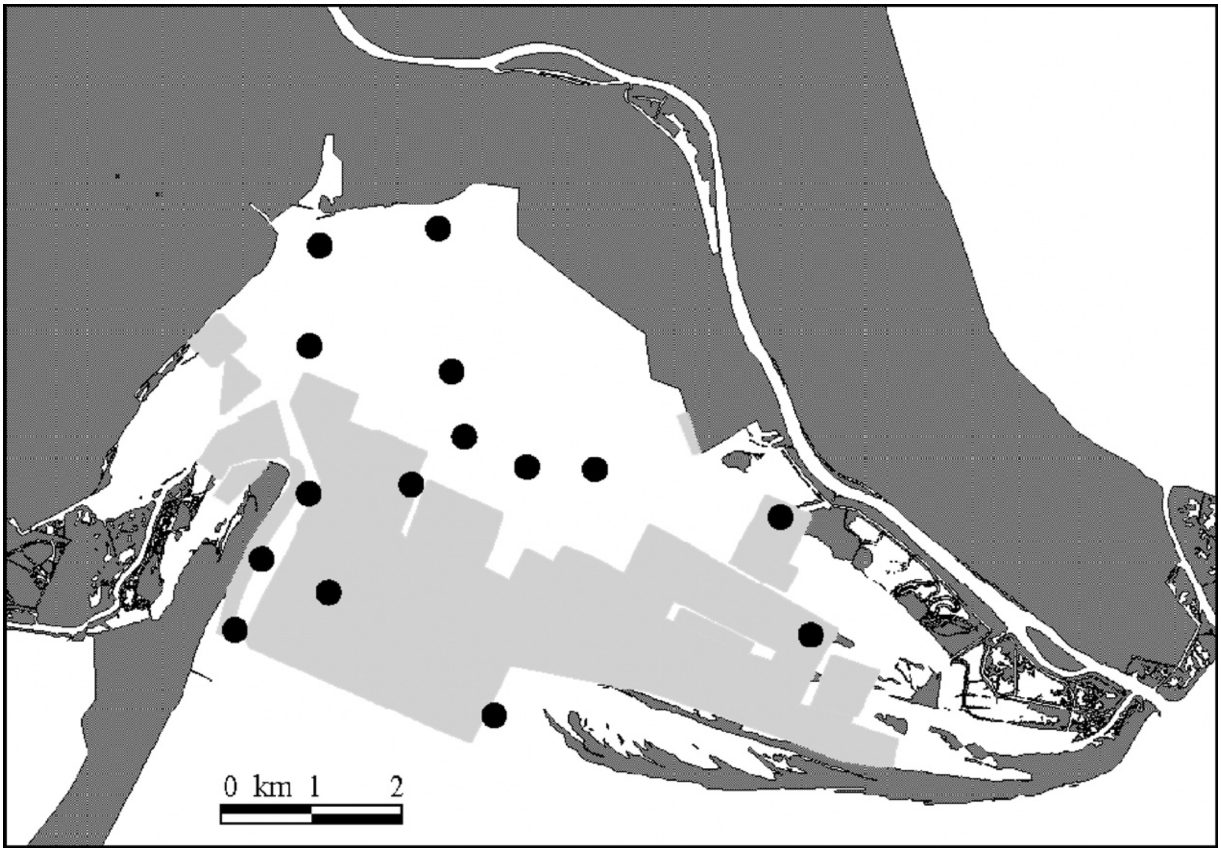

Fig. 2. Location of the rearing concessions and of the 15 sampling stations in the Goro lagoon.

interpreted independently. In a fisheries context, Stefansson (1996) suggested to use either a log-normal or a gamma distribution to model the positive values. In our case, the two-part modelling approach allows us to take into account in model formulation the "true zero" densities arising from a low frequency of occurrence of *T. philippinarum* linked to the limited range of values of critical environmental parameters suitable for clam growth and survival.

Our paper is organized as follows: after a brief description of the study area, of the environmental factors regulating clam growth and survival and of available data, we briefly illustrate the main features of the conditional model and calibrate and validate the model to the Sacca di Goro lagoon by using two independent data sets derived by the available data. Then, we apply the conditional model to the Goro lagoon to obtain estimates of clam yield potential. Finally, in the last section, we discuss the relevant features, limitations and further development of the conditional model for clam yield assessment.

