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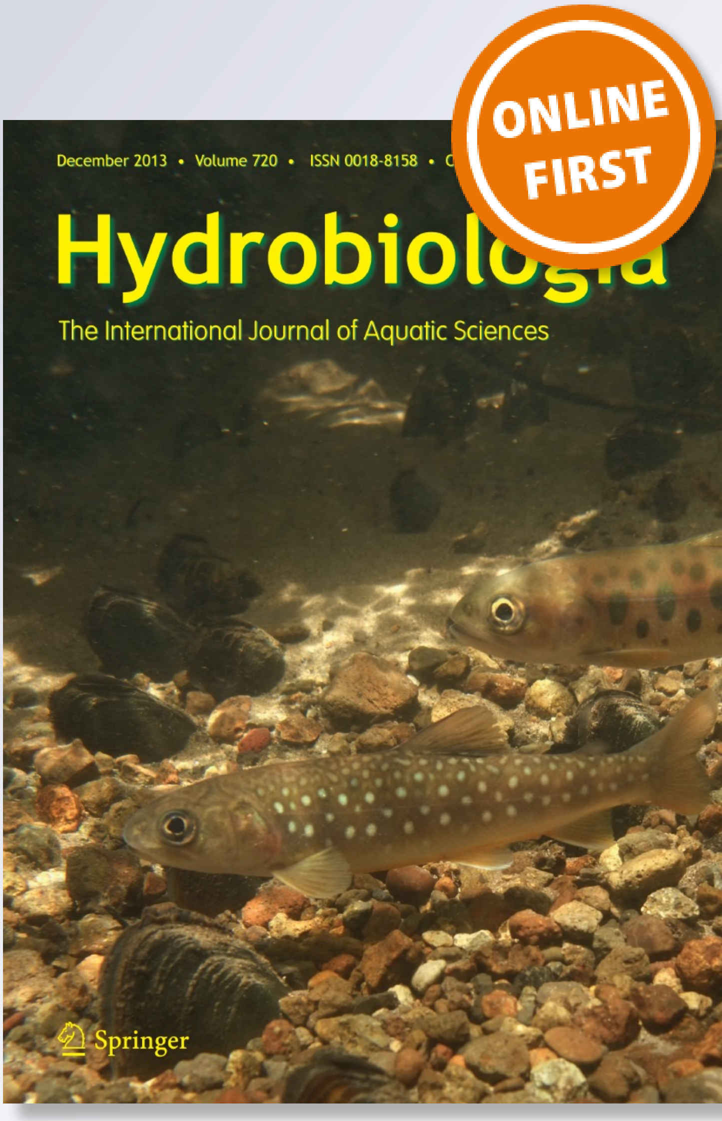

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PRIMARY RESEARCH PAPER

Rapid estimation of potential yield for data-poor *Tapes philippinarum* fisheries in North Adriatic coastal lagoons

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Abstract We show how a simple species distribution model can be used for the rapid estimation of potential yield and for the identification of suitable sites for farming of *Tapes philippinarum* in two North Adriatic lagoons (Caleri and Marinetta-Vallona, Italy) in the face of limited data. We used a two-part species distribution model with sediment type, hydrodynamism, dissolved oxygen, and salinity as predictors of *T. philippinarum* potential yield. The first model component uses logistic regression to identify the areas in which clams occur, while the second component uses a weighted geometric mean of suitability values to estimate the potential annual yield (kg m^{-2} $year^{-1}$) for the sites where *T. philippinarum* is predicted to be present. We used site-specific yield data from Caleri and Marinetta-Vallona to estimate the weights of the geometric mean by constrained linear regression. We validated the two-part model on an independent set of yield data ($R^2_{adj} = 0.82$), and we then estimated the spatial distribution of potential yield in the two lagoons. The calibration and application of a simple species distribution model are useful tools for objectively identifying the most suitable sites for farming of *T. philippinarum* in North Adriatic lagoons.

Keywords Data-poor system · Aquaculture · Two-part model · Clam farming · Species distribution model

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Introduction

According to the most recent reports, aquaculture is among the fastest-growing food production industries (9.1% annual growth in the last three decades) and it currently supplies around 46% of the world's fish (FAO, 2010) for a world total of 52.5 t produced in 2008. The strong expansion of aquaculture activities will continue in the next few decades, albeit at a slower pace, and aquaculture is expected to dominate fish and bivalve production by 2030 (Brugère & Ridler, 2004). The environmental and economic sustainability of commercial farming and harvesting of lagoon natural resources, such as fish species (finfish and shrimp) and

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bivalves (oysters, mussels, and clams), is only one of the many conflicting goals in the management of coastal lagoons. Although policies and aims for aquaculture activities are often not clearly stated, among the general and shared goals are maintaining the viability of the fishery and the related employment of fishermen, as well as preserving the ecological integrity of the exploited system, including ecosystem services (Aguilar-Manjarrez et al., 2010). The sustainability of aquaculture activities would greatly benefit from the design and implementation of adaptive management policies limiting the ecological and economic consequences of over- and under-exploitation, as well as explicitly acknowledging the complexity of lagoon ecosystems and the need to optimize multiple conflicting goals (Silva et al., 2011).

