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Abstract: During the last twenty years the economic activity of clams exploitation has been intensively developed in the southernmost coastal lagoon of the Italian Po river delta, Sacca di Goro. Still, clam breeding is in danger because of frequent summer algal blooms, due to *Ulva rigida* macroalgae. These blooms cause anoxic crises leading clams to collapse, with a consequent deep impact on the whole economic sector of clams exploitation.

Several strategies have been developed to avoid the loss of commercial production, yet none of them has been assessed on a mathematical basis. In this work we develop a simple stochastic mathematical model of *Ulva rigida* growth to quantitatively evaluate the economic costs of algal harvesting and the related benefits in terms of avoided 'economic loss' of clams production due to an effective prevention of algal blooms. Algal growth is simulated by means of a discrete time difference equation of *Ulva rigida* biomass where the finite growth rate depends only upon water temperature. In order to explicitly include environmental variability, a seasonal autoregressive model calibrated on available data is used to simulate water temperature. By means of Monte Carlo simulations, different harvesting strategies are analysed in terms of the number of harvesting vessels employed and the threshold biomass of *Ulva rigida* at which vessels start to operate. In particular, with reference to previous works by the same authors, more realistic harvesting functions are estimated, taking into account the effects of reduced efficiency of the vessels in the case of low density of *Ulva rigida* biomass. Also costs of algal harvesting and disposal, as well as monetary damages resulting from the collapse of clam production as a consequence of algal blooms, are refined.

Keywords: Bioeconomic analysis; stochastic modelling; algal blooms management; *Tapes Philippinarum*

1. THE PROBLEM

Management of natural fish resources has been a traditional topic in ecology since World War I. During the last fifteen years, in Northern Italy a lot of effort has been put into effect to give new impulse to the economic activity of clam exploitation, after the great crisis of the late seventies led this market to ruin [Carrieri et al., 1992]. In most of the North-oriental Italian lagoons, in fact, the introduction of the exotic Manila clam *Tapes philippinarum* (Adams & Reeve, 1850) gave new hopes of large-scale exploitation. Nonetheless, the success of bivalve farming is threatened by the enormous nutrient load due to anthropic activities. The resulting eutrophication processes are characterized by frequent blooms of ephemeral macroalgae (*Ulva rigida*, from now on simply referred as *Ulva*), and the consequent anoxic crises cause massive bivalve mortality, dramatically reducing commercial yields.

With reference to this problem, a very interesting testing ground is represented by the Sacca di Goro, the southernmost lagoon of the Po river delta. The lagoon has a surface of about 26 Km^2, 10 Km^2 of which are exploited for the aquaculture of the *Tapes philippinarum*, sustaining about 1200 workers with a gross return of 15 million Euros per year. The Goro lagoon is characterized by anthropogenic eutrophication, due to high nutrient inputs from the Volano branch of Po river delta. While the high nutrient load has certainly improved clam yields (about ten thousand metric tons per year for one thousand farmed hectares), it is also responsible for the recurrent extensive algal blooms caused by the seaweed *Ulva*. These lead to dystrophic events and high mortality rates of benthic fauna [Viaroli et al., 2001]. In the last ten years several episodes of algal blooms occurred in Sacca di Goro,

pushing the lagoon managers to take actions aimed at reducing the risks of dystrophic crises. In order to avoid the economic losses due to anoxic crises, several short-term, allegedly cost-effective strategies were devised, such as the dredging of channels to improve water circulation and re-oxygenation or, alternatively, harvesting and disposing of macroalgal biomass (for a complete survey of these techniques, see Scheffer [1998]), but none of these strategies was evaluated on a quantitative basis. We understand that long-term, detailed studies of the lagoon system are required to provide biologically based reliable policies [Solidoro et. al, 1997]. On the other hand, lagoon managers require fast and cost-effective ways to preliminary assess the effectiveness of alternative scenarios of algal bloom control. To this purpose, we apply in this work a simplified methodology which neglects most of the complexity of biological phenomena, as it is aimed at quickly screening viable management strategies with a limited modelling effort.

