

# A stochastic bioeconomic model for the management of clam farming

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## Abstract

The Manila clam *Tapes philippinarum* is one of the most important commercial mollusc species in Europe. Intensive clam farming takes place in several coastal lagoons of the Northern Adriatic Sea, supporting local economy but raising the problem of the environmental sustainability of this activity. In this work, we propose a bioeconomic model that provides guidelines for an efficient management of intensive clam farming. Clam demography is described by a stochastic model of growth and survival, accounting for the effect of water temperature, seeding substratum and density dependence of vital rates. The model is calibrated on and applied to the case of Sacca di Goro, a lagoon located in the Po River Delta (Northern Italy). We consider two distinct management criteria: the optimisation of the marketable yield and the optimisation of monetary benefits, respectively. The use of a stochastic formulation allows us to reveal the existing trade-off between maximizing the median yield or profit and minimizing its variance. A Pareto analysis shows that seeding in spring or fall on sandy substrata and harvesting 18 months later provides the best compromise between these two contrasting objectives, maximizing profits while minimizing the associated uncertainty level. Finally, we show that seeding clams at high densities (more than 750 clams  $\text{m}^{-2}$  on muddy substrata and more than 1500 elsewhere) can have not only a potentially negative impact on the ecological sustainability of clam farming, but also a negative economic effect.

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## 1. Introduction

Effective management of mollusc farming is of crucial importance for both socioeconomic and ecological reasons. Intensive mollusc farming is indeed the basis of local economy in many coastal areas of Europe such

as, for example, the lagoons of the Northern Adriatic Sea in Italy. Since its introduction in the early 1980s, the Manila clam *Tapes philippinarum* has become one of the most important commercial species in Italy together with the mussel *Mytilus galloprovincialis*. Today, Italy is the major European producer of clams, and the third mollusc producer after Spain and France (FAOSTAT, 2004). Recent work, however, has shown that high densities of filter-feeding bivalves can have important

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impacts on the trophic status of coastal ecosystems affecting oxygen and nutrient dynamics, altering the structure of the phytoplankton community and stimulating macroalgal growth (Prins et al., 1998; Sorokin et al., 1999; Smaal et al., 2001; Bartoli et al., 2001). The production of Manila clams in the Sacca di Goro lagoon (Po River Delta, Northern Adriatic Sea), one of the major areas of intensive clam rearing in Italy, grew up to 16,000 t at the beginning of the 1990s, but a decline in productivity did occur in recent years and the current production is about 10,000 t (Rossi and Paesanti, 1992; Rossi, 1996; Solidoro et al., 2000). This phenomenon has been mainly ascribed to dystrophic events caused by extensive macroalgal blooms. High clam densities, however, like those observed in some areas of Sacca di Goro (in some cases exceeding 2000 individuals  $m^{-2}$ ), have been shown to have a detrimental effect on oxygen availability in the water column (Bartoli et al., 2001; Melià et al., 2003). In areas where clam fishing is not regulated, like the lagoon of Venice, further problems are caused by sediment resuspension due to extensive trawling, use of illegal fishing tools, and overfishing, while consumers' health is at risk because fishing may be performed in polluted zones (Pastres et al., 2001; Solidoro et al., 2003). Building reliable management models is fundamental to developing efficient and sustainable exploitation strategies for coastal ecosystems. Pastres et al. (2001) combined data about water pollution, bathymetry and trophism to build a suitability index for clam rearing in the lagoon of Venice. They also used a bioenergetic model (Solidoro et al., 2000) to estimate the productive potential of the different areas. However, their study was chiefly focused on the identification of the most suitable areas for rearing and did not analyse the bioeconomic aspects of the problem. Solidoro et al. (2003) developed a demographic model for the Manila clam and used it to evaluate the economic income associated with different fishing and rearing strategies. The deterministic formulation of the model, though, allowed the authors to provide only an estimate of the average performance of a given policy without information regarding the uncertainty of the forecasted benefits. When planning an effective exploitation of biological resources, this latter aspect is indeed of paramount importance. There is, in fact, a typical trade-off between maximizing the average productivity and minimizing its variability (see, e.g. the seminal work by Ricker, 1958, and the subsequent work

by Gatto and Rinaldi, 1976; May et al., 1978; Aanes et al., 2002). In this paper, we perform a bioeconomic analysis of clam farming based on a stochastic demographic model. We describe growth and survival of Manila clams using the model proposed by Melià et al. (2004) and consider two distinct management criteria: the optimisation of the marketable yield and the optimisation of monetary benefits, respectively. The use of a stochastic formulation allows us to associate a risk level with the estimates of the objective functions and to point out the existing trade-off between maximizing yield or profit in the average and minimizing its variability. We finally carry out a Pareto analysis to identify the seeding and harvesting policies that provide the best compromise between these two contrasting objectives.

## 2. Model formulation

### 2.1. Demographic model

The demographic model used in this work to describe growth and survival of *T. philippinarum* was presented in detail elsewhere (Melià et al., 2004). Water temperature and clam density were identified as the main drivers of the demographic rates. Here, we describe only the major features of the model which encompasses body growth and natural mortality.