Recently, an "Ecosystem Approach to Aquaculture" (EAA) has been proposed (Aguilar-Manjarrez et al., 2010). The optimization of site selection is among the EAA fundamental actions, along with real-time management of aquaculture operations and the estimation of the carrying capacity of the system. It follows that the estimation of site-specific potential yields through the application of Habitat Suitability (HS) or species distribution models (the two terms will be used interchangeably in this work) should be considered as an essential element of the decision-making process in the overarching ecosystem-based approach to aquaculture management.

HS models have been extensively used to improve our understanding of the relationship between habitat features and species distribution in both space and time, as well as to predict the likelihood of occurrence and abundance of a species using habitat attributes that affect its survival, growth, and reproduction (Elith & Leathwick, 2009; Dormann et al., 2012). Geographical Information Systems (GIS) and powerful new statistical and modeling techniques have been increasingly been used to support the development of sophisticated species distribution models that quickly process, represent, and manage a huge amount of spatial information (Elith & Graham, 2009; Elith & Leathwick, 2009).

In aquaculture contexts, simple HS approaches have been used for identifying appropriate sites mostly for finfish farming (e.g., Kapetsky et al., 1988; Aguilar-Manjarrez & Ross, 1995). On the other hand, although greatly needed, species distribution models are still rarely applied to the estimation of potential yield of mollusk species (Silva et al., 2011; Cho et al., 2012). As the biology and ecology of aquaculture species are usually well studied, the rare application of specie distribution model is often caused by (i) lack of data, and (ii) the lack of necessary expertise by fishery managers for the development and application of sufficiently-sophisticated models (Silva et al., 2011). However, even in the absence of data, statistical understanding, technical capacity, or human capital necessary to develop basic models of species distribution, managers must provide policies and regulations for aquaculture activities. Thus, there is a pressing need to develop species distribution models that can overcome those common limitations and be effectively used by decision makers (Silva et al., 2011).

Species distribution models for aquaculture species are greatly needed in the North Adriatic region—in particular in the Po River delta—where the suitability of many coastal lagoons for mollusk farming led to the development of flourishing activities of commercial aquaculture in the last three decades (Abbiati et al., 2010). HS models for the estimation of potential yield of *T. philippinarum* in the Sacca di Goro lagoon (North Adriatic, Italy) have been developed using semi-empirical and zero-inflated regression models (Vincenzi et al., 2006a, b, 2007). However, apart from Sacca di Goro (Melià et al., 2003; Marinov et al., 2008) and the Venice lagoon (Solidoro et al., 2003; Pranovi et al., 2004; Pellizzato & Ros, 2005; Vincenzi et al., 2011), data collection and monitoring of both the ecological and economic components of aquaculture activities in the Po River delta have been inconsistently approached (Abbiati et al., 2010).

Located in the Po River delta, Eastern Polesine (Province of Rovigo, northeastern Italy) is characterized by a vast region of brackish water areas, including "fishing valleys", lagoons, and various types of canals. These transitional waters have been traditionally exploited for finfish, shellfish, and crustaceans (Abbiati et al., 2010). Mussel (*Mytilus galloprovincialis*) farming was introduced in Polesine in the 1960s. In the 1970s, production levels remained rather low since farming of mussel merely acted as an economic integrator for the prevailing traditional fishing activities in lagoons and deltaic branches of the Po River, as well as for the harvesting of mollusks from natural colonies, in particular of *Tapes decussatus*. The Manila clam *Tapes* (or *Ruditapes*) *philippinarum* was introduced in 1985 in two lagoons of

Polesine (Caleri and Scardovari) as a culture species, as its large tolerance for lagoonal environmental conditions and resistance to anoxic conditions allowed higher yields with respect to the native species *T. decussatus* (ESAV, 1990). *T. philippinarum* quickly found favorable environmental conditions for growth and reproduction in several North Adriatic lagoons and became one of the most important commercial aquaculture species in the whole region, leading Italy to be—with an annual production of about 50,000 t—the major European producer of *Tapes* (Pellizzato & Ros, 2005) and the second in the world after China (1,5000,000 t, Guo et al., 1999).

The annual production of *T. philippinarum* in Polesine increased to almost 14,000 t in the mid 1990s, but a sharp decline in productivity occurred in more recent years (only 4,000 t in 2003). The current (2008, last year with data) annual production is about 12,000 t. A similar decline in production has been observed in other North Adriatic lagoons where *T. philippinarum* is intensively farmed and harvested, such as the Venice lagoon and the Sacca di Goro lagoon, and has been mainly ascribed to pollution (Munari & Mistri, 2007) and eutrophication of waters leading to anoxic crises (Sorokin et al., 1999).

In North Adriatic lagoons, including those of Polesine, regulatory agencies progressively shifted from a free-access regime to a concession-based regime, i.e., to a system where harvesting 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 to harvesting sites and exploitation effort (Pellizzato & Ros, 2005). However, the transition to a "culture-based fishery" based on technically-correct, ecologically-sustainable, and reasonably-predictable rearing procedures also able to efficiently respond to fluctuations in market prices cannot be considered as successfully completed (Pellizzato & Ros, 2005).