The goal of this paper is to quantitative compare different algal harvesting strategies in order to find the most cost-effective one, considering both direct and indirect costs of intervention. In this sense we develop the proposals of De Leo et al. [2002], who drafted a method to evaluate whether inputs of algal blooms on intensive farming of *Tapes philippinarum* can be controlled by harvesting *Ulva* with special vessels; if so, to evaluate also whether this management strategy is also effective from an economic point of view. We are thus going to investigate if the costs of harvesting and disposing of *Ulva* biomass are more than compensated for the reduction of economic damages due to algal blooms.

The problem may be positively approached by developing a stochastic model based on a set of simple difference equations, which allows us: i) to simulate algal growth and blooms; ii) to explicitly consider the variability that typically characterises these environments and dramatically reduces the effectiveness and the predictive power of purely deterministic models [Hilborn, 1987]; iii) to include in the analysis the most important bioeconomic variables, in order to assess the economic performances of *Ulva* removal.

The initial proposals of De Leo et. al. [2002] have been thoroughly revised. With respect to that analysis, the original aspects of this work are mainly related to the predictor model for water temperature, to the definition of the harvesting function, to the identification of fixed and variable harvesting costs and to the simulation step in *Ulva* dynamics modelling. We will describe them in detail in the following paragraphs.

2. THE DYNAMICS OF ULVA GROWTH

2.1 Basic assumptions

A number of simplifying hypotheses has been made in order to match the goal of deriving a reasonably simple and sufficiently rapid procedure to assess the effectiveness and efficacy of algae harvesting. Our biological model of *Ulva* growth, in fact, might be seen as "black-box" one, focused on the reproduction of the frequency and seasonal pattern of algal blooms, instead of the biology underlying them.

According to data provided by Viaroli et al. [1996], the finite growth rate $\lambda(T)$ has been assumed to be an unimodal function of water temperature T [°C]. Because of the lack of available data, as a first approximation, we have also assumed that no density-dependent mechanisms controlling *Ulva* growth occur at the densities at which the harvesting vessels will operate. This implies that nutrients are not considered as growth limiting factors, thus being available at a constant rate from year to year.

2.2 The biological model

Let A_t be the *Ulva* biomass (in grams of dry weight per square meter, $g\ m^{-2}$) on day t. With reference to traditional population ecology theories, the model of *Ulva* dynamics may be represented by the following equations:

$$(1) \quad A_{t+1} = \begin{cases} \lambda(T_t)\, A_t & \text{if } A_t < 600 \\ \\ 0.2 & \text{if } A_t \geq 600 \end{cases}$$

where we have assumed that when algal density exceeds $600\ g\ m^{-2}$ a dystrophic crisis occurs with the consequent collapse of *Ulva* biomass. In fact, data reported by Viaroli et al. [2001] show that Ulva biomass reaches about 500-$700\ g\ m^{-2}$ in the days before algal collapse, and that collapse happens as a catastrophic event.

A formal validation of the biological model has not been performed yet; nevertheless, the model proved to predict algal blooms frequencies and patterns with a satisfactory level of precision (Chiara Naldi, personal communication).

Concerning the deterministic prediction of the average daily temperature $T(t)$, we used the seasonal sinusoidal model estimated by Melià [2001]. In order to take into account environmental variability, a stochastic model must be used instead of a deterministic one. To this purpose we use the extended version among the models suggested by Melià. This stochastic model also considers temperature autocorrelation among one day and the next one. If $x(t)$ is the difference between the observed temperature and the estimated one at time t, that is,

$$(2) \quad x(t) = T_{obs}(t) - T(t)$$

a simple autoregressive model of this difference might be

(3) $\qquad x(t+1) = \alpha \cdot x(t) + \varepsilon(t)$

where $\varepsilon(t)$ is a Gaussian term, with mean $\mu=0$ and standard deviation σ to be estimated. As the model is to be used according to an *a priori* approach, we cannot access the data of the temperature observed values. For this reason, we assumed the observed temperature is