Body growth is described by a modified von Bertalanffy (1938) model accounting for seasonal fluctuations of the Brody growth constant driven by water temperature. The mean instantaneous variation in shell length  $L$  is described as

$$\frac{dL}{dt} = k_T T(t)(L_\infty - L(t)) \quad (1)$$

where  $L_\infty$  is the asymptotic mean size,  $T(t)$  is the average temperature of the water column at time  $t$ , and  $k_T$  is a proportionality coefficient between the Brody growth constant and temperature. Temperature fluctuations are simulated using the sinusoidal curve proposed by Melià et al. (2003) for the Sacca di Goro lagoon:

$$T(t) = f \sin\left(\frac{2\pi}{365}(t + e)\right) + g \quad (2)$$

where time  $t$  is measured in days, with  $t=0$  corresponding to the first of January, and temperature is measured in  $^{\circ}\text{C}$ , with  $e = -114.74$  (phase),  $f = 9.76$   $^{\circ}\text{C}$  (maximum

temperature variation), and  $g = 16.35\text{ }^{\circ}\text{C}$  (mean annual temperature).

To account for spatial and environmental stochasticity, a random factor is then introduced in the integral over time of Eq. (1) as multiplicative noise. More precisely, the length increment in the time period  $(t_0, t)$  is given by

$$\Delta L(t_0, t) = \Delta \hat{L}(t_0, t, L_0) \exp(\varepsilon_L(t_0, t)) \quad (3)$$

where  $\Delta \hat{L}(t_0, t, L_0)$  is the mean length increment obtained by integrating Eq. (1) over the time interval  $(t_0, t)$ , starting from an initial length  $L_0$ , and  $\varepsilon_L(t_0, t)$  is a Gaussian random variable with mean zero and variance given by  $(t - t_0)\sigma_L^2$ . The variance increases with elapsed time because the logarithms of length increments in each elementary time unit follow a Brownian motion process. Three different parameter sets were estimated to describe clam growth on different substrata (sandy, intermediate and muddy).

The survival process is described by a model in which natural mortality is determined by the sum of a baseline mortality rate and a linear function of both clam density and water temperature, namely

$$\frac{dN}{dt} = -[\mu_0 + \mu_T T(t) + \mu_N N(t)]N(t) \quad (4)$$

where  $N(t)$  is the average clam density at time  $t$ ,  $\mu_0$  the baseline mortality,  $T(t)$  the average temperature of the water column at time  $t$ , and  $\mu_T$  and  $\mu_N$  are proportionality coefficients. A multiplicative noise is introduced in the integral over time of Eq. (4) to account for the effect of environmental stochasticity. Therefore, clam

density at time  $t$  is given by

$$N(t) = \hat{N}(t_0, t, N_0) \exp(\varepsilon_N(t_0, t)) \quad (5)$$

where  $N(t_0, t, N_0)$  is the mean clam density obtained by integrating Eq. (4) over the time interval  $(t_0, t)$ , starting from an initial density  $N_0$ , and  $\varepsilon_N(t_0, t)$  is a Gaussian random variable with mean zero and time-increasing variance  $(t - t_0)\sigma_N^2$ . Natural recruitment and dispersal are considered to be negligible compared to seeding and displacement operated by fishermen.

The model was calibrated on the basis of an extensive data set collected in the Sacca di Goro lagoon during 1993–1995 (Rossi, 1996). Parameter estimates for the growth and survival models, including noise variances, are reported in Table 1.

A Monte Carlo approach has then been used to derive probability distributions of clam length and density at various times following the seeding month. After generating random realizations of the stochastic processes  $\varepsilon_L$  and  $\varepsilon_N$ , the growth and survival models have been integrated numerically using the *ode45* function of Matlab (The MathWorks Inc.), which is based on an explicit Runge–Kutta (4,5) formula (Dormand and Prince, 1980). The models have been run over a 3-years horizon, recording length and density at monthly intervals. By performing a sufficient number of simulations (in this work, we have used 100 iterations, the number being limited by computational constraints), we have obtained histograms approximating the probability distributions of clam length and density, from which relevant statistics (percentiles, variance, coefficient of variation) can be easily derived.

Table 1  
Parameters of the demographic model

$k_T$	$0.89 \times 10^{-4}\text{ }^{\circ}\text{C}^{-1}\text{ d}^{-1}$ (mud) $1.40 \times 10^{-4}\text{ }^{\circ}\text{C}^{-1}\text{ d}^{-1}$ (intermediate) $1.45 \times 10^{-4}\text{ }^{\circ}\text{C}^{-1}\text{ d}^{-1}$ (mud)	Temperature coefficient of the growth model
$L_{\infty}$	50.60 mm (mud) 46.94 mm (intermediate) 54.64 mm (sand)	Asymptotic mean length
$\sigma_L$	$4.59 \times 10^{-2}\text{ d}^{-0.5}$ (mud) $4.84 \times 10^{-2}\text{ d}^{-0.5}$ (intermediate) $2.76 \times 10^{-2}\text{ d}^{-0.5}$ (sand)	Standard deviation of the noise term for the growth model
$\mu_0$	$3.55 \times 10^{-3}\text{ d}^{-1}$	Baseline mortality rate
$\mu_N$	$6.29 \times 10^{-6}\text{ ind.}^{-1}\text{ d}^{-1}$	Density coefficient of the survival model
$\mu_T$	$-2.17 \times 10^{-4}\text{ }^{\circ}\text{C}^{-1}\text{ d}^{-1}$	Temperature coefficient of the survival model
$\sigma_N$	$1.58 \times 10^{-2}\text{ d}^{-0.5}$	Standard deviation of the noise term for the survival model