2. Materials and methods

Detailed information on study area, main environmental factors affecting clam growth and survival in the Sacca di Goro lagoon and sampling routine have been described in detail elsewhere (Vincenzi et al., 2006). Therefore, only the aspects relevant for this study are described hereafter.

2.1. Study area

Sacca di Goro is a shallow Northern Adriatic lagoon (surface 26 km^2, average depth 1.5 m) located in the southern area of the Po river delta (44.78–44.83° N, 2.25–12.33° E) (Fig. 1). The lagoon is separated from the Adriatic Sea by a narrow sandy barrier with two mouths of about 0.9 km each regulating saltwater exchanges and it has four freshwater inlets, namely Po di Goro and Po di Volano rivers and Bianco and Giralda channels. At present, the limitations of exploitation activities (Fig. 2) imposed by the regulatory agency permit a annual production of about 10,000 t (Pellizzato and Da Ros, 2005).

2.2. Environmental factors affecting clam growth, survival and farming

According to a number of studies performed in the Sacca di Goro (Rossi, 1996; Paesanti and Pellizzato, 2000; Pastres et al., 2001; Solidoro et al., 2003, Melià et al., 2004) the main biogeochemical and hydrodynamic factors affecting clam growth, survival and farming are salinity, sand content in the sediment, hydrodynamism (i.e. water current), water depth, dissolved oxygen and chlorophyll "a". As for mean annual temperature, while it is a crucial determinant of clam growth, it does not exhibit a sufficient spatial variation in the Goro lagoon to determine variability in clam yield potential (Vincenzi et al., 2006); as a consequence, temperature has not been explicitly included in the model to assess the clam yield potential of the whole lagoon and to identify spatial differences in suitability within the lagoon.

2.3. Data and sampling survey

Due to its geographic and economic importance, a number of sampling surveys have been carried out in the last years to gather information on the main biogeochemical and hydrodynamic parameters, primary productivity, water quality etc. In particular, in the year 2003, a carefully planned sampling survey was performed to investigate also areas currently not exploited for farming.

2.3.1. T. philippinarum density

Density samples of *T. philippinarum* density were acquired by local expert fishermen in the 2003 by means of gear locally called "rasca" (Vincenzi et al., 2006). In order to collect clam samples of all size, *rasca* with 6 mm fine mesh net bags were used in the harvesting processes. A total of 107 density samples were collected during the sampling survey.

2.3.2. Biogeochemical and hydrodynamic parameters

Data on physical–chemical parameters, namely salinity, chlorophyll "a" and dissolved oxygen were gathered seasonally in the year 2003 in 15 different stations

Table 1
Basic statistics of environmental parameters sampled in the study area

Parameter	Mean±SD	Range	Vital limits	Optimal range
H (m s^{-1})	0.06±0.06	0 – 0.36	0.1 – 2	0.3 – 1
Sa (‰)	24.63±1.20	21.89 – 27.08	15 – 40	25 – 35
Sd (% sand)	0.45±0.30	0.19 – 0.99	>0.2	>0.6
B (m)	1.48±0.89	0 – 5.5	0.2 – 3	0.8 – 1.5
C (μg l^{-1})	5.97±1.67	3.50 – 14.18	0.1 – 23	2–12
O (% of saturation)	78.14±2.39	70.76 – 83.86	>40	>80

Vital limits and optimal range refer to knowledge of experts of *T. philippinarum* farming in North Adriatic lagoons (Paesanti and Pellizzato, 2000). H = Hydrodynamism; Sa = Salinity; Sd = Share of sand in the sediment; B = Bathymetry; C = Chlorophyll "a"; O = Dissolved oxygen.

located within the lagoon (Fig. 2) by using a multi-parametric probe (IDRONAUT OCEAN SEVEN 301M). The probe was programmed to sample every 30 cm from surface to the bottom, recording parameter values. Observed values were then averaged to compute the annual means. Data on bathymetry were gathered by using an Eco-Sounder (248,000 points total).

Sediment sampling was performed by the Geology Department of the University of Ferrara (Simeoni et al., 2000) giving as result the sand content of the sediment; in fact, it is well known that *T. philippinarum* performs better in sandy sediment rather than in muddy sediment (Barillari et al., 1990; Rossi, 1996; Paesanti and Pellizzato, 2000).