(4)
$$T_{obs}(t) = \hat{T}(t)$$

Thus, the stochastic temperature model is

(5) $\quad \hat{T}(t+1) = T(t+1) + \alpha \cdot (\hat{T}(t) - T(t)) + \varepsilon(t)$

Again, the value of the parameter estimated on available data can be found in Melià [2001].
Using this model we expressly consider a seasonal regular pattern in temperature variation, and, at the same time, the typical high level of variability within and between years which characterises natural systems. We know, in fact, that potential algal blooms may occur with different frequency and at different times of the year, depending upon the actual pattern of the exogenous and stochastic driving forces.

3. THE MANAGEMENT ANALYSIS

3.1 The decision variables

Having derived a simple but representative demographic model of *Ulva* dynamics, we can use it to evaluate different management strategies. In the simplest case, two decision variables can define a specific management alternative:

- the number of harvesting vessels to be used in a given season
- the threshold density of *Ulva* biomass above which one or more vessels start to operate.

In fact, when *Ulva* biomass attains a very low density (<50 g m^{-2}), it is simply too costly to harvest it. On the other hand, if a vessel starts to operate when *Ulva* has already formed a thick layer on the lagoon surface and its growth is extremely fast, it might simply be impossible to avoid a massive algal bloom. Of course, the more vessels are used, the easier it is to control algal growth, but the higher the harvesting costs. Conversely, fewer vessels imply lower harvesting costs but a higher risk of mass blooms and anoxic crises with potentially catastrophic consequences and huge economic losses. The problem is obviously to find the optimal trade-off between these different components in order to minimise the overall management costs.

3.2 The management model

The harvesting strategy is based upon the definition of the model of the vessels operations, that is, upon the harvesting function H_t. We made the hypotesis that at each time t the lagoon manager checks the value of *Ulva* density A_t and then decides if the vessels have to operate or not: vessels operate all working day long (i.e. for eight hours) if the density A_t overcomes the threshold density A_{th}, otherwise they do not operate and *Ulva* is let free to grow according to a Malthusian dynamics. Moreover, vessels do not operate when density A_t is greater than 600 g m^{-2}, after which the anoxic crisis takes place and *Ulva* is naturally going to reach a value close to zero. Thus, the model of *Ulva* dynamics becomes:

(6) $A_{t+1} = \begin{cases} \lambda(T_t)\, A_t & \text{if } A_t < A_{th} \\ F(\lambda, A_t, H_t) & \text{if } A_{th} \le A_t < 600 \\ 0.2 & \text{if } A_t \ge 600 \end{cases}$

where H_t is the daily harvested biomass and F the harvesting function which takes into account both the phenomena of *Ulva* growing and harvesting. Harvesting H_t has been here assumed dependent upon the number of vessels operating (let it be E [*vessels Km^{-2}*]), their harvesting efficiency (let it be q [*ton day^{-1}*]) and Ulva density. Every vessel has been here assumed to have the same maximum harvesting capacity q (namely 100 metric tons of wet weight of *Ulva* per day and square kilometre, according to Viaroli & Sartore [1997]). The actual biomass harvested by a vessel is here represented by an increasing saturating function of *Ulva* density, namely

(7) $\qquad R(A) = \dfrac{\alpha \cdot A}{1 + \beta \cdot A}$

where the parameters α and β are respectively equal to 0.016 and 0.013.
To better follow the growing and harvesting process, the dynamics of *Ulva* is simulated on an hourly basis, during which biomass grows and it is harvested. Simulation is run for eight consecutive hours each day for which the average water temperature has been estimated by using (5). The hourly harvesting function H_h can be represented as follows:

(8) $\qquad H_h(A,E) = q' \cdot E \cdot R(A_h(t))$

where $A_h(t)$ is *Ulva* biomass at hour h of day t ($h=1..8$) and $q' = q/8$ is the harvesting efficiency on a hour basis
Beside the harvesting, *Ulva* keeps growing according to a Malthusian model, with a finite growth rate which is a function of the daily rate presented in (1)[1]. Thus the hourly model becomes:

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[1] As *Ulva* does not grow during the night, we can suppose the effects of the finite daily growth rate happen during eight hours, and simply re-scale it.