## 2.2. Marketable yield

The yield associated with a given seeding policy can be simply forecasted by combining the growth and survival models. The standing biomass available at time  $t$ , after seeding  $N_0$  clams of length  $L_0$  at time  $t_0$ , is a random variable given by

$$B(t_0, t, L_0, N_0) = N(t_0, t, N_0) w(L(t_0, t, L_0)) \quad (6)$$

where  $N$  is the clam density at the end of the period ( $t$ ,  $t_0$ ) and  $w$  the weight of a clam.  $w$  has been estimated from the shell length by using the length–weight allometric relationship  $w(L) = 2.6 \times 10^{-4} L^3$  (Solidoro et al., 2000), where  $w$  is expressed in gram and  $L$  in millimeter. If harvesting is concentrated in time and removes all the biomass of a certain area at the end of a rearing cycle, the standing biomass coincides with the harvest. However, the benefits are spread over the time elapsed between seeding and harvesting. Also, the actual marketable yield depends upon the probability that clams have reached the minimum commercial size (25 mm in the Sacca di Goro lagoon). Assuming that all market-sized clams are harvested at the end of the period, the marketable yield per unit time is defined as

$$Y(t_0, t, L_0, N_0) = \begin{cases} 0 & \text{if } L(t_0, t, L_0) < 25 \\ \frac{N(t_0, t, N_0) w(L(t_0, t, L_0))}{(t - t_0)} & \text{if } L(t_0, t, L_0) \geq 25 \end{cases} \quad (7)$$

Assuming independence of the random noises affecting survival and body growth, one can derive the probability distribution of  $Y$  from the probability distributions of  $N$  and  $L$ . We do not write it down, because it is quite cumbersome. In practice, we derive the histograms of  $Y$  in any month  $t$  by randomly extracting a value of  $L$  and  $N$  from those obtained by stochastic simulation and calculating the corresponding yield.

## 2.3. Economic return

Estimating the marketable yield associated with different rearing policies can provide useful management information. However, yield is a rather poor indicator of socioeconomic sustainability, which can be better evaluated by calculating the net economic benefit associated to a given seeding and harvesting policy.

The revenue a fisherman can obtain by selling his harvest is easily calculated by multiplying the yield by the market price of clams. In principle, the selling price of clams is an increasing function of clam size. Hence, we can write revenues  $R$  as

$$R(t_0, t, L_0, N_0) = p(L(t_0, t, L_0)) Y(t_0, t, L_0, N_0) \quad (8)$$

where  $p(L)$  is the market price of 1 kg of clams of length  $L$ .

Rearing costs are the sum of fixed costs (e.g. seeding and harvesting costs) plus variable costs multiplied by the span of the rearing cycle:

$$C(t_0, t, L_0, N_0) = \sum_i c_{fi} + (t - t_0) \sum_j c_{vj} \quad (9)$$

where  $c_{fi}$  is the  $i$ th fixed cost and  $c_{vj}$  the  $j$ th variable cost. Profits at time  $t$ , as deriving from seeding  $N_0$  clams of length  $L_0$  at time  $t_0$ , are calculated simply as the difference between revenues and costs. As we did for yield, we must spread profit over the length of the rearing cycle. Therefore, we have finally calculated the profit per unit time as

$$\Pi(t_0, t, L_0, N_0) = \frac{[R(t_0, t, L_0, N_0) - C(t_0, t, L_0, N_0)]}{(t - t_0)} \quad (10)$$

The histograms of  $\Pi$  are thus derived by randomly extracting  $L$  and  $N$  at any month  $t$  from the results of the Monte Carlo simulations, determining the corresponding revenues and costs, and calculating the consequent profits.

## 2.4. Economic data

Information on local market prices were provided by Edoardo Turolla, a researcher of Centro Ricerche sui Molluschi (CRIM), a centre funded by the fishermen consortium of the Sacca di Goro (CoPeGo).

The selling price of marketable clams is currently about  $3.5 \text{ € kg}^{-1}$ , although it has varied recently between 3 and  $5 \text{ € kg}^{-1}$ . These figures are rather high with respect to what reported by Solidoro et al. (2003), but are representative of the market prices of the last 2 years (in fact, prices have nearly doubled since the introduction of the Euro currency). The minimum marketable size is 25 mm, but clams are usually harvested when they are about 35 mm long (equivalently,

100–120 pcs kg<sup>-1</sup>). To account for the higher market value of bigger clams, we describe the selling price (in € kg<sup>-1</sup>) as a piecewise linear function of clam size, namely

$$p(L) = \begin{cases} 0 & \text{for } L < 25 \\ 0.1L & \text{for } 25 \leq L < 35 \\ 3.5 & \text{for } L \geq 35 \end{cases} \quad (11)$$

Commercial hatchery spat is rarely used in Italy, where small clams are usually collected in natural nurseries due to the abundance of natural recruitment (Turolla, 1999). This does not mean, however, that the seed has no cost for fishermen. In fact, only a few fishermen participate in seed collection, and their work is then paid for by the other members of the cooperative to which they belong. Seed price is a function of seed size and the currently available amount of seed. Average prices range between 10 and 20 € kg<sup>-1</sup> for 8–10 mm long clams (4000–7000 pcs kg<sup>-1</sup>) and between 2 and 3 € kg<sup>-1</sup> for 20–25 mm clams (250–500 pcs kg<sup>-1</sup>).