The efforts of regulatory agencies and harvesters to preserve the sustainability and economic profitability of *T. philippinarum* aquaculture activities in North Adriatic lagoons would greatly benefit from the application of HS models able to estimate site-specific differences in potential yield as well as whole-lagoon potential yields. However, most of the North Adriatic lagoons are data-poor environments, and the collection of sufficient data for the development of ad hoc models would require years. This condition of data poorness has clear parallels with those experienced by data-poor sea and ocean fisheries, usually defined as fisheries for which sufficient information or data to conduct a conventional stock assessment are lacking. Data-poor sea and ocean fisheries include fisheries with few available data as well as fisheries for which an abundance of data exists, but there is limited understanding of stock status due to poor data quality, lack of proper data analysis, or limited knowledge of the biology of the exploited fish species (Honey et al., 2010). However, as in the case of fisheries for which data and other information are insufficient for a conventional stock assessment, alternative or modified methods can inform aquaculture management tasks with science-based understanding that may help reduce the application of untransparent (i.e., not data-driven) policies (Honey et al., 2010).

Recently, the issue of transferability has been scrutinized in the context of species distribution modeling, i.e., whether a species distribution model developed in one region can provide correct predictions of species distribution in a different region, or to a lesser degree, whether models developed with data and processes relative to a specific time period (e.g., season) can predict species distribution in a different time period characterized by other weather or climatic conditions. The lack of transferability of species distribution models emerges more clearly when predictors are not mechanistically linked to the response variable (Wenger & Olden, 2012).

Here, we show that the two-part HS model presented by Vincenzi et al. (2007) can be used as a general (i.e., transferable) framework for the estimation of potential yield of *T. philippinarum* in lagoons of the Po River delta and thus be a reasonable and efficient alternative to the full development of lagoon-specific models. The model has two components: the first component predicts the presence/absence of *T. philippinarum*, while the second one predicts—using a weighted geometric mean—the potential annual yield per unit of surface for sites where *T. philippinarum* is predicted to be present. We developed and applied the model to two North Adriatic lagoons: Caleri and Marinetta-Vallona.

For the first model component, we used the same logistic regression model developed in Vincenzi et al. (2007) for Sacca di Goro (located 25 km south of Caleri and Marinetta-Vallona), while we estimated the weights of the weighted geometric mean using annual yield data for sites within Caleri and Marinetta-Vallona lagoons where *T. philippinarum* was present. We validated the two-part model by comparing model predictions with observed yield data for the two lagoons, and we then applied the two-part model to estimate total potential yield of the lagoons as well as site-specific differences in potential yield. Finally, we discuss the implications of our approach for other data-poor environments, and how the integration of the HS model with biogeochemical and production models will further the development of an EAA for the lagoons of the Po River delta.

Materials and methods

Study area

The Lagoon of Caleri is a large (1,000 ha) and shallow (maximum depth 2 m) coastal lagoon in the northern part of the Po River Delta. The hydrodynamic regime of the lagoon is mainly driven by the water exchange with the sea through a narrow (120 m wide) mouth. The lagoon contains 3 flat sandy islands ("barene") that affect the circulation regime. In the easternmost part of the lagoon, close to the sea mouth, an area of 40 ha is divided into concessions for clam aquaculture (Fig. 1). The Lagoon of Marinetta-Vallona is a shallow (maximum depth 2.5 m) lagoon, with an area of 1,150 ha. About 650 ha of the lagoon are claimed as private property in which exploitation activities are not allowed. The lagoon is connected to the sea by a narrow mouth (about 100 m wide). A deltaic branch of the Po River (Po di Levante) flows along the lagoonal NW–SE axis. An area with a total surface of 66 ha (Fig. 1) is given in concession to clam farmers in the westernmost part of the lagoon.

A commercial clam culture-based aquaculture operates in both lagoons. Wild juveniles (i.e., clam seed) are collected under a strict set of rules in natural