Water flow dynamics in the Sacca di Goro, in particular flow fields and flow capacity values (m^3 s^{-1} m^{-1}), were acquired from the study performed by Brath et al. (2000). Hydrodynamism was estimated in the whole lagoon for four different conditions, namely low tide, high tide, intermediate decreasing tide and intermediate increasing tide; the average value was used in this work.

Table 1 shows the basic statistics of the environmental parameters sampled in the Goro lagoon and vital limits and optimal conditions for *T. philippinarum* farming in North Adriatic lagoons.

2.3.3. Data interpolation and thematic maps

Point data were interpolated *via* a nearest neighbour algorithm over grid of 100 × 88 cells (each one of 1 ha of surface) by using the software SURFER™ of Golden Software Inc. ver. 7.02 to provide thematic maps of the

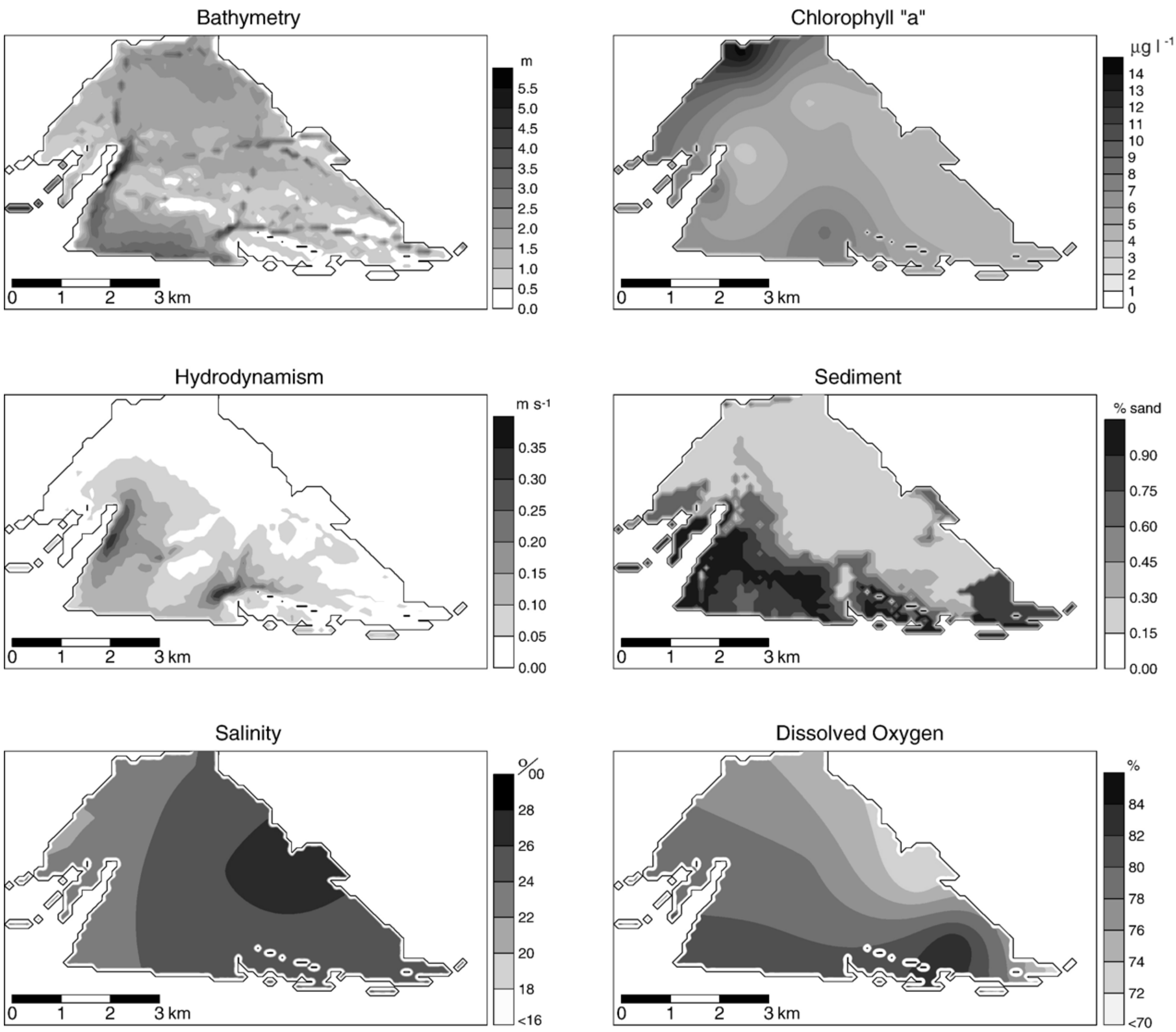

Fig. 3. Thematic maps representing bathymetry (m), chlorophyll "a" (μg l^{-1}), hydrodynamism (m s^{-1}), sediment type (% of sand), salinity (‰) and dissolved oxygen (% of saturation).

