MODELLING AQUATIC VEGETATION DYNAMICS WITH FUZZY CELLULAR AUTOMATA

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Abstract: This paper describes the evolution in time and space of the submerged vegetation in a lagoon. This model was developed for the Orbetello Lagoon Management Office to predict the development of both macroalgae and macrophytes and test the actions to favour the latter. Based on a previous model describing the interactions between nutrients and the submerged vegetation, this paper presents a further improvement introducing a cellular automata to describe the dynamics of wigeongrass *(Ruppia maritima)* and a hydrodynamic model for the water movements. The link among them is represented by the dependence of friction coefficients from the vegetation density. *Copyright © 2005 IFAC*

Keywords: Cellular logic, fuzzy modelling, ecology, environmental engineering, water pollution.

1. INTRODUCTION

The Orbetello lagoon, schematically shown in Figure 1, is located along Italy's west coast. It consists of two shallow coastal reservoirs with a combined surface of approximately 27 km^2, an average depth of 1 m and is connected to the Tyrrhenian sea through one port at each end of the western lagoon and one at the south end of the eastern lagoon. The two lagoons are linked by a narrow passage under a bridge of the road connecting the little town of Orbetello with Mount Argentario. Two water-quality monitoring stations, indicated by the two circles in Figure 1, transmit hourly physicochemical data to the Orbetello Lagoon Managerial Office headquarters. The five squares indicate the major anthropogenic point-source pollution discharges. The main problem in the Orbetello lagoon is the control of the submerged vegetation, both in biomass and inventory, given the critical coexistence between macroalgae and macrophytes (wigeongrass). While macroalgae may cause dystrophic crises, macrophytes oxygenate and stabilise the sediment and thus control the nutrient flux into the water. The mathematical model, now named *LaguSoft*, is described in Giusti and Marsili-

Libelli (2005). It was developed to describe the evolution of both groups and test the actions to favour macrophytes over macro-algae and this feature makes it useful in the context of a decision support system to assess the effectiveness of macroalgae harvesting policies.
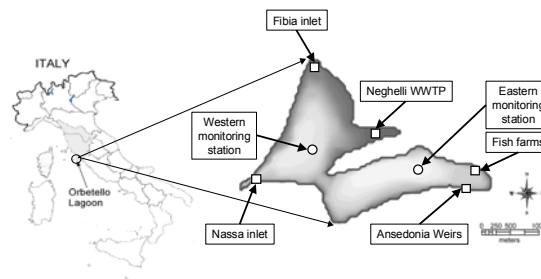

Fig. 1. General view of the Orbetello lagoon, showing the locations of the monitoring stations and the main discharge sites.

This model takes into account the interactions between nutrients and both groups of the submerged vegetation in a 2-D spatial context and interacts with a hydrodynamic model for the water movements, named **SWAMP** for **S**hallow **WA**ter **M**odelling

Program, whose original formulation is described in Covelli et. al. (2002). Both models (*SWAMP* and *LaguSoft*) use a regular 100 x 100 m grid and operate as two interlocked modules: each cell implements the kinetics of nutrients, vegetation and their interactions, running on an hourly basis to keep track of the circadian cycles, whereas the advection/diffusion model runs on a daily basis to account for mass transfer among neighbouring cells. The model output consists of daily variations in nutrient concentrations and vegetation biomass showing the relative abundance of either group as a function of environmental conditions. The mutual interactions between the hydraulic and ecological models are illustrated in Figure 2, showing that the Manning friction coefficients are the feedback elements linking the macrophytes development with the velocity fields, which in turn play a key role in seed dispersal and burial.