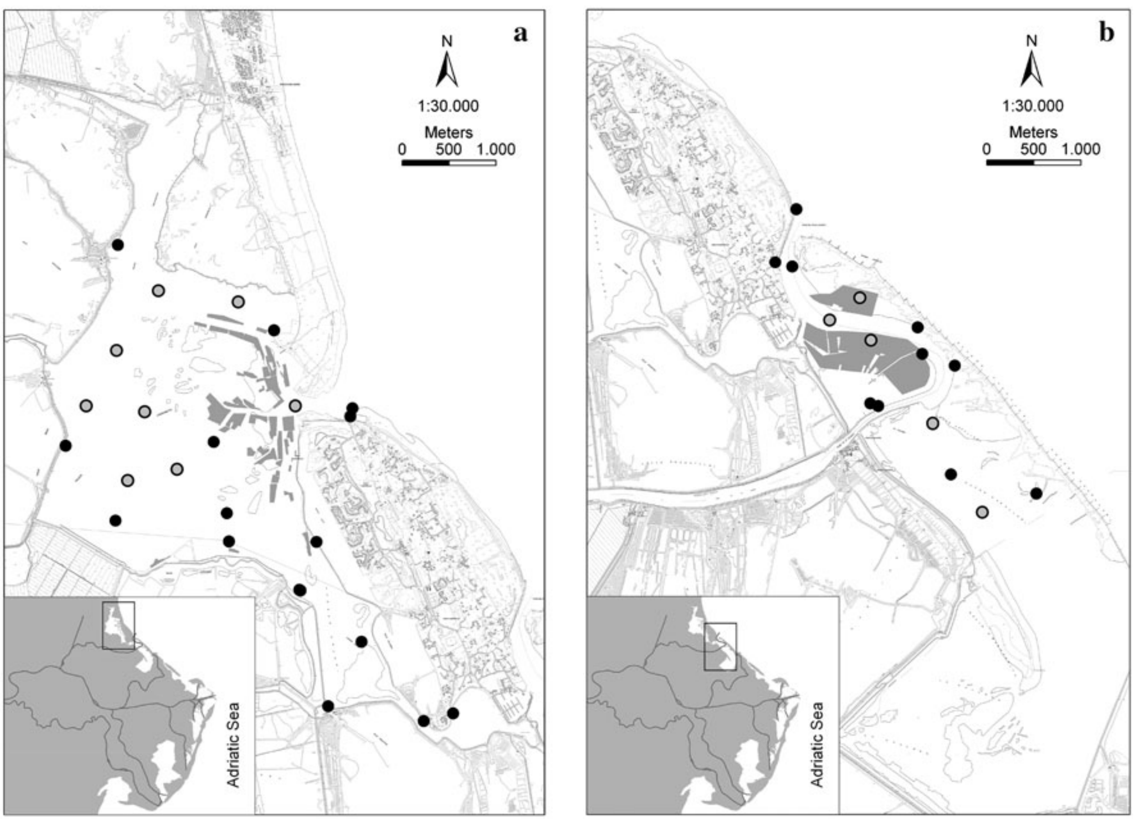


Fig. 1 Location of **a** Caleri and **b** Marinetta-Vallona lagoons of the rearing concessions (*gray areas*) and of the sampling stations for both *T. philippinarum* and environmental variable (*black dots*) and only environmental variables (*gray dots*)

nursery areas and then "seeded" in concessions. Juvenile clams (i.e., seed) are collected in two periods, spring (15 April–15 June) and autumn (15 September–15 December), according to the two reproductive peaks that *T. philippinarum* exhibits in North Adriatic lagoons (Sbrenna & Campioni, 1994). In farmed areas, *T. philippinarum* densities can be up to two orders of magnitude greater than in sites with only natural recruitment (Abbiati et al., 2010).

Primary production in the Northern Adriatic Sea is the main source of phytoplankton biomass for the Po River delta lagoons and is primarily driven by Po River discharge and associated nutrient loadings (Abbiati et al., 2010). Po River discharge peaks in spring and late autumn.

Environmental and biotic data

As reported by Paesanti & Pellizzato (2000), *T. philippinarum* is quite tolerant to mid-high variations of relevant habitat features of coastal lagoons. According to previous studies in North Adriatic lagoons (Paesanti & Pellizzato, 2000; Vincenzi et al., 2006a, b, 2007, 2011; Munari et al., 2009), the most important environmental variables for the successful establishment and relative abundance of *T. philippinarum* are salinity, sand content in the sediment, hydrodynamism (i.e., water current), and dissolved oxygen. Other environmental variables were used in species distribution models for *T. philippinarum* for the Sacca di Goro lagoon, namely, water depth and chlorophyll "a" concentration, but they had lower predictive importance (Vincenzi et al., 2007).

Data relative to water flow dynamics in Caleri and Marinetta-Vallona were acquired from studies carried out by the Consorzio di Bonifica Delta Po Adige. A mathematical model of water circulation was applied to the two lagoons (D'Alpaos & Defina, 1995; Defina, 2000) using data recorded in 2007 and 2008 on tide levels, meteorology (atmospheric pressure, temperature, relative humidity, and wind speed and direction), and flow rates, including water velocity. Flow rates were obtained using an Acoustic Doppler Current Profiler (ADCP) Rio Grande 1,200 kHz ZedHed (RDI Instruments, San Diego, CA) current meter carried by a boat, which allowed the measurement of flow rates through the mouth and five other sections of the lagoons.

Twenty-three (Caleri) and fifteen (Marinetta-Vallona) stations were used in two different years (2008 and 2009) to collect environmental and biotic data (Fig. 1). Each station was geo-referentiated with a GPS Garmin®60. Water parameters (salinity and dissolved oxygen) were collected with an OxyGuard® Mk III probe and an ATAGO S/Mill-E refractometer. Sediment cores (4.5 cm i.d.) were sampled for particle size analysis, and characteristics of the surface sediment were determined by wet sieving and pipette analysis (Folk, 1980). Point data for environmental and biotic data were interpolated via a nearest neighbor algorithm over a grid of 72 × 53 cells for Caleri and 38 × 34 cells for Marinetta-Vallona using the software SURFER™ of Golden Software Inc. ver. 7.02 in order to produce thematic maps of the whole Caleri and Marinetta-Vallona lagoons for the annual mean (average of seasonal data) of each of the four environmental variables considered. The resolution (i.e., operational scale) chosen for the study was 100 × 100 m cells (site). As a measure of hydrodynamism, we used for each cell the average of the values of water speed obtained from the water circulation model for four different conditions, namely, low tide, high tide, intermediate decreasing tide, and intermediate increasing tide.

Samples of *T. philippinarum* density were collected with the help of local fishermen on the same day during harvesting, by means of a manual gear locally called "rasca" (Paesanti & Pellizzato, 2000). In order to collect clam samples of all sizes, "rasche" with 6-mm fine mesh net bags were used. Since the same site is harvested about once a year, density samples (kg m^{-2}) were treated as estimates of annual yield (kg m^{-2} $year^{-1}$) (Vincenzi et al., 2011).