Table 2
Pearson's r correlations between the biogeochemical and hydrodynamic variables

	Salinity	Sediment	Hydrodynamism	Bathymetry	Oxygen	Chlorophyll "a"
Salinity	–	−0.12	0.05	−0.12	−0.28*	−0.29*
Sediment	−0.12	–	0.26*	−0.29*	0.24	−0.04
Hydrodynamism	0.05	0.26*	–	−0.04	0.29*	−0.16
Bathymetry	−0.12	−0.29*	−0.04	–	−0.26*	−0.08
Oxygen	−0.28*	0.24	0.29*	−0.26*	–	0.03
Chlorophyll	−0.29*	−0.04	−0.16	−0.08	0.03	–

*$p<0.05$.

whole Goro lagoon for each of the environmental parameters considered.

2.4. Statistical methods

Given the relatively high presence of true zeros counts and overdispersion caused by large counts, a two-part conditional model was fitted to explore the relationship between clam yield (kg m^{-2} $year^{-1}$) and the main biogeochemical and hydrodynamic parameters affecting clam growth and survival and to assess clam yield potential in the Goro lagoon.

The original data set ($n=107$) was randomly splitted in two parts: the calibration data set ($n=80$) and the validation data set ($n=27$). Two further data sets were extracted from the calibration data set: one indicating whether *T. philippinarum* was present or not (presence dataset) and the other reporting the density (in kg m^{-2} $year^{-1}$) for those sites in which *T. philippinarum* was present (abundance dataset). Multiple correlation analyses were used to identify correlations between independent variables (Pearson's $r>0.7$), as collinearity can seriously affect conclusions from multiple regression models (Tabachnick and Fidell, 1996; Quinn and Keough, 2002). The presence data and the abundance data were modelled in terms of the explanatory variables, using logistic and ordinary regression, respectively. Hydrodynamism and bathymetry values were log-transformed to improve normality. We computed log (bathymetry+1) to account for the presence of zero values. Preliminary analysis on data distribution showed the adequacy of the log-normal distribution to model the positive densities of *T. philippinarum*.

For both parts of the conditional model the best model was chosen by a backward stepwise selection procedure based on the AIC value of the model (Akaike, 1974)

Table 3
Estimates, standard errors and standardised estimates of the coefficients for the explanatory variables for the selected logistic and ordinary regression models chosen using stepwise selection based on the AIC value of the model

Logistic regression				Ordinary regression		
Parameter	Estimate	Std. error	Standardised estimate	Estimate	Std. error	Standardised estimate
H	3.66	1.25	2.93	−18.00	10.68	−1.69
Sa	–	–	–	−2.05	0.47	−4.36
Sd	6.04	3.09	1.95	81.56	17.83	4.57
B	–	–	–	−21.08	11.6	−1.82
C	–	–	–	−31.37	10.37	−3.03
O	0.74	0.28	2.64	−0.44	0.89	−0.49
Sa:C	–	–	–	0.42	0.07	6.00
Sd:C	–	–	–	−0.93	0.31	−3.00
Sd:O	–	–	–	−0.95	0.22	−4.32
C:O	–	–	–	0.25	0.12	2.08
C:H	–	–	–	−0.45	0.13	−3.46
C:B	–	–	–	0.93	0.28	3.32
O:I	–	–	–	0.25	0.13	1.92
O:B	–	–	–	0.23	0.14	1.64
H:B	–	–	–	1.50	0.46	3.26
R^2	–	–	–	0.82	–	–
σ^2	–	–	–	0.21 (76 d.f.)	–	–

H=log (Hydrodynamism); Sa=Salinity; Sd=Share of sand in the sediment; B=log(Bathymetry+1); C=Chlorophyll "a"; O=Dissolved oxygen. Couples of variables indicate interaction between variables.