The cost of a motor boat is about 10,000–15,000 €. In principle, this should be considered as a fixed cost. However, it can be amortised in about 10–15 years (the average life span of a boat) and can therefore be considered as a variable cost. Maintenance costs are about 10% of the total value of the boat, i.e. range around 1000–1500 € year<sup>-1</sup>. Each boat is used by two to three fishermen. The cost of fishing devices is about 300–600 € year<sup>-1</sup> per fisherman. The concession fee for the rearing field is about 250 € ha<sup>-1</sup> year<sup>-1</sup>, whilst guardianship costs can be evaluated around 550 € ha<sup>-1</sup> year<sup>-1</sup>. Costs for maintenance of the fields are almost negligible. Finally, packaging costs are around 8 € t<sup>-1</sup>.

### 3. Results and discussion

By running the bioeconomic model under different initial conditions, we are able to estimate yields and profits associated with different rearing policies. In principle, the decision variables would be four: seed size, clam density at seeding, and seeding and harvesting time. In fact, however, seed size is not a true decision variable, as it depends upon the current size of the spat collected by fishermen. The most common size of juveniles collected in natural nurseries (which is indeed also a usual size for hatchery spat) is about 10 mm. For

this reason, in all our simulations we have set the initial size at  $L_0 = 10$  mm. As for the length of the rearing cycle (difference between harvesting and seeding times), it would be impractical to consider cycles of any duration, as this would imply different seeding months in different years. Thus, we have considered only multiples of 6 months (namely 6, 12, 18 and 24). Since the demographic rates vary with the season, for 12 and 24-month-long cycles we have calculated the associated yield/profit over one cycle, while the yield/profit has been calculated over two cycles for 6 and 18-month durations. In fact, in this latter case, there is a 6-month difference in seeding time between even and odd cycles. An important factor in determining the values of the performance indices is sediment type, which, however, is not a decision variable, as it depends on the location of the rearing field allocated to each fisherman. Because of its major influence on clam growth and, hence, on productivity, we have run the model with the three parameter sets corresponding to the three sediment types considered, in order to evidence the different performances that can be obtained from different substrata.

A first, significant, difference between rearing on different substrata is the fraction of marketable yield. Fig. 1 shows the percent of clams attaining the minimum marketable size (25 mm), as obtained by simulating clam growth on different sediment types. When

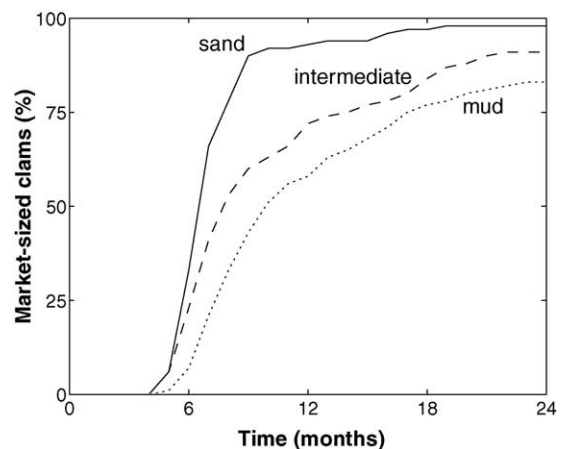


Fig. 1. Fraction of clams attaining the minimum marketable size (25 mm) as a function of time to harvesting and seeding substratum. Curves obtained by Monte Carlo simulation (100 iterations). Size at seeding: 10 mm; seeding month: January.



seeded on sand, most clams (93–100%) reach the marketable size within 1 year, and almost all (98–100%) attain it within 2 years. On intermediate sediments, the fraction is appreciably lower (depending upon the seeding month it ranges between 68–86% after 1 year and 83–94% after 2), and on mud it is even lower (52–69% after 1 year, 82–93% after 2).

As yield and profit are random variables obtained by Monte Carlo simulation, different statistics can be used to assess a given rearing policy. As an indicator of average performance we have chosen the median instead of the mean, because it is less influenced by extreme values and the stochastic model converges to the median trajectory as the number of simulations increases, whilst we have used the coefficient of variation (ratio of the standard deviation to the mean) to get a measure of the uncertainty of the yield/profit resulting from a certain policy. Figs. 2 and 3 illustrate the effect of changing seeding density and time on productivity and profitability, at a fixed length of the rearing cycle. Fig. 2 shows the performances of a 12-month rearing cycle on sand. In Fig. 3, the same results are shown for an 18-month rearing cycle. Yields increase (though less than linearly) for increasing seeding densities (Figs. 2a and 3a), whilst profits are highest for an initial density of about 750–1000 clams  $m^{-2}$  and decrease at higher densities (Figs. 2b and 3b). Intermediate densities appear to provide best results also with regard to profit variability as measured by the coefficient of variation (Figs. 2c and 3c).