Species distribution model

In this work, we use the general framework of the spatial distribution model that has been developed by Vincenzi et al. (2007) for the Sacca di Goro lagoon (HSM model).

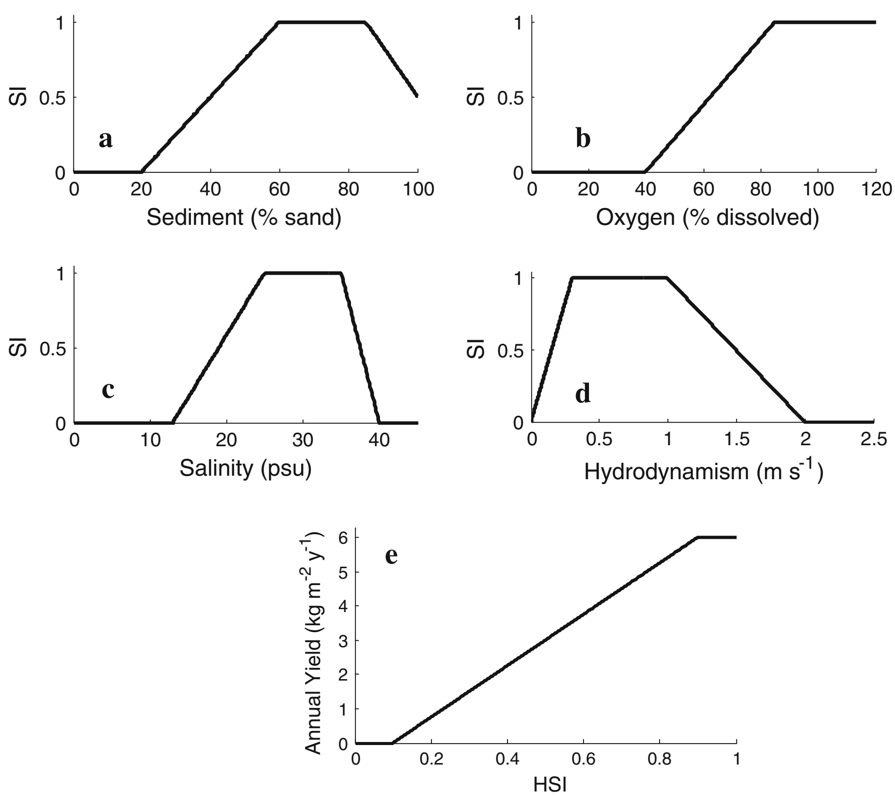
HSM is a two-part model combining a logistic model in which the response variable is the presence/absence of *T. philippinarum* and a weighted geometric mean model for the estimation of clam yield conditional on the presence of *T. philippinarum*. The two-part modeling framework is particularly useful when there is a relatively high presence of zero values in the dataset. This is usually the case when dealing with density or yield data of mollusks, as the presence of zero inflation is mainly linked to the patchy distribution of the organism and, in the case of aquaculture activities, to the "seeding" of young individuals. In the HSM model developed for the Sacca di Goro lagoon, Vincenzi et al. (2007) used Akaike Information Criterion (Akaike, 1974) to select the best model for the logistic part and a constrained regression to estimate the weights of the weighted geometric mean. The predictors for the logistic part of the HSM model were share of sand in the sediment, dissolved oxygen, and hydrodynamism (all continuous variables) (Vincenzi et al., 2007). The optimal cutoff value for transforming the continuous response from the logistic model in a binary output indicating the presence (1) or the absence (0) of *Tapes* in the Goro lagoon was determined from the Receiver Operating Characteristic (ROC) curve (Fielding & Bell, 1997).

For the logistic model for Caleri and Marinetta-Vallona, we kept the same predictors, parameters estimates, and cutoff value as reported by Vincenzi et al. (2007) for the Sacca di Goro lagoon, as the limited number of zero observations (i.e., absence of *Tapes*) in the dataset for Caleri and Marinetta-Vallona (see Section 2.4) did not allow either to select predictors using formal model selection procedures or to estimate the parameters of the logistic model.

In sites where the probability of occurrence was above the cutoff, the potential yield was estimated by applying the weighted geometric mean component of the HSM model using as predictors share of sand in the sediment, salinity, and hydrodynamism, as follows. First, we used the parameter-specific suitability functions *(PSSFs)* (Fig. 2) that assess the suitability of a given site with respect to each predictor (Paesanti & Pellizzato, 2000; Vincenzi et al., 2006a). For each predictor, suitability is expressed in terms of a Suitability Index (*SI*) ranging between 0 (non-suitable habitat) and 1 (most suitable habitat).

Then, the parameter-specific suitabilities, obtained by applying the $PSSF_i$ ($i = 1,\ldots,3$) to environmental data, were aggregated using a weighted geometric mean to compute a site-specific Habitat Suitability Index (*HSI*) for *T. philippinarum*, that is,

Fig. 2 *PSSFs* showing the relationship between model variables and *SI*: **a** sediment, **b** dissolved oxygen, **c** salinity, and **d** hydrodynamism. **e** Relationship between overall HSI and annual potential yield of *T. philippinarum*



$$HSI(x,y) = \left(\prod_{i=1}^{3} SI_i(x,y)^{w_i}\right)^{1/\sum_{i=1}^{3} w_i} \quad \text{with } w_i \geq 0, \tag{1}$$

where w_i are the weights defining the relative importance of each SI_i and *(x,y)* the geographical coordinates of the site.

