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MACROALGAE HARVESTING POLICY BASED ON A FUZZY CRITICALITY INDEX

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The Orbetello lagoon is a fragile ecosystem where the growth of vegetation must be controlled to avoid anoxic crises. This paper propose a harvesting policy, based on a previously developed ecological model, which takes into account both the environmental quality and the harvesting effort. Having defined a fuzzy water quality index, several harvesting schemes are compared through model simulation in order to select the best procedure from both an environmental and economic viewpoint.

INTRODUCTION

The Orbetello lagoon, located along the Tyrrhenian coast in central Italy, is composed of two communicating shallow coastal basins with a combined surface of approximately 27 km^2. Its hydraulics and nutrient loading make it a fragile environment exposed to the risk of eutrophication [1]. The submersed aquatic vegetation in the lagoon is composed of macroalgae and macrophytes. Macroalgae tend to form dense mats and absorb a large quantity of nutrients, eventually producing sudden blooms followed by anoxic crises, whereas macrophytes (*Ruppia)*, being rooted to the bottom play a key role in determining the oxidised or reduced state of the sediments, which is the primary factor controlling nutrient cycling [1]. Selective harvesting is therefore the key problem in the lagoon management and a mathematical model has been developed [2, 3] to describe the evolution of both vegetation groups and dead biomass as a function of environmental parameters.

Using this tool, this paper presents a selective harvesting policy based on a fuzzy criticality index to select the lagoon areas where harvesting of macroalgae is appropriate, not only in terms of current loading, but also considering the future biomass evolution and subsequent threat of anoxic crises. The harvesting policy takes into account several factors: the reaping effort in terms of boating and disposal costs, the necessity to preserve the *Ruppia* prairies, which exert a beneficial influence on water quality, and the uncertainty of meteorological conditions which influence the vegetation development.

This paper is a first attempt to build a decision support system to determine the most appropriate harvesting policy, with the validated model [3] providing the necessary long-range prediction capability required to answer the crucial "*what - if*" questions asked by the harvesting manager. After a brief summary of the lagoon model [3], the paper describes the structure of the decision support system, which hinges on the computation of a synthetic water quality indicator assessing the reaping effect. Several scenarios are computed with differing harvesting thresholds and the operational costs are computed in terms of working days and boating mileage for biomass collection. Then the optimal combination of environmental quality and harvesting costs is selected by a simple enumeration technique, given the (so far) limited number of simulated scenarios.

Structure of the ecological model

A comprehensive hydraulic-ecological model **LaguSoft 2** [3] was produced by integrating two pre-existing modules: ecological model **Lagusoft 1** [2] and the hydrodynamic model **Swamp** [4], which were previously used independently. Both models use a regular 100 x 100 m grid and operate as two interlocked modules. The **Swamp** module generates the velocity fields induced by the wind and the pumping scheme at the three inlets. These are then used in the ecological module **LaguSoft 1**, where each cell contains the kinetics of nutrients and their interactions with the submersed vegetation. The cell dynamics runs on an hourly basis to keep track of the circadian cycles, whereas the advection/diffusion model has a daily time-base, enough to account for mass transfer among adjacent cells. The velocity field is also used to compute the growth of *Ruppia* through seed dispersal and burial. In turn, the *Ruppia* density determines the Manning friction coefficients which act as a feedback to the velocity computation through **Swamp** for the next day.

The **LaguSoft 2** combined model [3] represents a considerable advance in two main aspects:

1. *Vegetation-dependent Manning friction coefficients*, which are modelled as a function of the *Ruppia* density with a feedback on the hydrodynamics;
2. *Seed dispersal and germination*, which are modelled with a fuzzy cellular automaton taking into account, among other factors, the varying Manning coefficients.

The structure of the integrated model **LaguSoft 2** is shown in Figure 1, where the outer loop is iterated daily, given the slower growth of the rooted plants with respect to hydraulic variability. The feedback paths provide a velocity field compatible with the development of the *Ruppia* prairies. The inner ecological loop (**LaguSoft 1**) is operated on an hourly basis to track the diel fluctuations of the vegetation dynamics.