The model used in this study represents a considerable advance with respect to the original model (Giusti and Marsili-Libelli, 2005), in which the wigeongrass dynamics consisted of a growth and decay balance modulated by several environmental factors. In the new context the following additional factors have been introduced:

1. Vegetation-dependent Manning friction coefficients are determined as a function of macrophytes development and are used in turn to compute velocity fields;
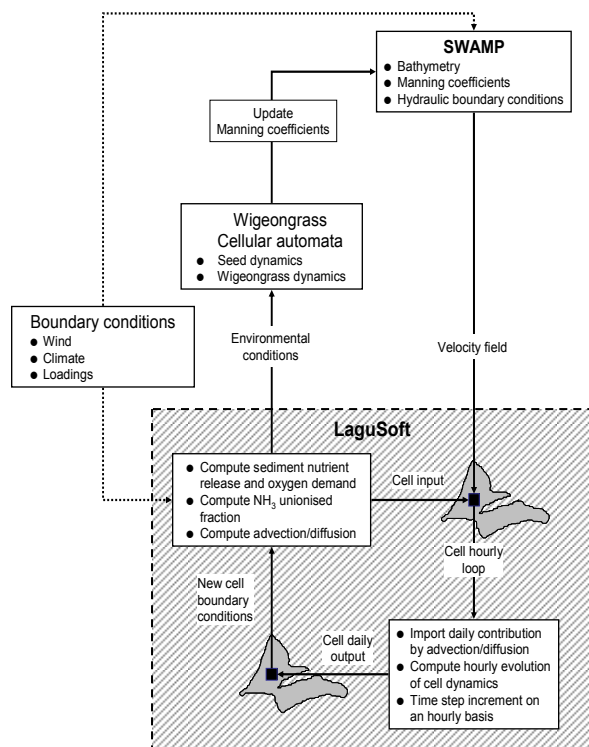

Fig. 2. Software engineering of the ecological model for the Orbetello lagoon.

2. The modelling of seed dispersal and germination has been modelled with a fuzzy cellular automata taking into account the main factors affecting seed fate: water velocity, pH, ORP.

3. A feedback path now exists between the hydrodynamic model **SWAMP** and the combination of the ecological model **LaguSoft** and the wigeongrass cellular automata through the computation of Manning friction coefficients. At the generic day the cellular automata computes the development of the wigeongrass prairie, which in turn determines the Manning friction coefficients to be used in the SWAMP model for the next day.

The combined model, illustrated in Figure 2, improves the accuracy of long-term predictions describing the propagation of wigeongrass prairies over several successive years.

The paper is organised as follows: after recalling the main features of the basic model, the ecology of wigeongrass is recalled with an emphasis on the elements which constitute the propagation mechanism. In the following section the mathematical details of the new wigeongrass dynamics are introduced and discussed, and in the last section some simulation results are presented.

2. THE SUBMERGED VEGETATION IN THE ORBETELLO LAGOON

The submerged aquatic vegetation in the lagoon is composed of macroalgae and macrophytes. Their differing physiological requirements tend to produce a mutual exclusion with either group colonising separate areas, depending on the local hydrology, water chemistry and sediment composition. Macroalgae, though of epiphytic origin, float in dense mats and absorb a large quantity of nutrients, eventually producing sudden blooms followed by dystrophic crises. On the other hand macrophytes, 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. Selective harvesting is therefore the key problem in the lagoon management and a mathematical model is required to describe the development of either group in time and space, indicating the location and extent of "hot spots" where pre-emptive harvesting may be beneficial.

The macroalgae species commonly found in the Orbetello lagoon are *Chaetomorpha linum, Cladophora vagabunda, Gracilaria verrucosa,* and *Ulva rigida.* They are well documented in the literature (Duarte and Ferreira, 1997; McGinty and Wazniak, 2002). Though their biological characteristics may be slightly different, in the sequel they will be globally referred to as macroalgae and modelled as a single state variable.

Macrophytes are represented in the Orbetello lagoon by *Ruppia maritima*, commonly known as wigeongrass. In the last few years this species has been expanding at the expenses of macroalgae, forming compact meadows (Di Biasi et al., 2003).

The ecology of the most common *Ruppia* species is well described in the literature (Calodo and Duarte, 2000; Touchette and Burkholder, 2000; da Silva and Asmus, 2001) and the characteristics described in those papers form the knowledge basis for the present model.