Finally, we estimated commercial yield by applying (Vincenzi et al., 2006a)

$$E(Y) = \begin{cases} 0 & \text{if HSI} \leq 0.1 \\ 6\left(\frac{HSI-0.1}{0.8}\right) & \text{if } 0.1 < \text{HSI} < 0.9\,, \\ 6 & \text{if HSI} \geq 0.9 \end{cases} \tag{2}$$

where $E(Y)$ represents the annual potential yield (kg m^{-2} year^{-1}). The maximum yield estimated for the Sacca di Goro lagoon was 6.25 kg m^{-2} year^{-1} (Vincenzi et al., 2006a), but according to the maximum yield observed in Caleri and Marinetta-Vallona lagoons and expert knowledge, a more conservative value of 6 kg m^{-2} year^{-1} was chosen for Caleri and Marinetta-Vallona.

To estimate weights of the geometric mean model, we obtained *HSI* values from density samples (see Section 2.4) by applying the inverse of Eq. 2.

Then, Eq. 1 was log-transformed to obtain the linear relationship:

$$\log HSI(x,y) = \sum_{i=1}^{3} w_i \log SI_i(x,y) \tag{3}$$

Weights w_i were then estimated by solving a constrained linear least-square problem with $w_i \geq 0$ and sum of weights equal to 1. To readily assess the relative importance of the different predictors, weights were then normalized as $w_i^* = w_i/\max(w_i)$.

The logistic model and the weighted geometric mean model were then combined to estimate the potential yield of *T. philippinarum* in the Caleri and Marinetta-Vallona lagoons, as follows. The potential yield was set to zero in the areas of the lagoon for which the probability of occurrence as predicted by the logistic model was below the cutoff value, while in the areas where the probability of occurrence was above the cutoff, the potential yield was estimated by applying Eqs. 1 and 2.

Model calibration and validation

We used density samples associated with habitat features ($n = 80$) as observational data for (i) the estimation of weights in the weighted geometric mean component of the HSM model and (ii) validation of the whole HSM model for the two lagoons. Given the limited sample size and in order to include temporal variation in the dataset, data from 2008 and 2009 for both Caleri and Marinetta-Vallona were pooled together; we thus developed a single model for the two lagoons. Since we log-transformed *HSI* values in Eq. 3, we used data for the estimation of weights for which *HSI(x,y)* > 0 ($n = 70$). The observational dataset (n) was randomly split in two parts: the calibration dataset ($n = 50$, from the 70 data points for which *HSI(x,y)* > 0) and the validation dataset ($n = 30$). The dataset included only a few samples with yield lower than 2 kg m^{-2} year^{-1} (Fig. 3).

The HSM model was validated on the validation dataset using R^2_{adj} with respect to the 1:1 line and mean absolute error as measures of predictive accuracy of the model. The model was then applied to the whole surfaces of Caleri and Marinetta-Vallona lagoons.

Results

We report the mean values of environmental parameters for Caleri and Marinetta-Vallona lagoons in Table 1. With respect to Caleri, Marinetta-Vallona has on average higher salinity, a higher share of sand in the

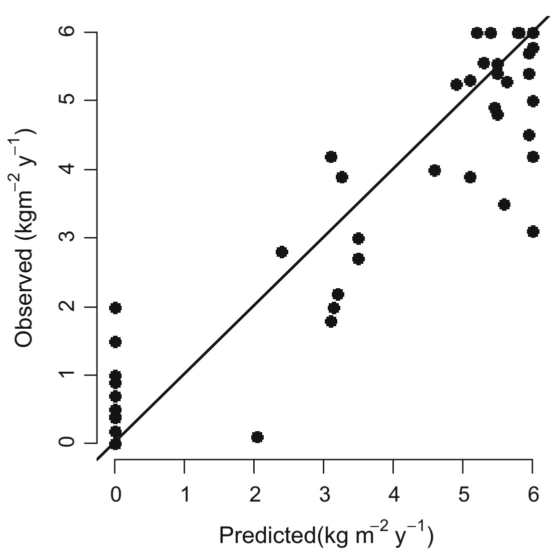


Fig. 3 Validation of the HSM on an independent dataset of yield data from Caleri and Marinetta-Vallona ($n = 30$). The HSM was able to explain 82% of the observed variation in productivity

sediment, and higher dissolved oxygen. We report estimates of the coefficients for the explanatory variables for the logistic part of the HSM model in Table 2.

Mean estimates of the normalized weights w_i^* of Eq. 1 obtained by constrained regression were as follows: sand content in the sediment = 0.53; salinity = 0.28; and hydrodynamism = 1. The estimated weights were very similar to those estimated in the Sacca di Goro lagoon (sediment = 0.5; salinity = 0.23; and hydrodynamism = 1). The model provided a good prediction of the observed yield in the validation dataset ($R^2_{adj} = 0.82$, Fig. 3), with a mean absolute error of 0.94 kg m^{-2} $year^{-1}$. The logistic model predicted all the observations with yield smaller than 2 kg m^{-2} $year^{-1}$ as area with no suitability for clam harvesting.