starting from the full model which incorporates interactions among variables. Adequacy of the ordinary regression model was checked by inspection of the residuals. The presence of continuos covariates did not allow a reliable lack-of-fit test for the logistic regression (Hosmer et al., 1997). The logistic and ordinary regression models were then combined to estimate the potential commercial yield of *T. philippinarum* in the Sacca di Goro lagoon. Let $Y(\mathbf{w})$ be the density of *T. philippinarum* where $\mathbf{w}$ is the vector of the explanatory variables and let $Z(\mathbf{x})$ be the binary variable — equal to 1 when *T. philippinarum* is present and 0 when not — where $\mathbf{x}$ is the vector of the explanatory variables. The expected value of Y is given by:

$$E(Y) = \Pr(Z=1)E(Y|Z=1) + \Pr(Z=0)E(Y|Z=0),$$

$$= \Pr(Z=1)E(Y|Z=1),$$

$$= \pi\mu$$

As showed by Stefansson (1996) and Welsh et al. (1996), the estimate of the expected density of *T. philippinarum* is computed as follows:

$$\hat{E}(Y) = \hat{\pi}\hat{\mu}$$

where

$$\hat{\pi} = \Pr(Z=1) = \exp(\mathbf{x}'\hat{\beta})/\{1+\exp(\mathbf{x}'\hat{\beta})\}$$

and

$$\hat{\mu} = E(Y|Z=1) = \exp(w'\hat{\theta} + \hat{\sigma}^2/2)$$

are the estimates of π and μ computed from the two regression models. Thus, $\hat{\beta}$ is the vector of the estimates of the coefficients in the logistic regression, $\hat{\theta}$ is the vector of the estimates of the coefficient in the ordinary regression and $\hat{\sigma}^2$ is the residual mean square in the ordinary regression model for the positive values, as described by Crow and Shimizu (1988).

The conditional model was then validated on the validation dataset.

3. Results

Results from the sampling surveys showed a maximum observed density of 6 kg m^{-2}, as already reported by Rossi (1996) and Melià et al. (2004). As clams are gathered in the same site approximately once a year, 6 kg m^{-2} year^{-1} is assumed to be the maximum attainable yield. Density samples of *T. philippinarum* were characterized by a large number of zero values (22% of total observations), which justifies the use of a two-part conditional model of clam yield potential to fit the data. Thematic maps are shown in Fig. 3 for mean concentration of chlorophyll "a", share of sand in the sediment, bathymetry, hydrodynamism, salinity and dissolved oxygen. Biogeochemical and hydrodynamic variables show little or no correlation to each other (always Pearson's $r<0.3$, Table 2). Table 3 shows the parameter estimates for the logistic and ordinary regression models. Share of sand in the sediment, dissolved oxygen and hydrodynamism were the only significant parameters in the logistic part of the conditional model. For the presence data, the selected model does not include any interaction among the environmental parameters. Figs. 4 and 5 show estimates of probability of presence and the expected clam yield potential of *T. philippinarum*, respectively, as a function of the environmental parameters included in the selected models. The model has been validated on the validation data set by estimating the variance in observed yield