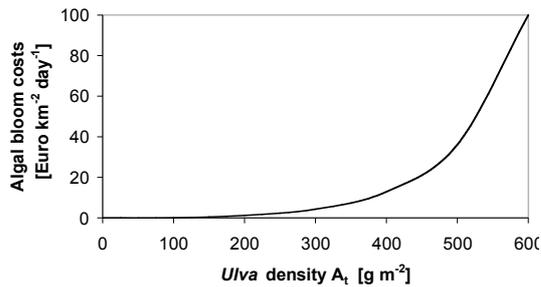$$(9) \qquad A_{h+1} = \lambda(T)^{\frac{1}{8}} \cdot A_h - H_h(A_h, E)$$

Figure 1 Algal bloom costs [Euro km^{-2} day^{-1}]

3.3 The estimation of costs

Information about management costs and economic losses due to algal blooms was obtained at Centro Ricerca sui Molluschi (an applied research center on mollusca culture supported by the Fishery consortium of Goro, CO.PE.GO.), and at the Environmental Office of Ferrara province, where a wealth of information concerning environmental quality and clam production in Sacca di Goro is regularly collected. According to these data, we have separately accounted for fixed harvesting costs and management harvesting costs. Fixed harvesting costs represent the annual rent of the vessels, labour costs (which refer to the whole season availability of two workmen per vessel) and all insurance costs, while management harvesting costs represent fuel costs, computed on a daily basis only if a vessel operates. Fixed harvesting costs have been evaluated in 100 thousand Euros per boat per year, while management harvesting costs are considered equal to 500 Euros per boat per day. The costs of biomass disposal are in the range of 50 Euros/ton of *Ulva* wet weight. Economic losses due to algal blooms are represented with the function estimated by De Leo et al. [2002], which assumes that no monetary damage to *Tapes philippinarum* yields occurs when daily algal densities are below 100 $g\ m^{-2}$ of dry weight, while losses peak at their maximum (100 Euros km^{-2} day^{-1}) when *Ulva* density exceeds $600\ g\ m^{-2}$ because of the massive clam mortality due to the consequent anoxic crises (see Figure 1). Annual damages are simply computed as the sum of daily damages, while total costs are obtained as the algebraic sum of algal bloom costs, biomass disposal costs, fixed and management harvesting costs.

3.4 The results…

For each given management strategy (number of vessels *E* and value of the *Ulva* density threshold) we analysed the economic performances over one year using a Monte Carlo stochastic approach [Manly, 1991], by which we can correctly take into account environmental variability.

We simulated the effects of different strategies making A_{th} values vary between 50 and 200 $g\ m^{-2}$, which respectively are the value under which vessels cannot detect *Ulva*, and the value occurring when most of the lagoon is covered with a thick layer of algae, making ineffective any kind of intervention of this kind. According to the Monte Carlo approach, every strategy has been simulated for one year and replicated 1000 times, and then statistical analyses have been performed on the output, in order to estimate expected costs and the corresponding standard deviations for each strategy. For each simulation, each individual repetition differs from the others in the daily temperature values, which, as we showed before, are extracted from the stochastic predictor model presented in (5). As an example, Figure 2 shows one of the trajectories we obtained with the $A_{th} = 50\ g\ m^{-2}$ and $E = 0.8$ *vessels Km^{-2}* strategy: in this case, the strategy is effective in controlling the summer algal bloom.
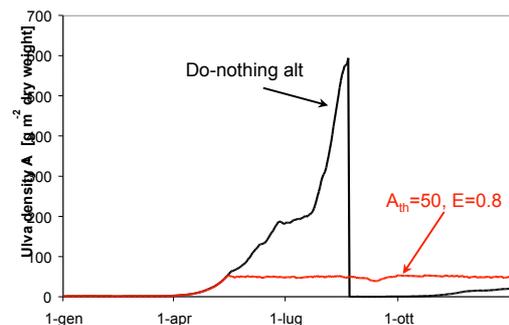