Maps of predicted potential yield of *T. philippinarum* in the Caleri and Marinetta-Vallona lagoons and a map reporting the range of predicted yields are shown in Fig. 4. The HSM model provided an estimate of potential yield of about 24,700 t $year^{-1}$ for the lagoon of Caleri and of about 23,900 t $year^{-1}$ for the lagoon of Marinetta-Vallona.

Discussion

Our paper shows the application of a rapid method for the estimation of potential yield of *T. philippinarum* in two data-poor North Adriatic lagoons. The total annual revenues for clam farming in North Adriatic are about 200 million Euros, and approximately one-fifth of the total North Adriatic production is from Caleri and Marinetta-Vallona (Turolla, 2008).

The two-part (HSM) model provided a good prediction of the observed yield in the validation dataset and it was thus used to predict the potential yield of sites within the Caleri and Marinetta-Vallona lagoons. Spatial distribution of potential yield within the Caleri lagoon, as predicted by the HSM model, is highly heterogeneous, while almost the whole Marinetta-Vallona lagoon presents optimal conditions for clam harvesting. Our analyses show that the potential yield predicted by the model by also including the areas outside the sites currently farmed could theoretically be around 24,700 t $year^{-1}$ for Caleri and 23,900 t $year^{-1}$ for Marinetta-Vallona. In intensively exploited lagoons, studies have shown that the clam harvesting methods based on sediment dredging as well as the high clam densities caused by excessive seeding of juveniles jointly contribute to oxygen depletion, high nitrogen loading, and consequent massive clam mortalities (Bartoli et al., 2001). Thus, it is unlikely that the potential yield predicted by the HSM model can be maintained over time, and our estimates should be considered a theoretical maximum yield.

The ideal management model should rely on a few key variables, with the time spent on data collection, laboratory analyses, and data integration being compatible with the request of managers or decision makers. An important—although often overlooked—aspect of the development and application of models in data-poor contexts is the identification of which variables should be prioritized in data collection and/or modeling. The HSM model uses only four environmental variables, namely, salinity, share of sediment type, hydrodynamism, and dissolved oxygen, which are typically sampled in monitoring programs of coastal lagoons even in data-poor contexts.

Table 1 Basic statistics of environmental variables sampled in the study areas

Variable	Caleri		Marinetta-Vallona		Vital limits	Optimal range
	Mean ± SD	Range	Mean ± SD	Range		
H (m s^{-1})	0.15 ± 0.1	0–0.3	0.3 ± 0.2	0–0.5	0.1–2	0.3–1
S (psu)	31.2 ± 2.9	24–34	22.3 ± 5.6	14–33	15–40	25–35
Sd (% sand)	58.6 ± 28.5	12–89	71.2 ± 29.2	23–99	>20	>60
O (mg l^{-1})	8.8 ± 1.7	6–12	10.9 ± 1.4	9–14	>4	>8

H hydrodynamism, *S* salinity, *Sd* share of sand in the sediment, and *O* dissolved oxygen

Vital limits and optimal range refer to knowledge of experts of *T. philippinarum* farming in North Adriatic lagoons (Paesanti & Pellizzato, 2000)

Table 2 Estimates and standard errors of the coefficients for the explanatory variables for logistic part of the HSM model (Vincenzi et al., 2006b)

Parameter	Estimate ± SE
log(Hydrodynamism) (H)	3.66 ± 1.25
Share of sand in the sediment (Sd)	6.04 ± 3.09
Dissolved oxygen (O)	0.74 ± 0.28

Hydrodynamism was log-transformed to improve normality. Units of measure for variables as in Table 1 and Fig. 2. Cutoff value to predict the presence/absence was set at 0.5

The selection of the model variables and modeling approach (i.e., correlative or mechanistic) is among the most critical issues when developing species distribution models for species and ecosystem management. Wenger & Olden (2012) found that the lack of transferability of species distribution models is more common when predictors are not mechanistically linked to the response variable.

Vincenzi et al. (2011) used nine predictors (share of sand in the sediment, time of residence, hydrodynamism, turbidity, dissolved oxygen, salinity, water depth, temperature, and chlorophyll "a") to estimate productivity of *T. philippinarum* in the Venice lagoon using a Random Forest algorithm (Breiman, 2001). Vincenzi et al. (2011) found that share of sand in the sediment plays a major role in determining the potential yield of *T. philippinarum* in the Venice lagoon along with salinity and water depth. In the Venice lagoon, sites with water depth greater than 10 m were found to be not suitable for harvesting of *T. philippinarum*. In lagoons of the Po River delta, water depth is rarely more than 2 m and this allows for optimal growth and survival of *Tapes* (Paesanti & Pellizzato, 2000).