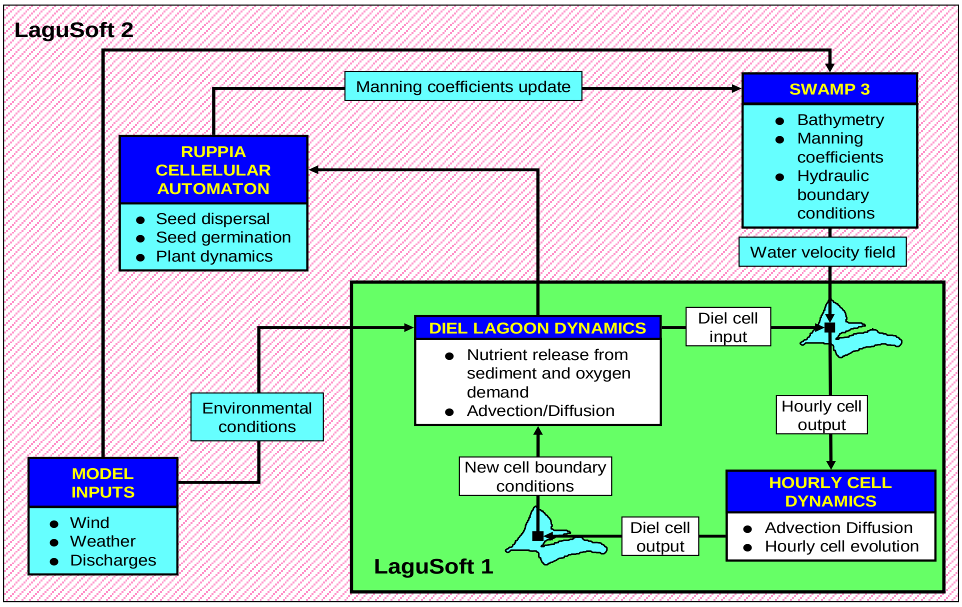


Figure 1 - Block diagram of **LaguSoft 2**, the software implementing the Orbetello lagoon quality model. In this context it is used to generate the system response to harvesting policies.

HARVESTING POLICY

The submerged vegetation is represented by three separate variables: macroalgae (M), *Ruppia* (R), and dead biomass (D). In the most productive months they are collected by special boats equipped with an upward-moving conveyor belt. Biomass is collected by ploughing through the vegetation canopy where the floating biomass (M and D) is retained by the rakes of the conveyor without affecting the rooted vegetation (R). The proposed harvesting policy is based on the daily model response to the environmental inputs (weather and loading data) and is active whenever the total floating biomass (M+D) exceeds a prescribed threshold in a minimum number of cells. When harvesting is active, the macroalgae (M) and the dead biomass (D) in the generic harvested cell (i,j) are reduced by a given percentage δ, so that the next-day values are computed as

$$M^{t+1}_{i,j} = M^{t}_{i,j} - \delta \frac{M^{t}_{i,j}}{M^{t}_{i,j} + D^{t}_{i,j}}; \qquad D^{t+1}_{i,j} = D^{t}_{i,j} - \delta \frac{D^{t}_{i,j}}{M^{t}_{i,j} + D^{t}_{i,j}}; \tag{1}$$

As a result, the vegetation density in the harvested cells is clamped to the prescribed level, as shown in Figure 2, where the inset shows the jagged evolution of biomass due to the alternating effect of growth and harvesting with $\delta = 20\%$. For comparison, the natural (no harvesting) evolution is also shown, demonstrating the effectiveness of early harvesting over the whole year evolution, particularly in avoiding the autumn peak.