Figure 2 A possible trajectory of *Ulva* density

Some managing strategies, especially those corresponding to low level of threshold density for vessel intervention, are effective in controlling algal blooms provided that a sufficiently high number of vessels is used every year. This does not mean that this management strategy is also cost effective. In fact, as shown in Figure 3(a), total expected costs may skyrocket as a consequence of high fixed costs for vessel renting and high disposal costs of Ulva biomass. Examining Figures 3(b), 3(c) and 3(d) it is possible to understand the results of our simulations: if we use a high number of vessels (increasing with the threshold density) we will succeed in controlling algal bloom damages, even if with different rates of success. In the best cases the expected costs of blooms will tend to zero, in the worse they will tend to a value close to one third of that in the do-nothing alternative (see Figure 3(b)). The total amount of algae removed – and therefore their disposal expected costs – will reach a sort of a saturation level, slightly

diminishing (see Figure 3(c)), as well as expected harvesting management costs (see Figure 3(d)). However, to attain this result we need a great number of vessels, which causes expected fixed harvesting costs to sensibly increase. As a consequence, for large values of harvesting effort, the overall costs are an increasing function of the number of vessels (see Fig. 3(a)).

On the other hand, using a very small harvesting effort, whatever A_{th} is, algal bloom control is not efficient: the harvesting costs, in fact, are not compensated by any benefit in clam exploitation. Apparently quite surprisingly, indeed, low harvesting effort strategies show higher bloom costs than the do-nothing alternative: this happens when harvesting is not able to control algal blooms, and for a certain period of time keeps *Ulva* density to intermediate values, after which the bloom inevitably occurs.

From the total expected costs viewpoint, thus, strategies with an intermediate harvesting effort must be preferred.

Let's now consider the threshold A_{th}: according to Figure 3(a), in terms of operative management our analysis shows that when *Ulva* biomass exceeds $100 \ g \ m^{-2}$ of dry weight any attempt to effectively control the algal bloom will be vain, unless the number of vessels is so elevated that total costs become higher than those of the do-nothing alternative. As total expected costs increase with the threshold value, the best strategy consists in acting as soon as possible, whenever *Ulva* starts being detected (A_{th} equal to $50 \ g \ m^{-2}$ of *Ulva* dry weight). In particular, one optimal strategy does exist, namely the $A_{th} = 50 \ g \ m^{-2} \ E = 0.8$ *vessels* Km^{-2} alternative (8 vessels for the whole Sacca di Goro). This option should almost halve expected total costs when compared to the do-nothing alternative. In this case, in fact, total expected costs would be equal to $(430 \pm 26) \ 10^3$ *Euros* $year^{-1} \ Km^{-2}$, while in the do-nothing alternative they would be equal to $(730 \pm 320) \ 10^3$ *Euros* $year^{-1} \ Km^{-2}$.

3.5 …and their reliability

We are currently working to quantify the effects of environmental variability regarding the stability and the goodness of the results obtained. By means of error bars, Figure 4 shows the entity of the uncertainties related to the total expected costs values for the simulations with the threshold A_{th} set to $50 \ g \ m^{-2}$. Our analysis shows that relatively high uncertainties (measured in terms of the standard deviation, which in some cases reaches the 50% of the total expected costs) happen when a low harvesting effort is used. These are chiefly due to bloom costs, as a low harvesting effort can effectively control algal blooms risk only in some cases, according to the environmental conditions.

4. CONCLUSIONS

The inclusion of a stochastic component in the model of algal dynamics is very important, as it allows us to explicitly consider in the economic analysis the effects of rare but potentially catastrophic events such as algal blooms and the consequent dystrophic crises (Hilborn [1987]). In this regard, the stochastic model provides a more conservative and safe strategy than a deterministic model as shown for other fisheries models by Clark [1990].