3. WIGEONGRASS PHYSIOLOGY AND ECOLOGY

Wigeongrass *(Ruppia maritima L.)* is a very common and widespread submersed macrophytes (a very thorough description can be found in Kantrud, 1991). In habitats such as the Orbetello lagoon the plant behaves as a perennial. It reproduces by releasing seeds (drupelets) at the top of emerged stalks. The dry weight of below-ground parts averages about 30-45% of maximum seasonal biomass. The below-ground biomass develops best at well-oxygenated sites in coarse-textured bottom sediments, which are low in free H_2S. In fact, complete degeneration of the root system can occur in very highly reduced organic sediments. The root system is delicate and unable to penetrate deeply into sediments. This makes the species susceptible to water turbulence.

4. CELLULAR AUTOMATA FOR WIGEONGRASS DEVELOPMENT

The basic growth and death mechanism underlying the vegetative cycle of wigeongrass, already included in the previous model, is here enhanced to take the form of a cellular automata (Balzter et al., 1997; Gronewold and Sonnenschein, 1998), including seed production, transport, burial and germination, as described in Sect. 3. In addition to the basic dynamics, the automata consists of a number of rules controlling the growth of *Ruppia* within the cell and seed dispersal if favourable conditions occur in adjacent cells. These conditions are determined by other model variables and are updated at each daily time-step.

A detailed ecological model for *R. chirrosa* was developed by Calodo and Duarte (2000) and for *R. maritima* by da Silva and Asmus, (2001). The sediment pH and ORP appear to have a primary influence on the establishment and development of *Ruppia* meadows, whose expansion in the last ten years has been accompanied by constant decline of macroalgae (de Biasi et al., 2003; Lenzi et al., 2003). The correlation between nutrients and submersed vegetation was also considered, following the reported link between total nitrogen and macroalgal volume (McGinty and Wazniak, 2002). For space reasons only the *Ruppia* section of the model is reported here, whereas the dynamics of nitrogen and macroalgae can be found in a previous paper (Giusti and Marsili-Libelli, 2005).

4.1 Basic wigeongrass growth dynamics

The wigeongrass dynamics is a balance between growth ρ and decay Ω_R, mediated by the nutrient cell quota N_{int}^R

$$\frac{dR}{dt} = (\rho - \Omega_R) \cdot R \qquad (1)$$

$$\frac{dN_{int}^R}{dt} = v_{NH_4}^R \cdot \frac{NH_4}{NH_4 + K_{NH_4}} \cdot$$
$$+ v_{NO_3}^R \cdot \frac{NO_3}{NO_3 + K_{NO_3}} - \rho_N \cdot N_{int}^R \qquad (2)$$

The specific growth rate in Eq. (1) is the product of four limiting factors

$$\rho = \rho_{max} \cdot g(d) \cdot f_R(T) \cdot f_R(N_{int}^R) \cdot f_R(R), \quad (3)$$

depending on photoperiod d

$$g(d) = 1 - \frac{1}{1 + b \cdot e^{a(d-f_o)}}, \qquad (4)$$

temperature T

$$f_R(T) = \frac{1}{1 + \left(\left(\frac{T - T_o}{c}\right)^2\right)^d}, \qquad (5)$$

density function R

$$f(R) = 1 - e^{-\left(\frac{R - R_{max}}{SL}\right)}, \qquad (6)$$

and internal nutrient quota N_{int}^R

$$f(N_{int}^R) = \frac{N_{int}^R - N_{min}}{N_{cri} - N_{min}}, \qquad (7)$$

whereas the decay is a function of temperature.

$$\Omega_R = SR \times \left(0.098 + e^{-6.59 + 0.2217 \cdot T}\right). \qquad (8)$$

Equations (1 - 8) describe the dynamics of the adult wigeongrass population in each cell of the lagoon.