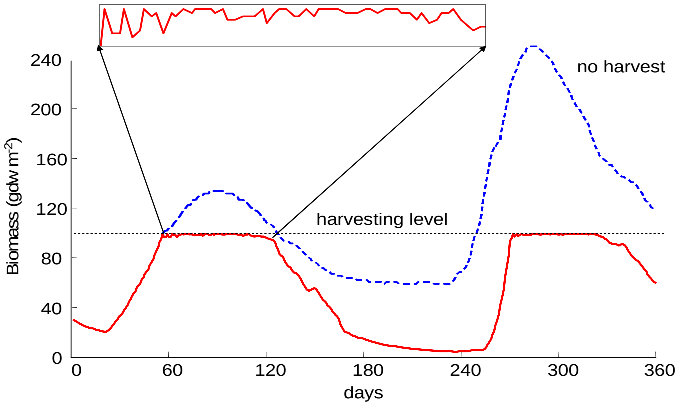


Figure 2. Effect of harvesting with a threshold of 100 (g dw m^{2}) on a generic lagoon cell. The inset shows the jagged evolution of biomass due to successive harvesting. The dashed curve shows the evolution of biomass without harvesting for comparison.

A fuzzy quality index

The effect of harvesting is evaluated along the simulation by the fuzzy algorithm described by the rules of Table 1. Based on the current density of the three vegetation species (M, R, D) the lagoon quality is assessed according to the fuzzy rules of Table 1, which implement a Mamdani fuzzy inference system [5, 6]. A similar approach has been adopted [7] for the management of the Manila clam farming in the Sacca di Goro, in the context of computer-based environmental management systems [8].

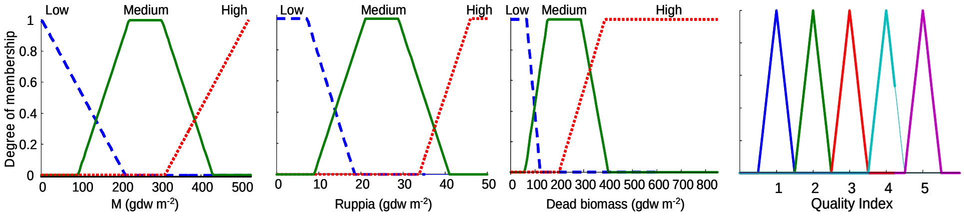


Figure 3. Inpout/output membership functions used to compute the Quality Index.

The rationale behind the rules of Table 1 is that the *Ruppia* is beneficial to the water quality whereas a high concentration of macroalgae and/or dead biomass is detrimental. Similar consideration lead to the specification of the following rules, which are less than the complete set of 3x3x3=27 rules. The fuzzy output is the quality index Q, which can assume any integer value in the $Z \in (1, 2, 3, 4, 5)$ set, representing the five quality classes with 1 being the best and 5 the worst.

Table 1. Set of fuzzy rules yielding the quality index.

1. If (M is low) and (R is low) and (D is low) then (Q is 1)
2. If (M is medium) and (R is low) and (D is medium) then (Q is 4)
3. If (M is medium) and (R is medium) and (D is medium) then (Q is 3)

4. If (M is medium) and (R is high) and (D is medium) then (Q is 2)
5. If (M is high) and (R is medium) and (D is high) then (Q is 4)
6. If (M is high) and (R is low) and (D is high) then (Q is 5)
7. If (M is low) and (R is high) and (D is low) then (Q is 2)
8. If (M is high) and (R is high) and (D is high) then (Q is 3)
9. If (M is low) and (R is low) and (D is medium) then (Q is 3)
10. If (M is low) and (R is low) and (D is high) then (Q is 4)
11. If (M is medium) and (R is low) and (D is high) then (Q is 5)
12. If (M is high) and (R is low) and (D is medium) then (Q is 4)

The quality index is obtained by rounding to the nearest integer the membership weighted average in the *Z* set

$$q_t(i,j) = round\left[\frac{\sum_{k \in Z} Q_k \mu_k}{\sum_{k \in Z} \mu_k}\right] \tag{2}$$

The Fuzzy Quality Index (FQI) is then computed over an yearly basis as the average of the 15-day average quality index $\overline{q}_t$ over the whole set of N_{cell} cell, i.e.

$$FQI = \frac{1}{24}\sum_{t=1}^{24} \overline{q}_t \quad \text{where} \quad \overline{q}_t = \frac{1}{N_{cell}}\sum_{i,j} q_t(i,j) \tag{3}$$

The FQI given by Eq. (3) is an "a posteriori" harvesting assessment, associating a figure of merit to a given policy over a one-year horizon, evaluated at 15-day intervals. However, the harvesting feedback shown in Figure 4 is active on a daily basis and the model is updated accordingly.