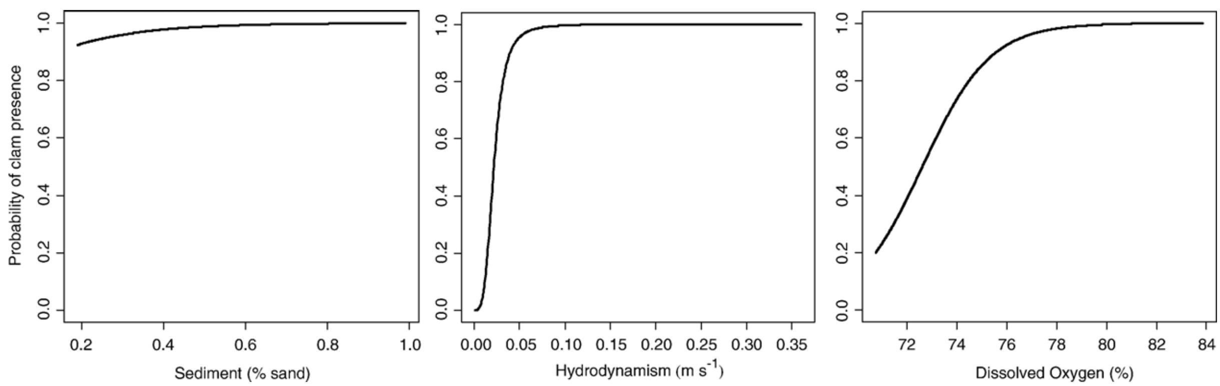

Fig. 4. Estimates of probability of presence of *T. philippinarum* plotted against share of sand in the sediment (%), hydrodynamism (m s^{-1}) and dissolved oxygen (% of saturation). Predictions are for an average site, that is, with the other environmental parameters values set at their means in the study area.

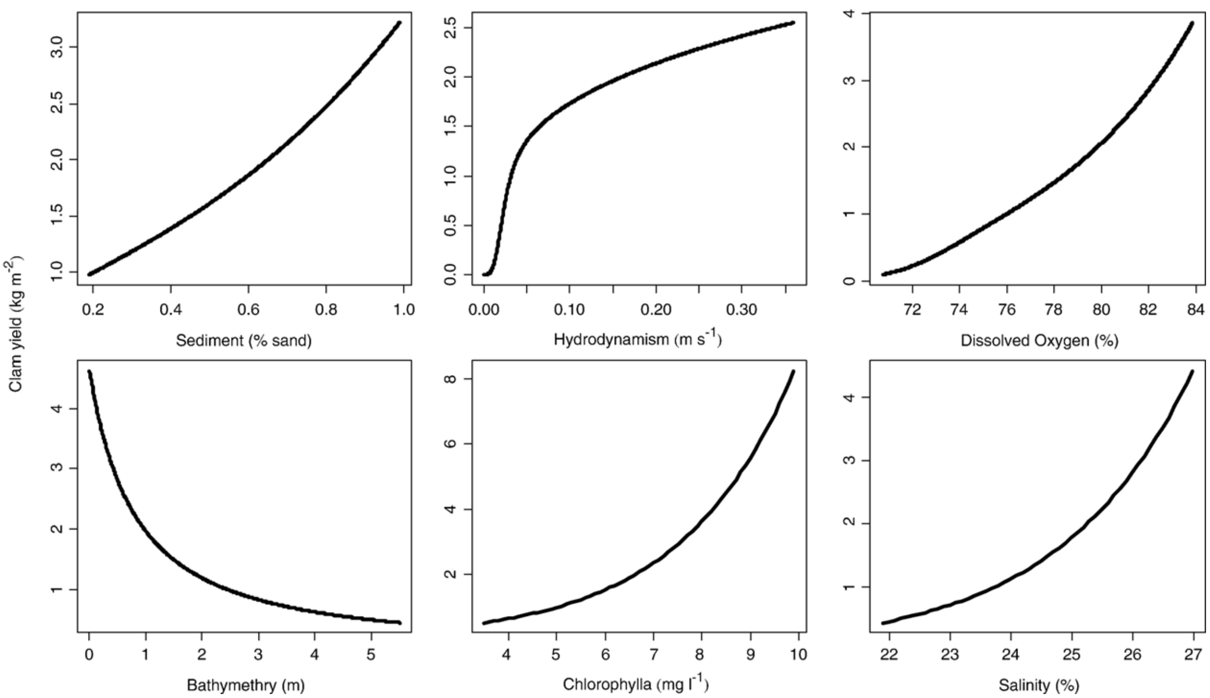

Fig. 5. Estimates of expected abundance of clam yield potential against environmental parameters values. Predictions are for an average site, that is, with the other environmental parameters values set at their means in the study area.

explained by the model (Fig. 6). As it can be noted in Fig. 6, the conditional model provides a good prediction of the observed yield, with a R^2 equal to 0.87. The conditional model was then applied to the whole Goro lagoon to estimate the total annual productivity and to identify areas of different potential commercial yield within the lagoon (Fig. 7). The conditional model provides an estimation of the potential commercial yield of about 32,000 t year^{-1} for the whole lagoon on a suitable area of about 1400 ha, with an average productivity of about 1.4 kg m^{-2} year^{-1}.