The weights derived by the constrained linear regression of Eq. 3 are similar to those estimated for Sacca di Goro (Vincenzi et al., 2007). For the three lagoons (Sacca di Goro, Caleri, and Marinetta-

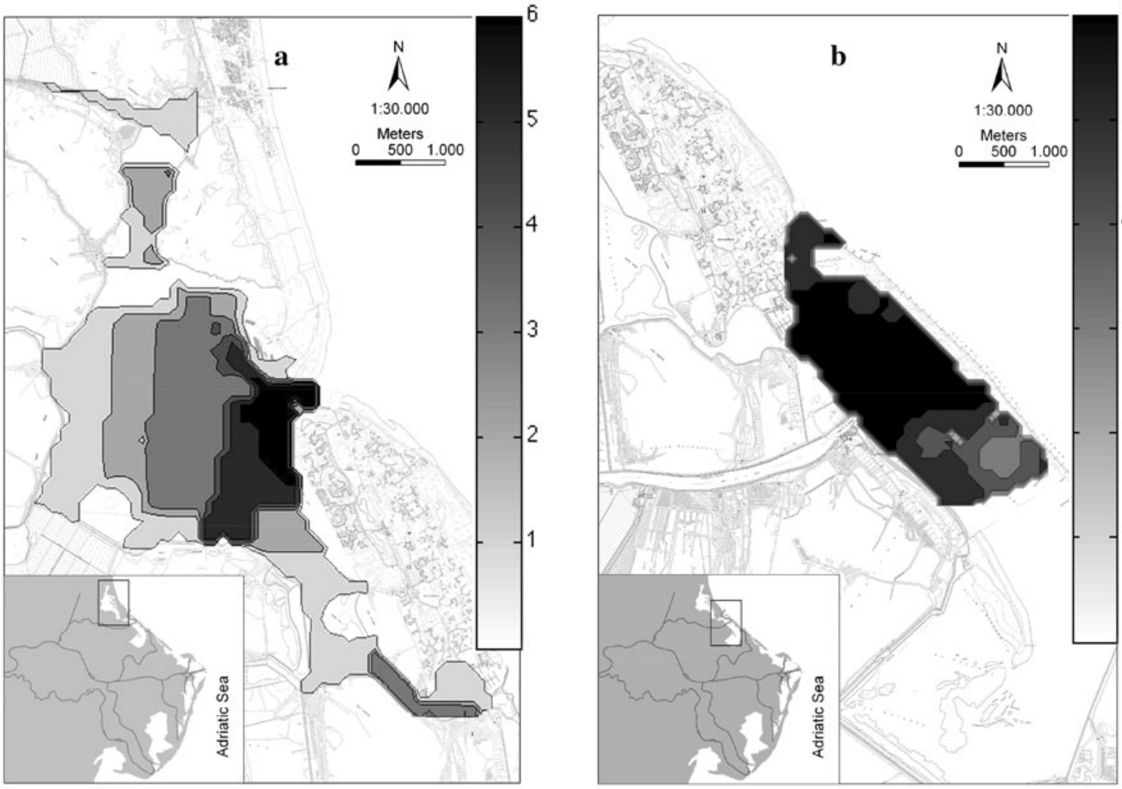


Fig. 4 Site-specific potential yield (kg m^{-2} year^{-1}) of *T. philippinarum* in the **a** Caleri and **b** Marinetta-Vallona lagoons as estimated by the HSM model

Vallona), hydrodynamism plays the most important role in determining within-lagoon spatial differences of potential yield. On the contrary, in the Random Forest model developed for the Venice lagoon by Vincenzi et al. (2011), hydrodynamism was the least important predictor of site-specific potential yield. This confirms the importance of a lagoon-specific estimation of at least some of the most critical parameters and suggests caution when scaling up from small lagoons like those in the Po River delta to big basins like the Venice lagoon. The HSM model presented here is based on well-studied processes linking environmental variables to the occurrence and growth of *T. philippinarum* (Paesanti & Pellizzato, 2000), and this, combined with the lagoon-specific estimation of a number of parameters, should increase its potential transferability. We did not explicitly include temperature in the model. While it is a crucial determinant of clam survival and growth (Paesanti & Pellizzato, 2000), temperature does not exhibit a sufficient spatial variation in the Caleri and Marinetta-Vallona lagoons to determine variability in clam potential yield.

Both mechanistic and correlative approaches are currently used to model species distribution (Buckley et al., 2010; Dormann et al., 2012). The main goal of the HSM model is the coarse-grained prediction of the spatial distribution of potential yield of *T. philippinarumi* within lagoons. On the other hand, process-based approaches have also been used to analyze optimal management strategies or to identify suitable rearing sites for *T. philippinarum* (Pastres et al., 2001; Solidoro et al., 2003). These process-based models, besides providing an estimate of species presence and abundance, can also address more fine-grained aspects, such as long-term sustainability of exploitation activities, effects of alternative rearing strategies (e.g., seeding size and density), and alteration of ecosystem processes with intensive rearing practices, including the dreaded risk of dystrophic crises and algal blooms (Bartoli et al., 2001). However, when a coarser-grained approach to aquaculture management is sufficient or recommended given time and resources, the HSM model (partially) calibrated on the available data can (i) provide information on site-specific potential yield, especially for areas outside the concession areas; (ii) suggest particular traits or processes to include in a mechanistic model and the need for additional sampling of critical variables; and (iii) guide the application of mechanistic models, for instance by limiting the costly application of computing-intensive mechanistic models to sites where potential yield is above a certain minimum threshold.

We are confident that the calibration and application of the simple HSM can prove to be extremely useful for objectively identifying the most suitable sites for aquaculture activities as well as supporting the sustainability of clam harvesting activities in coastal lagoons of the Po River delta where lack of data does not allow the full development of ad hoc species distribution models. More generally, we suggest to test in data-poor contexts whether the estimation of a small number of parameters (especially when predictors are mechanistically linked to the response variable) of models previously developed for and applied to similar environments (e.g., Sacca di Goro and Caleri/Marinetta-Vallona) is a viable alternative to the full development of an ad hoc model.

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