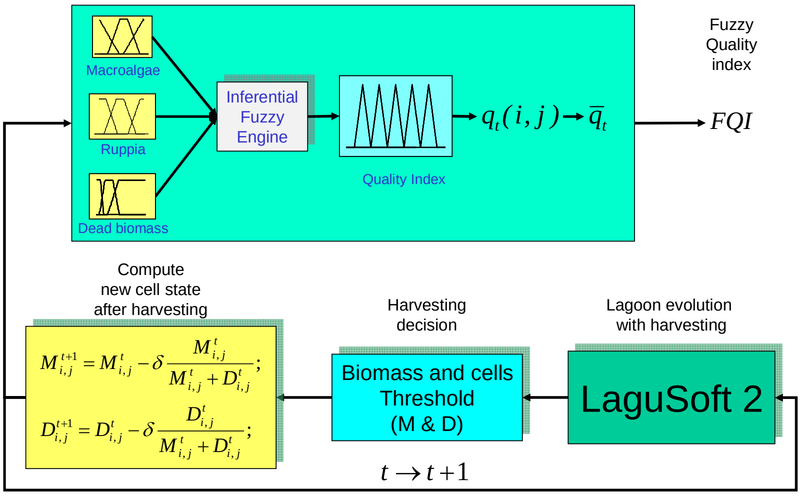
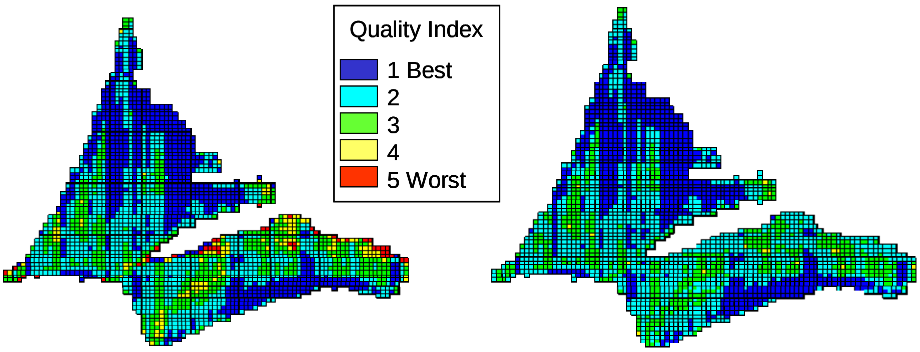


Figure 4. Lagoon evolution during harvest. The cell biomass is changed as a consequence of proportional harvesting before the control is reverted to **LaguSoft 2**. Meanwhile, the water quality index is computed to assess the quality improvement.

As an example of the water quality improvement due to harvesting, the FQI obtained with the policy S2 (see Table 2) is compared in Figure 5 to the no-harvest case. It can be seen that all the worst cells have been removed and several have been upgraded from FQI = 4 to 3. A more significant improvement could have been obtained at the expense of a larger harvesting effort. To determine the best compromise two further aspects have been included in the policy assessment in addition to FQI: the number of working days (W) and the total mileage (K) run by the boats in their daily rounds, assuming a maximum carrying capacity of 28 tonnes of wet weight per boat per trip.



Reference scenario: no harvest
$Q = 1.2695; W = 0; K = 0$

Harvest scenario S2
$Q = 1.2210; W = 134; K = 109$

Figure 5. Comparison of FQI in the natural case (no harvesting) and the harvesting scheme corresponding to the Scenario S2. It can be seen that all the cells in the worst class (5) have been improved to 4 and many have been upgraded from 4 to 3.

Assessing the harvesting scenarios

Three factors have been considered in ranking the harvesting policies: improvement in the Fuzzy Quality Index (FQI), total Working days (W) and total Mileage (K) to implement the policy. Six simulations were run, in addition to the base case of no harvesting, with differing thresholds and the results are grouped in Table 2.