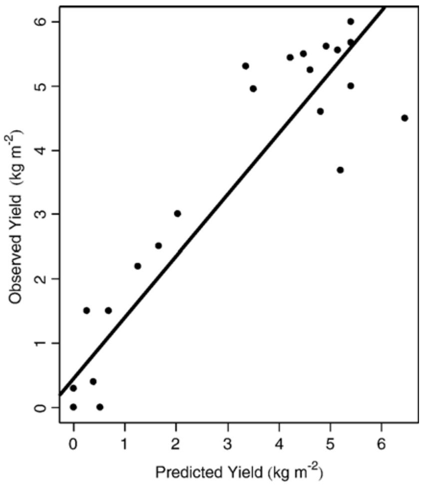

Fig. 6. Linear regression in the form $y = a + b\mathbf{x}$ of yield predicted by the conditional model on the observed yield in the validation data set ($p < 0.001$, $R^2 = 0.84$, $a = 0.44 \pm 0.25$, $b = 0.95 \pm 0.07$). Six predicted and observed yields are equal to 0.

4. Discussion

Our paper shows the application of a conditional model for the estimation of commercial yield potential of a patchily-distributed organism and for the identification of sites of different suitability within a coastal lagoon where intensive farming is performed. Excess

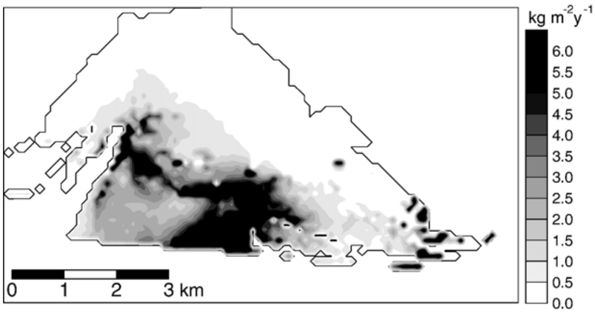

Fig. 7. Annual commercial yield of *T. philippinarum* in the Goro lagoon (kg m^{-2} year^{-1}) as estimated by the conditional model.

true zeros are a result of ecological processes (Martin et al., 2005) whose occurrence may be related to the rarity of the species under study (Gaston, 1994) or being the result of habitat conditions or, as in the case of *T. philippinarum*, of the patchy aggregation of the species. In our example, the magnitude of zero inflation is substantial and therefore the choice of a modelling approach not accounting for it can lead to an overestimation of the variance and hence increase the risk of type I error (Martin et al., 2005). Conditional models for zero inflated data have been already used in both an ecological context (Welsh et al., 1996) and marine setting (Lo et al., 1992; Stefansson, 1992). In particular, conditional models combining the binomial distribution for the zero component of the data and the log-normal distribution for the non-zero part (initially defined as delta distribution, Aitchison and Brown, 1957) have been used to model mackerel egg counts (Pennington, 1983), health statistics (Zhou and Tu, 2002), air contaminant levels (Tu, 2002), habitat suitability of common sole *Solea solea* (Le Pape et al., 2004). To our knowledge conditional models were never applied to estimate the commercial yield of bivalves in coastal lagoons.

In presence of multiple competing exploiters of a renewable resource (bivalves, shrimps etc.) the adoption of a transparent and objective methodology (i.e. based on quantitative statistical methods) by the regulatory agency is mandatory in order to reduce the perception of subjective bias in the subdivision and assignment of the harvestable areas. In our work, we have shown how the application of a zero-inflated conditional model allows for a rigorous and objective estimation of clam yield potential in different areas within the lagoon, a basic step for optimizing the harvesting activities where extensive clam farming is performed. Moreover, the analysis here presented allowed the assessment of the effects of a number of biogeochemical and hydrodynamic factors on the yield potential of *T. philippinarum* in the Sacca di Goro lagoon. The prediction of the conditional model fitted on the calibration data set provided a good explanation of the observed yield in the evaluation data set (Fig. 6). In our application of the conditional model to the Goro lagoon, we chose a set of crucial biogeochemical and hydrodynamic parameters fundamental in determining clam occurrence and abundance (Barillari et al., 1990; Paesanti and Pellizzato, 2000; Vincenzi et al., 2006) and which can be sampled at a fairly low cost. As can be noted from Table 3, share of sand in the sediment, dissolved oxygen and hydrodynamism play a major role in determining the occurrence of *T. philippinarum* in the Sacca di Goro lagoon. As shown in Fig. 4 optimal sites for clam farming are characterized by mean water currents in the range 0.1–0.3 m s^{-1}; particularly in the case of the dreaded anoxic crises, water currents allow for faster water reoxygenation with respect to areas of still water, where only diffusion processes occur through the water column. As for sediment, analyses by Rossi (1996) and Melià et al. (2004) show that rearing sites with sandy sediments are more suitable for clam farming than sites with silty bottoms in terms of juvenile settlement, growth speed and maximum attainable size. As for other biogeochemical and hydrodynamic parameters (i.e. hydrodynamism, share of sand in the sediment, bathymetry, salinity and dissolved oxygen) the estimates of the conditional model (Fig. 5) confirm the findings of Barillari et al. (1990) and Paesanti and Pellizzato (2000) on the optimal values of the main biogeochemical and hydrodynamic parameters influencing clam growth and survival in the Goro lagoon. As reported by Vincenzi et al. (2006) and in Table 1, *T. philippinarum* requires water salinity in the range 25–35‰ for optimal growth, concentration of chlorophyll "a" up to 11 μg l^{-1} and a degree of dissolved oxygen saturation of more than 80%. As for bathymetry, optimal sites for *T. philippinarum* are located in water depths less than 2 m for easy harvesting and because clams grow faster in shallow waters.