In conclusion we point out that, according to our main purpose, our results were obtained in a relatively rapid and easy way, with limited sets of data and analysis effort, thus satisfying the pressing demands of the lagoon managers. Needless to say, we are aware of the limits of our analysis and of the need for a validation of the biological model, in order to be able to apply our results to real management problems.

Most important, our results need a thorough review concerning the estimates of the parameters of the cost functions, for which we have planned a sensitivity analysis. This will be helpful in refining our evaluations concerning the goodness of the choice of the optimal strategy, also with respect to the effects of environmental variability. We are currently working to extend *Ulva* life cycle model in order to explicitly include density-dependent phenomena and nutrient dynamics; we intend to compare as soon as possible these extended results with those derived using more detailed and sophisticated mathematical models of the Sacca di Goro lagoon.
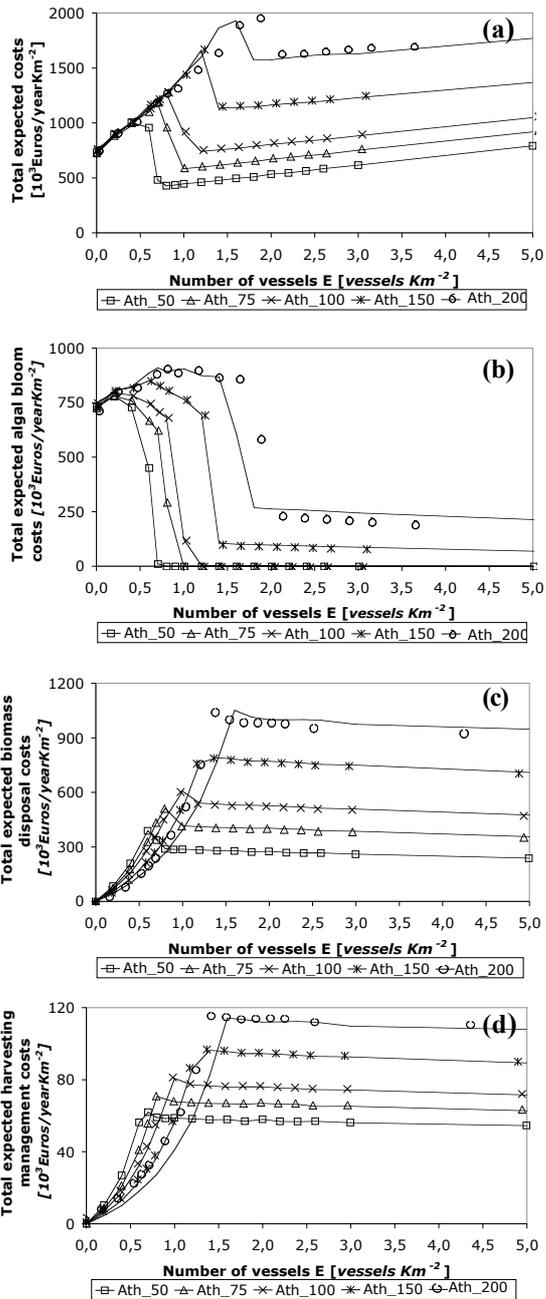
5. ACKNOWLEDGMENTS

Figure 3 Expected costs under different management strategies: **a)** Total costs, **b)** Algal bloom costs, **c)** Biomass disposal costs, **d)** Harvesting management costs
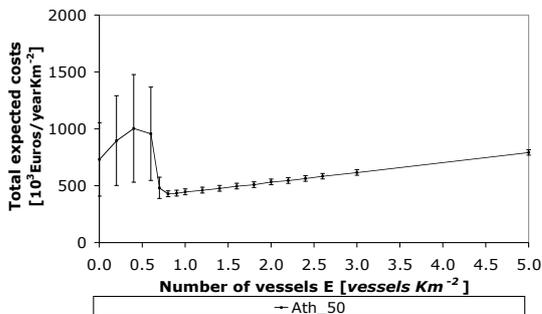

Figure 4 The total expected costs and their standard deviation with the threshold A_{th} equal to 50 $g\ m^{-2}$

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