4.2 Cellular automata for seed dynamics

Seed dispersal, burial and germination is modelled with a set of rules, depending on environmental conditions. The cellular automata approach is particularly suited to model the yearly evolution of wigeongrass, which tend to form long-term, rather compact colonies (prairies). It is supposed that as far as sexual reproduction is concerned, the scheme of Figure 3 represents the relationship between adult plants and seeds. The adult plants generate seeds with rate P_s, the seeds lie dormant until the next season when a fraction G generates new plants. Given the perennial nature of *Ruppia* in mild climates, the new plants increase the standing population according to the scheme of Figure 3. This, however, does not take into account the spatial dimension of seed propagation nor the influence of the environmental conditions in seed burial and germination. To link seed production to adult biomass and take into account seed dispersal, the following cellular automata is introduced, which considers seed transport by water movements as defined in Figure 3.
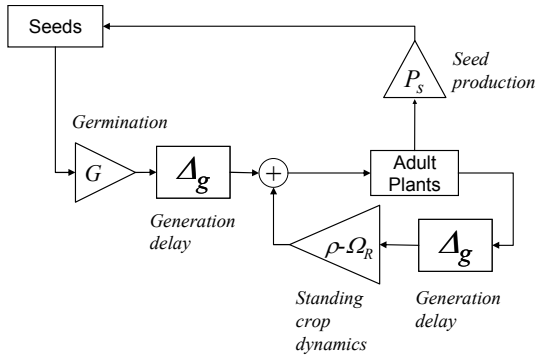
Fig. 3. Interaction between seeds and adult plants, including the generation delay Δg.

Equation (9) describing the seeds dynamics was derived directly in discrete-time form to fit into the daily module governing the cell evolution, with daily Δt time steps. In Eq. (9), $P_s R_{i,j}^t$ represents the seed production rate of the standing crop at time t in the (i,j) cell. The other terms model water transport, where the boolean parentheses account for the flow direction and the fact that seed deposition is possible only if the flow does not exceed a maximum shear velocity Φ, which is assumed here 0.02 m s^{-1} (McGinty and Wazniak, 2002).

Equation (9) is active only during the seed production period, which according to the physiology outlined in Sect. 3, lasts for about two weeks after flowering. From the modelling viewpoint, it is therefore assumed that Eq. (9) is activated when the total biomass is below 10% of the maximum vegetative peak and runs only for a limited number of days.

$$
\begin{aligned}
V_{i,j}S_{i,j}^{t+1} = {} & V_{i,j}S_{i,j}^t + \Delta t P_s R_{i,j}^t \\
& - \Delta t S_{i,j}^t A_x \left| u_{i,j} \right| \\
& - \Delta t S_{i,j}^t A_y \left| v_{i,j} \right| \\
& + \Delta t S_{i-1,j}^t A_x \left| u_{i-1,j} \right| \times \left(\Phi > u_{i-1,j} > 0 \right) \\
& + \Delta t S_{i+1,j}^t A_x \left| u_{i+1,j} \right| \times \left(-\Phi < u_{i+1,j} < 0 \right) \\
& + \Delta t S_{i,j-1}^t A_y \left| v_{i,j-1} \right| \times \left(0 > v_{i,j-1} > \Phi \right) \\
& + \Delta t S_{i,j+1}^t A_y \left| v_{i,j+1} \right| \times \left(-\Phi < v_{i,j+1} < 0 \right)
\end{aligned}
\qquad (9)
$$

At the end of this period the seed distribution is considered final and recorded into a matrix which is introduced as additional initial condition at the start of next year simulation, together with the existing standing crop at the end of the previous year.

4.3 Environmental conditions for seed germination

Other growth conditions regards the state of the sediment. Though no definitive results are available, from literature information and direct observations it can assumed that the main factors affecting seed burial and germination are the water velocity (Vel), Oxido-Reduction Potential (ORP) and pH. The known facts about soil fertility for wigeongrass seeds have been coded into a fuzzy inferential engine based on the following four rules (out of a possible 3x3=9 set of rules) of Table 1, which yield the germination likelihood of sowed seeds, using the

Fuzzy Logic Toolbox (Gulley and Jang, 1995) in the Matlab programming environment.