Table 2 compares the maximum productivities associated with different substrata and different lengths of the rearing cycle. Seeding on sandy fields provides the best performances both in terms of median yield (productivity is almost double on sand than on mud) and yield variability (the coefficient of variation for sand is 50–70% lower than for mud). A length of the rearing cycle of 12–18 months seems to be the most appropriate regardless of the substratum. If the aim is to maximise yield, it is convenient to keep seeding density as high as possible (2000–2500 clams  $m^{-2}$ ). Notice that we did not contemplate seeding densities higher than 2500 clams  $m^{-2}$ , as their impact on the lagoon would certainly be unsustainable from the ecological point of view. As for the seeding period, spring and fall are the most suitable seasons, the best month depending upon sediment type and length of the rearing cycle.

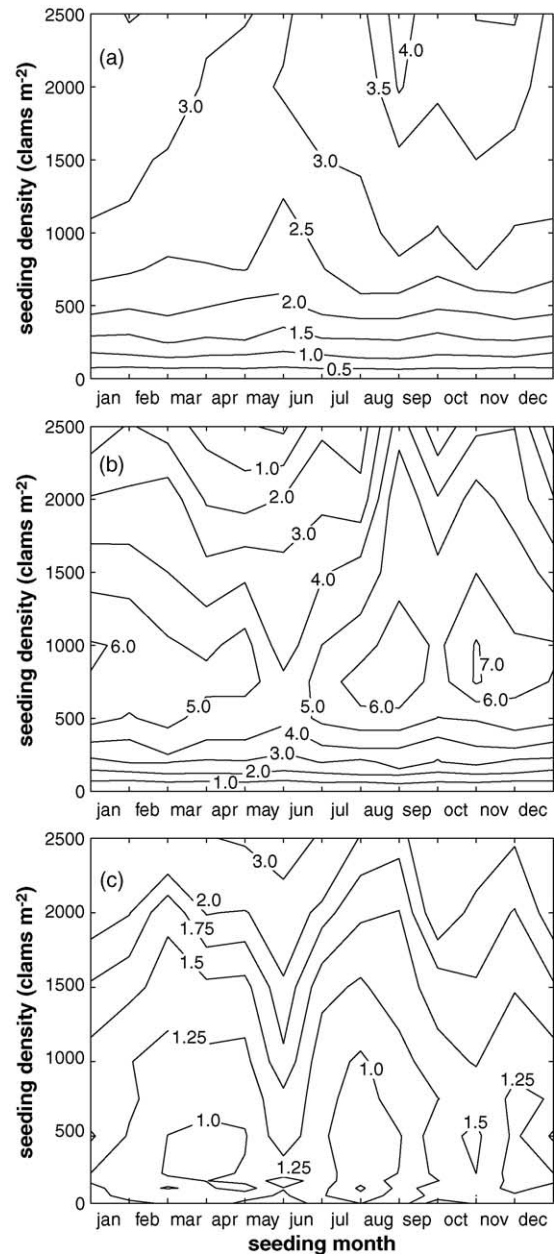


Fig. 2. Productivity and profitability of 12 month-long rearing cycles as a function of seeding month and density (substratum: sand). Contour lines of: (a) median yield ( $t\ ha^{-1}\ month^{-1}$ ); (b) median profit ( $10^3\ €\ ha^{-1}\ month^{-1}$ ); (c) coefficient of variation of the profit.

Table 2  
Productivity of rearing cycles of different length, by sediment type

Substratum	Cycle length (months)	Seeding density (clams m <sup>-2</sup> )	Seeding month	Median yield (t ha <sup>-1</sup> month <sup>-1</sup> )	CV
Sand	6	2500	April/October	3.87	0.66
	12	2500	September	4.24	0.77
	18	2500	March/September	3.67	0.66
	24	2000	November	2.89	2.16
Intermediate	6	2500	June/December	2.72	1.07
	12	2500	November	3.19	1.88
	18	2000	May/November	3.32	1.83
	24	2500	November	2.68	2.60
Mud	6	–	–	0	–
	12	2500	November	2.28	2.70
	18	2000	March/September	2.29	1.70
	24	2500	September	1.60	4.26

Seeding month and density are those maximising the median yield. CV: coefficient of variation.

Results in terms of profitability are reported in Table 3. Again, seeding on sand provides the best performances, with maximum profits being more than double on sand (up to more than 8000 € ha<sup>-1</sup> month<sup>-1</sup>) than on mud (less than 4000 € ha<sup>-1</sup> month<sup>-1</sup>). Sand also guarantees considerably lower uncertainty of the achievable profit. A length of the rearing cycle of 12–18 months seems again to be the most suitable, the best performances being provided by 18-month-long cycles (both higher profit and lower uncertainty). Spring (March–June) and fall (November–December) are, again, the best seeding periods. It is when identifying the best seeding densities that results become significantly different depending on the performance indicator that is chosen. High

clam densities at seeding, in fact, provide good performances in terms of yield, but do not in terms of profit. The most suitable density, if the aim is to maximise profits, is indeed around 500–750 clams m<sup>-2</sup>. Fig. 4 compares the performances (in terms of expected profit and associated variability) of seeding on different sediment types and in different periods at a fixed seeding density (750 clams m<sup>-2</sup> on sandy and intermediate sediments, 500 clams m<sup>-2</sup> on mud). It is apparent from the boxplot that the seeding season has indeed a minor influence on profitability if compared with substratum type. The maximisation of the median yield or profit alone, however, cannot be the only objective when planning a sound management policy. In fact, the uncertainty of the likely harvests or eco-