To select the best option, a global figure of merit G was defined weighting the three factors in Table 2 with appropriate normalizing factors λ_1 and λ_2, i.e.

$$G = FQI + \lambda_1 W + \lambda_2 K \tag{4}$$

Figure 6 shows the ranking of the six scenarios, with S2 emerging as the best for the given normalizing factors $\lambda_1 = \lambda_2 = 0.005$.

Finally, Figure 7 shows, as an example, the harvesting paths for October 11 in the two lagoons with the computation of the working hours w_1 and w_2 and the mileage k_1 and k_2.

Table 2. Harvesting scenarios (FQI, working days W and mileage K) as a function of threshold specifications. The grey row corresponds to the preferred scenario.

	Scenario	FQI	W	K
S0	No harvest	1.2695	0	0
S1	S=100 g dw/m^2 in at least 1 cell	1.0983	226	340
S2	S=150 g dw/m^2 in at least 1 cell	1.2210	134	109
S3	S=100 g dw/m^2 in at least 5 cells	1.0985	168	319
S4	S=100 g dw/m^2 in at least 10 cells	1.0986	125	282
S5	S=100 g dw/m^2 in at least 15 cells	1.0989	100	247
S6	S=150 g dw/m^2 in at least 10 cells	1.1913	98	221
S7	S=150 g dw/m^2 in at least 15 cells	1.2197	96	196

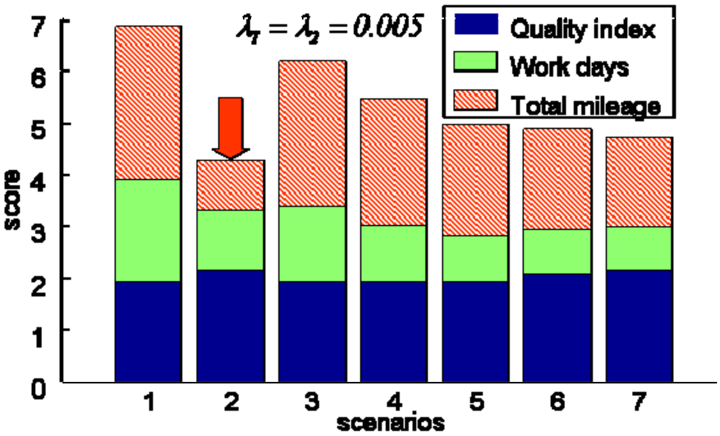


Figure 6. Comparison of scenarios in the search for the optimal solution, which appears to be S2 with the selected weights.

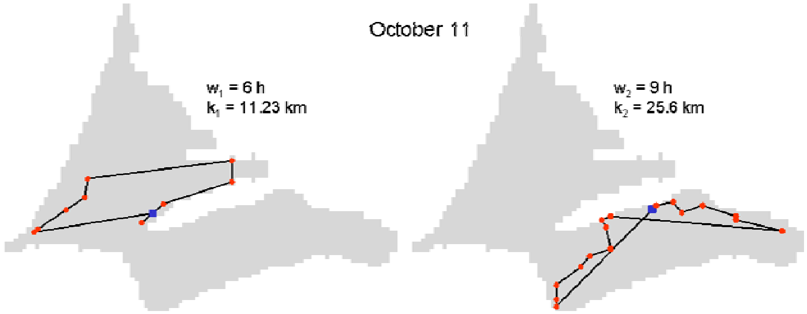


Figure 7. Harvesting paths for October 11. The dots indicate the harvested cells and the square is the docking point for the harvesting boats, one for each lagoon. The working hours are indicated as *w* and the mileage as *k*. The suffix refers to the western (1) and eastern (2) lagoon.

CONCLUSION

This paper has presented an algorithm to select the most appropriate harvesting policy to remove the floating vegetation from the eutrophication-prone Orbetello lagoon. The algorithm is based on an ecological model simulating the lagoon ecosystem coupled with a fuzzy quality index (FQI) assessing the improvement obtained with a given harvesting scheme. Several possible scenarios have been generated by simulation and a weighted performance index, including the harvesting effort in addition to FQI, has been defined to select the best compromise of water quality improvement and harvesting costs.

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