Table 1 Fuzzy rules for Soil Condition (SC).

R$_1$:	if pH is pH-high and ORP is ORP-high and Vel is Vel-low then SC is SC-high
R$_2$:	if pH is pH-low and ORP is ORP-low and Vel is Vel-high then SC is SC-low
R$_3$:	if pH is pH-medium and ORP is ORP-high and Vel is Vel-high then SC is SC-low
R$_4$:	if pH is pH-medium and ORP is ORP-medium and Vel is Vel-high then SC is SC-low

The result of these rules was then AND-ed with a seasonality function, representing the physiological time-window for seed germination (Calodo and Duarte, 2000). The complete inferential engine is then shown in Figure 4.
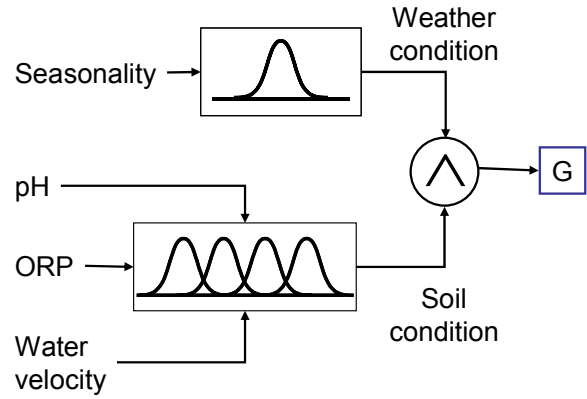

Fig. 4. Composite fuzzy inferential engine combining soil and weather conditions to obtain germination function G.

The implication surfaces resulting from the fuzzy rules of Table 1 are shown in Figure 5. The seed dynamics Eq. (9) and the fuzzy rules of Table 1 form the cellular automata which, together with Eqs. (1 - 8) form the wigeongrass dynamics.

To show the operation of the inferential engine, the 2002 weather data shown in Figure 5 were applied to the inferential engine, activating the individual rules of Table 1 as shown in. Figure 6.

After defuzzification with the centroid rule and multiplication with the seasonality function, the final output of Figure 7 was obtained. This represents the G function used in the germination scheme shown in Figure 3.

The main improvement of this model with respect to the previous results (Giusti and Marsili-Libelli, 2005) is the internal feedback between the hydrodynamic and quality models through the computation of the Manning friction coefficients as a function of the wigeongrass density, as suggested by Järvelä J., (2004) and Thompson et al., (2004). This feedback path, however, is iterated only once per day, given the slow growth of the rooted plants with respect to hydraulic variability which depends on wind and pumping. In this way the velocity field is always compatible with the current development of the wigeongrass prairies.
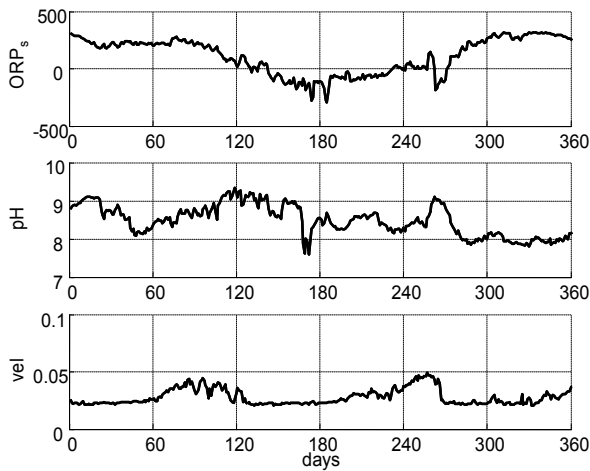
Fig. 5. Soil condition resulting from the application of 2002 weather condition to the fuzzy engine of Figure 4.
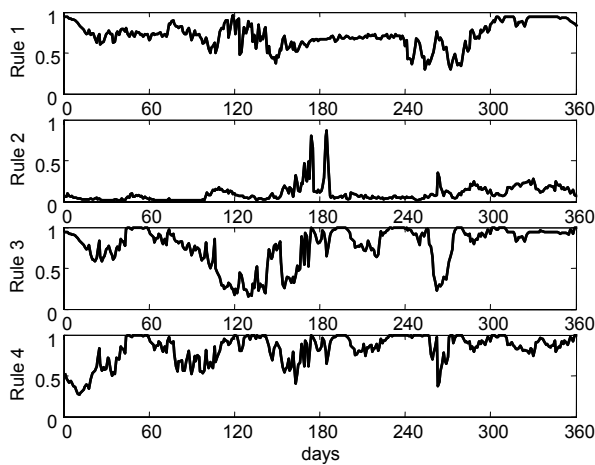