Table 3  
Profitability of rearing cycles of different length, by sediment type

Substratum	Cycle length (months)	Seeding density (clams m <sup>-2</sup> )	Seeding month	Median profit (10 <sup>3</sup> € ha <sup>-1</sup> month <sup>-1</sup> )	CV
Sand	6	500	May/November	2.15	1.63
	12	750	November	7.12	1.41
	18	750	May/November	8.56	1.08
	24	750	November	5.97	2.85
Intermediate	6	250	June/December	0.26	3.72
	12	750	November	4.60	2.95
	18	750	June/December	6.96	2.62
	24	750	November	5.49	3.36
Mud	6	–	–	<0	–
	12	500	November	1.38	3.50
	18	500	May/November	3.58	2.83
	24	500	March	2.36	3.02

Seeding month and density are those maximising the median profit. CV: coefficient of variation.

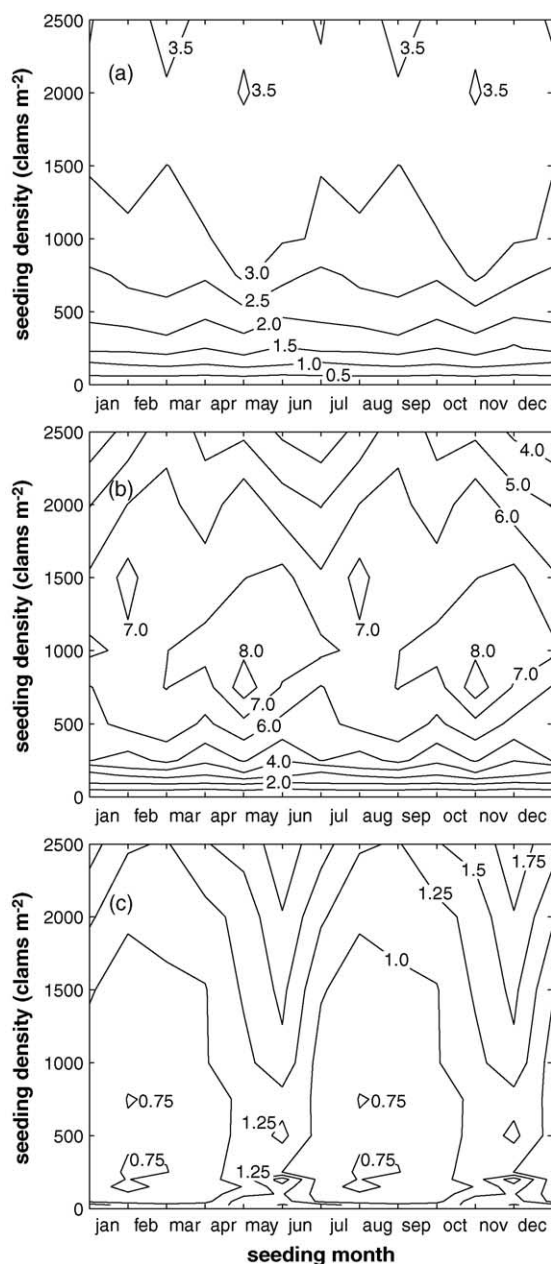


Fig. 3. Productivity and profitability of 18 month-long rearing cycles as a function of seeding month and density (substratum: sand). Contour lines of (a) median yield ( $\text{t ha}^{-1} \text{ month}^{-1}$ ); (b) median profit ( $10^3 \text{ € ha}^{-1} \text{ month}^{-1}$ ); (c) coefficient of variation of the profit.

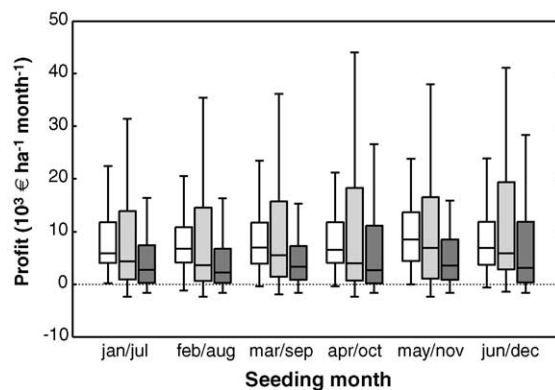


Fig. 4. Comparison between profitability of 18 month-long rearing cycles corresponding to different substrata and different seeding periods. Boxes identify quartiles and median, whilst whiskers extend to the most extreme data values within the  $1.5 \times$  interquartile range of the box. Seeding density is set to profit maximising levels for each substratum:  $750 \text{ clams m}^{-2}$  for sandy (white boxes) and intermediate sediment type (light gray),  $500 \text{ clams m}^{-2}$  for mud (dark gray).