The commercial yield potential estimated by the conditional model for the whole Goro lagoon (32,000 t) is about twice as much that reported by the regulatory agency and about 7000 t more than that estimated by the Habitat Suitability model based on experts opinion applied to the Sacca di Goro lagoon by Vincenzi et al. (2006). On the other hand, the amount of surface exploitable (i.e. where clam occurs) estimated by the conditional model (about 1400 ha), which is similar to that estimated Vincenzi et al. (2006) (1345 ha), is 40% larger than the present harvestable ground given in concession to fishermen by the regulatory agency. As a consequence, the difference in harvestable ground is likely to explain the difference between the potential yield estimated by our model and the actual yield reported by the regulatory agency and reflects the conservative harvesting policy adopted in the Goro lagoon which limits the harvesting activities to about one third of the whole lagoon.

We are confident that the model here derived provides a fair representation of the suitability and yield potential of different sites within the Goro lagoon. Anyway, this does not imply that the maximum overall yield predicted by the model might be sustainable in the long run. In fact, dystrophic crises linked to macroalgal blooms have been responsible of the decline in clam production in recent years. Some authors (Bartoli et al., 2001, 2003; Melià et al., 2003) have argued that these algal blooms are actually triggered by clam rearing activities. Therefore, to sustain the clam fishery and conserve the natural environment the regulation of exploitation activities must account for both the clam production and ecological carrying capacities, as argued by Nizzoli et al. (in press).

The approach here presented to identify areas of different yield potential and to assess the commercial yield potential of the whole Sacca di Goro lagoon can be applied to other Adriatic lagoons where intensive commercial harvesting activities are performed in a natural or semi-natural environment. Careful examination of the underlying distribution of non-zero observations is necessary to avoid biases and large reduction in efficiency (Myers and Pepin, 1990). As suggested by Fletcher et al. (2005) other distribution could be used to model non-zero skewed data, such as the gamma distribution (Stefansson, 1996), the truncated negative binomial or Poisson distribution (Welsh et al., 1996) or the Ades distribution (Perry and Taylor, 1985). In order to adopt the same approach to other lagoons and/or to other bivalve species of commercial interest, a rigorous statistical investigation is mandatory to identify if other environmental parameters, such as mean annual temperature, nutrients concentrations, mean length of day light etc., play a major role in determining bivalve growth and survival and the suitability of different sites in the same farming environment.

We believe that the data-driven modelling approach here presented significantly improves the estimation of clam yield potential with respect to the qualitative approach based on expert opinion proposed by Vincenzi et al. (2006). In fact, even if the degree of uncertainty relative to the values of explanatory variables in the lagoon and the results of the logistic and ordinary regressions remains non-trivial, the data-driven calibration of model functions and parameters places the approach in a more rigorous statistical and modelling framework.

Further studies will be carried out in order to examine the relative importance of annual fluctuations in the mean annual values of the biogeochemical and hydrodynamic parameters in determining the observed inter-annual variability of the commercial yield potential of the Sacca di Goro lagoon and to determine if the inclusion of other biogeochemical parameters could provide significantly better predictions of the conditional model.

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