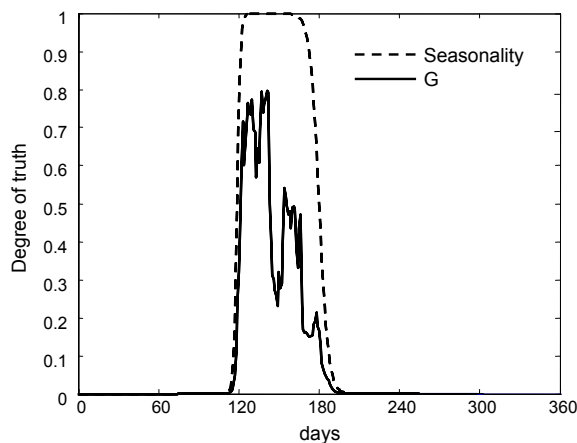Fig. 6. Individual rule output of the inferential engine of Table 1.

Fig. 7. Germination function G obtained from the inferential engine of Figure 4.

Figure 8 shows the influence of these meadows on the Manning coefficients and the ensuing velocity field with a mild NW wind. Two prairies were considered, one in each pond, in agreement with the current observations. The dense vegetation produces a significant increase in friction (from an average value of 0.008 in free-water cells to 0.02 in the meadow cells), resulting in a more than halving of the shear velocity.

Using a three-year daily wind time series derived from the data of the monitoring stations, the evolution of the two meadows was simulated, as shown in Figure 9. Though the figures refer to the maximum seasonal development of the meadows, the expanding trend is apparent. In particular, the eastern meadows expands more, due to the more favourable soil conditions and lower shear velocities.
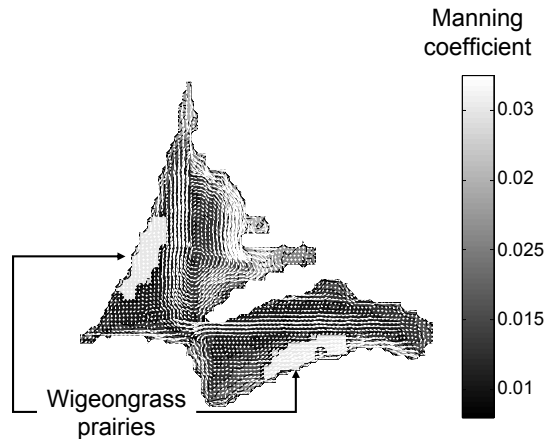

Fig. 8. Manning coefficients and velocity field computed taking into account the presence of the wigeongrass prairies.

5. CONCLUSION

The present study was motivated by and tested on the Orbetello lagoon, where a management problem exists regarding the competitive development of wigeongrass (*Ruppia maritima*) over macroalgae.

In particular, this paper has presented the integration of the original ecological "core" model (Giusti and Marsili-Libelli, 2005) with a hydrodynamic model derived from a previous result (Covelli et al., 2002), generating velocity fields as a function of rooted plants, whose growth was modelled with a fuzzy cellular automata.