conomic benefits is also an important performance index. To guarantee the socioeconomic sustainability of the rearing activity, slightly lower, though less variable, incomes could be preferred to higher median profits, achievable at the cost of a higher level of variability. To find out the rearing policies providing the best compromise between the two contrasting objectives of maximizing median yield/profits and minimizing the associated coefficient of variation, we have performed a Pareto analysis (Keeney and Raiffa, 1993). We have, thus, excluded all those policies that are Pareto dominated, i.e. such that there exists another feasible policy that is associated with both a higher productivity indicator (median yield/profit) and a lower uncertainty indicator (coefficient of variation of yield/profit). The non-dominated policies make up the so-called Pareto set, which is the set of optimal policies with respect to the two objectives. We have run two distinct analyses for each of the three sediment types, first using yield and then considering profit as an indicator of performance. Results of the Pareto analysis are shown in Tables 4 and 5, and are summarised in Fig. 5. Table 4 and Fig. 5a report the optimal policies (seeding month and density, cycle length, yield and coefficient of variation) obtained by optimising yield, while Table 5 and Fig. 5b show the Pareto sets obtained by optimising profit. The shape of Pareto boundaries indicates a clear trade-off between maximising median productivity



Table 4

Optimal rearing policies (Pareto sets) with respect to the two objectives of maximising median yield and minimising yield variability (coefficient of variation, CV), by sediment type

Substratum	Seeding month	Cycle length (months)	Seeding density (clams m <sup>-2</sup> )	Median yield (t ha <sup>-1</sup> month <sup>-1</sup> )	CV
Sand	August	12	150	1.05	0.52
	February/August	18	150	1.10	0.53
	August	12	750	2.86	0.54
	August	12	2500	3.34	0.54
	February/August	18	1500	3.35	0.55
	February/August	18	2000	3.36	0.58
	March	12	2000	3.40	0.60
	March/September	18	2000	3.45	0.63
	May/November	6	2500	3.76	0.66
	April/October	6	2500	3.87	0.66
	September	12	2000	4.06	0.70
	September	12	2500	4.24	0.77
Intermediate	June/December	6	750	1.82	1.05
	June/December	6	1500	2.22	1.06
	June/December	6	2500	2.72	1.07
	June/December	18	1000	2.78	1.23
	June/December	18	2500	3.18	1.29
	June/December	18	2500	3.18	1.29
	June/December	18	1500	3.20	1.31
	June/December	18	2000	3.30	1.37
	May/November	18	2000	3.32	1.83
Mud	March	12	1000	1.30	1.25
	March	12	1500	1.40	1.38
	March	12	2000	1.49	1.42
	June	12	2500	1.66	1.46
	September	12	2000	1.85	1.54
	March/September	18	2000	2.29	1.70

Table 5

Optimal rearing policies (Pareto sets) with respect to the two objectives of maximising median profit and minimising profit variability (coefficient of variation, CV), by sediment type

Substratum	Seeding month	Cycle length (months)	Seeding density (clams m <sup>-2</sup> )	Median profit (10 <sup>3</sup> € ha <sup>-1</sup> month <sup>-1</sup> )	CV
Sand	February/August	18	150	3.13	0.64
	February/August	18	250	4.56	0.73
	February/August	18	750	6.76	0.74
	March/September	18	750	7.02	0.78
	February/August	18	1500	7.35	0.85
	May/November	18	750	8.56	1.08
Intermediate	June/December	18	150	3.22	1.29
	June/December	18	250	4.38	1.45
	June/December	18	1000	6.51	1.45
	June/December	18	1500	6.74	1.62
	May/November	18	750	6.96	2.62
Mud	March/September	18	150	1.84	1.74
	March/September	18	500	3.33	1.81
	May/November	18	750	3.44	2.66
	May/November	18	500	3.58	2.83

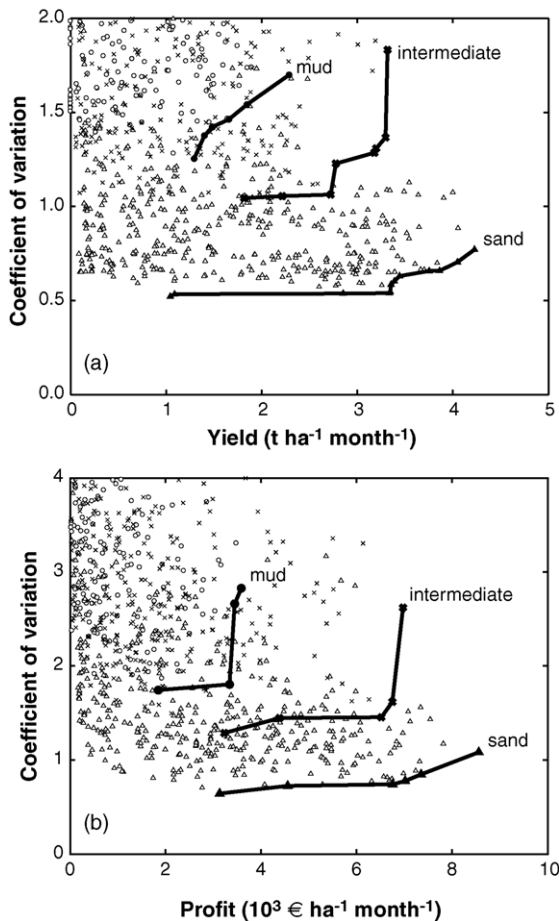


Fig. 5. Results of Pareto analysis with respect to: (a) maximising median yield vs. minimising yield variability; and (b) maximising median profit vs. minimising profit variability, differentiated by sediment type. Pareto sets are shown by points connected by solid lines, whilst small symbols identify non-optimal alternatives, differentiated by substratum (triangles: sand; crosses: intermediate; circles: mud).

and minimizing production variability. Which alternative should be finally chosen depends upon the relative weights that decision makers decide to assign to the two objectives. However, if there is an elbow of the Pareto boundary, alternatives on the elbow are usually considered to be best compromises, as they would be optimal under wide variations of the relative weights.

If we first consider the goal of optimising yield, we can notice that the set of Pareto options is quite wide. When clams are reared on sandy bottoms, there

is no clear elbow in the Pareto boundary; in most cases the best length of the rearing cycle is about 12–18 months and the optimal seeding density is between 1500 and 2500 clams  $\text{m}^{-2}$ . The best seasons for seeding and harvesting are spring (February–May) and fall (August–November). Median yields vary from 1 to 4  $\text{t ha}^{-1} \text{ month}^{-1}$ , whilst coefficients of variation range between 50 and 80%. On intermediate substrata median yields are only slightly lower, but uncertainty is significantly higher. There is an elbow in the Pareto set and the corresponding alternatives are characterised by an 18-month-long cycle and June–December as seeding months. The most suitable seeding densities range between 1500 and 2500 clams  $\text{m}^{-2}$ . Seeding on mud is confirmed to be a poor option, as yields are scarce and affected by a high degree of uncertainty.

Instead, if the goal of optimising the net monetary return is considered, the set of optimal alternatives becomes appreciably narrower. Under any case, the optimal duration of the rearing cycle is 18 months. When clams are seeded on sand, the best seeding periods are February–March and August–September. Optimal seeding densities are quite variable ranging between 150 and 1500 clams  $\text{m}^{-2}$ , with lower densities generally, though not always, associated with lower uncertainty of profits. If rearing fields are located on intermediate to muddy substrata it would be better to delay seeding to May–June or November–December. There is a clear elbow in both Pareto sets. Therefore, for intermediate substrata, the two solutions on the elbow which correspond to seeding 1000 or 1500 clams  $\text{m}^{-2}$  represent the best compromise; for muddy fields, seeding 750 clams  $\text{m}^{-2}$  is apparently the best compromise. Profits vary from 2000–3500  $\text{€ ha}^{-1} \text{ month}^{-1}$  on mud to 3000–8000  $\text{€ ha}^{-1} \text{ month}^{-1}$  on sand. The coefficient of variation is comprised between 60 and 110% on sand, whilst it is more than double on mud.

#### 4. Conclusions

By coupling a stochastic demographic model with socioeconomic information, we have developed a realistic framework to evaluate the performances of different rearing policies (as defined by seeding time, cycle length and seeding density) for the Manila clam. The stochastic formulation of the demographic model allowed us to account for the effect of

environmental variability on the uncertainty of production and economic return. This information, not provided by deterministic models, can indeed be very valuable to formulate risk-averse management policies. The results of our study confirm that sandy sediments are the most suitable substratum for clam rearing. We have shown that seeding on sand provides not only the best performances in terms of yield and profit, but also that the uncertainty level is appreciably lower than that predicted for seeding on muddy substrata.

Density at seeding is an important decision variable. Shifting the attention from sheer biomass yield to profit as a performance indicator, we demonstrate that seeding large quantities of juveniles (more than 750 clams  $m^{-2}$  in muddy fields and more than 1500 clams  $m^{-2}$  elsewhere) can be disadvantageous not only because it has a detrimental effect on water quality and the ecosystem health, but also because it can be counterproductive from the economic viewpoint. In fact, it is most likely that density-dependent survival sets the upper limits of productivity in intensive bivalve farming (Melià et al., 2004).

The most suitable seeding periods are spring and fall, with slight variations depending upon the substratum and the seeding density. It is to be noticed, however, that the period comprised between summer and the beginning of fall is often subjected, in Northern Adriatic lagoons, to dystrophic crises characterised by low oxygen concentration. Evaluating the risk of hypoxia and its consequences on clam survival is not easy (but see Melià et al., 2003, for a preliminary assessment), however, if it were possible, it could perhaps help us in tuning the beginning of autumn rearing cycles more precisely. As for the duration of the cycle, the optimal one turns out to be around 18 months, regardless of the seeding substratum.

Finally, a Pareto analysis has helped us identify the rearing policies that provide the best compromise between the two contrasting objectives of maximizing median yield or profit and minimizing the associated uncertainty level. The analysis of Pareto boundaries shows that, in many cases, the most performing alternatives in terms of median yield/profit may be characterised by unacceptably high risk levels, thus suggesting that decision makers should prefer rearing policies that provide slightly lower, yet more reliable, future yields/profits.

In conclusion, we believe that the bioeconomic model presented here provides useful guidelines for the development of effective rearing strategies of Manila clams in Mediterranean lagoons. Furthermore, if suitably coupled with an ecosystem-level model of nutrient circulation and algal growth, it could provide crucial information about the sustainability of intensive clam rearing.

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