The previous ecological model operated with precomputed velocity fields which did not take into account the development of the wigeongrass prairies and the consequent increase in friction. Now hydrodynamics and ecology are integrated into a single, comprehensive model in which Manning friction coefficients depend on the presence of rooted macrophytes and affect the water circulation, which in turn is a decisive factor for seed dispersal and burial, thus influencing the spread of the wigeongrass prairies. Further, the model now includes a cellular automata with a fuzzy inferential engine to determine the extent to which the environment (soil characteristics and water flow) is favourable to the macrophytes development.

The combined model has been used to simulate the vegetation growth in the lagoon with a repeating year-long climatic time-series and the results are in qualitative agreement with the observed behaviour of the existing wigeongrass meadows, which expand slowly but steadily where favourable conditions are met.
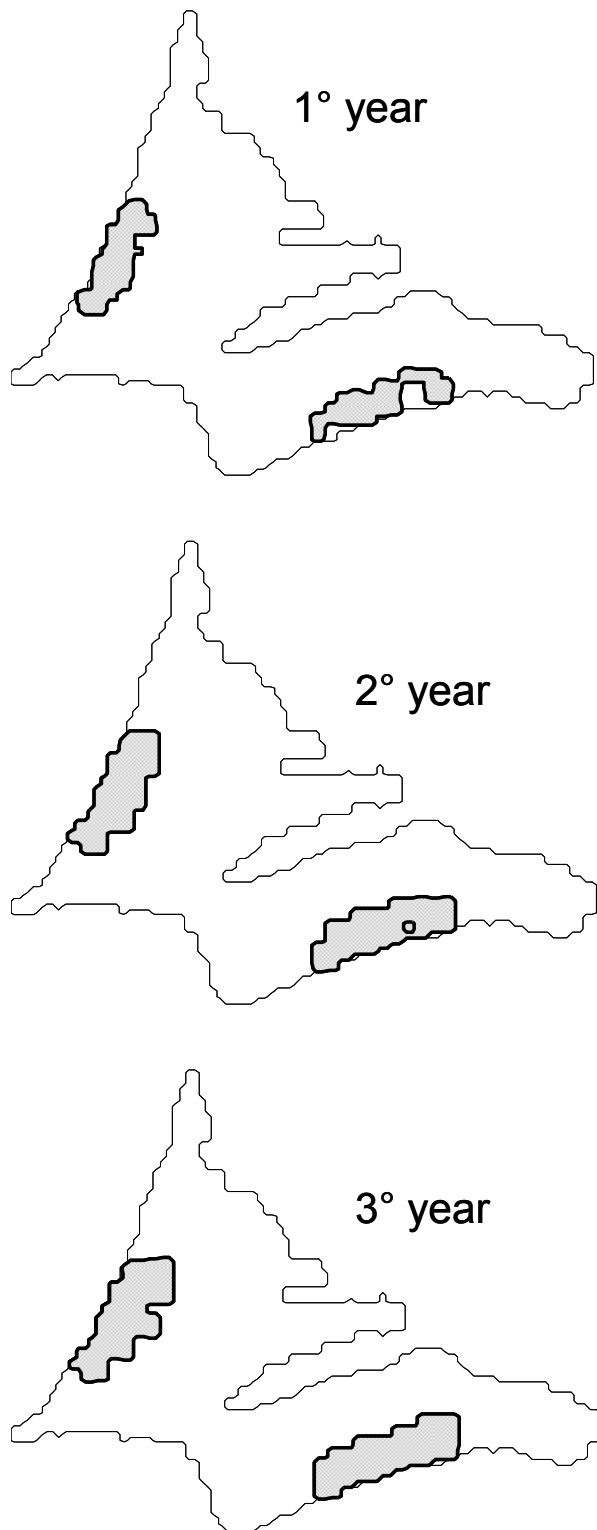
Fig. 9. Evolution of two main wigeongrass prairies over a three-year horizon.

Pending more validation experiments, this combined model has been adopted by the Orbetello Lagoon Management Office as the starting block of a future decision support system to assess the harvesting policies controlling the spread of macroalgae and preserving the wigeongrass prairies.

6. ACKNOWLEDGEMENT

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