Cellular Automata Modelling of Seagrass in the Orbetello Lagoon

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Abstract: This paper describes the evolution in time and space of wigeongrass *(Ruppia maritima)* meadows in the Orbetello lagoon, in central Italy, where the control of the submerged vegetation, with a critical coexistence between macroalgae and macrophytes, is the key management problem. While macroalgae are liable to cause dystrophic crises, macrophytes oxygenate and stabilise the sediment and thus control the nutrient flux into the water. This model was developed for the Orbetello Lagoon Managerial Office to predict the development of both groups and test the actions to favour macrophytes over macroalgae, in the context of a decision support system. A previous model was developed to account for the interactions between nutrients and the submerged vegetation in a 2-D spatial context, and this paper presents a further refinement, with the dynamics of wigeongrass *(Ruppia maritima)* including a hydrodynamic model for the water movements and an ecological model describing the interactions between nutrients and the submerged vegetation.

Keywords*: Cellular automata, Evolutionary computing, Water quality models, Ecological modelling.*

1. INTRODUCTION

The Orbetello lagoon, schematically shown in Figure1, 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 antropogenic 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 problematical coexistence between macroalgae and macrophytes, mainly wigeongrass.

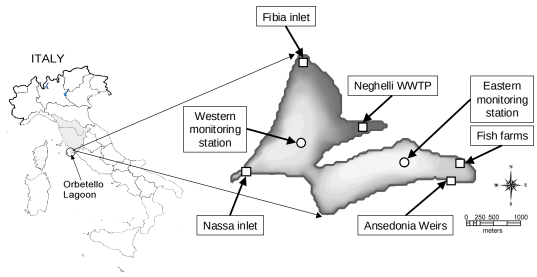

Fig. 1. General view of the Orbetello lagoon, showing the locations of the monitoring stations and the main discharge sites.

While macroalgae may cause dystrophic crises, macrophytes oxygenate and stabilise the sediment and thus control the nutrient flux into the water. A mathematical model has been developed to describe the development of both groups and test the actions to favour macrophytes over macro-algae. This model takes into account the interactions between nutrients and both groups of the submerged vegetation in a 2-D spatial context including a hydrodynamic model for the water movements. A preliminary version of this model has already been developed (Marsili-Libelli and Giusti, 2004). Using a regular grid of cells measuring 200 x 240 m the model operates with 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.

In the original model (Marsili-Libelli and Giusti, 2004) the wigeongrass dynamics consists of a growth and decay balance modulated by several environmental factors. This new contribution attempts at improving this dynamics by modelling the spread mechanism through seed dispersal and germination. The resulting model improves the accuracy of long-term predictions describing the propagation of wigeongrass meadows 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 (Coffaro and Sfriso, 1997; Duarte and Ferreira, 1997; McGinty and Wazniak, 2002; Naldi and Viaroli, 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 wigeongrass has been expanding at the expenses of macroalgae in the form of rather 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 macrophyte (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.

In sexual reproduction *R. maritima* produces a large number of seeds about two weeks after flowering. Ripe drupelets are transported short distances in floating vegetation, but may travel longer carried by winds, fish and waterfowl. In temperate climates, drupelets usually lie dormant underwater until the following spring. Most drupelets are found in the upper 5 cm of bottom sediment.

In asexual propagation, *R. maritima* expands by rhizomes. Rapid growth of rhizomes on overwintering plants begins about the same time as drupelet germination and, like germination, is probably temperature controlled. The peak development is controlled by light and temperature; however, times of maximum light and temperature may not be in phase and can pose some problems for wigeongrass. If light exceeds photosynthetic saturation levels, the plants may be temperature-stressed and attain higher biomass later in the growing season when water temperatures are lower.

The interactions included in the basic ecological model (Marsili-Libelli and Giusti, 2004) are shown in Figure 2.

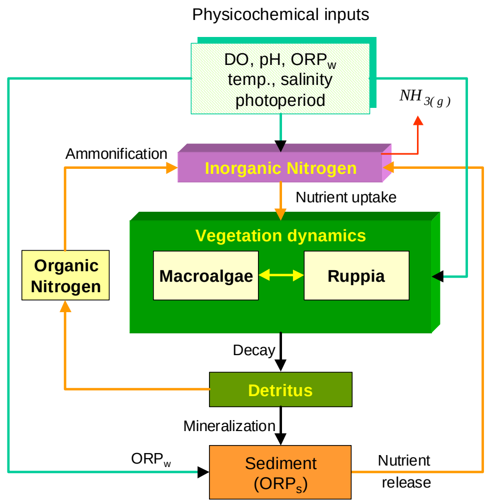

Fig. 2. Basic interaction in the ecological model of the Orbetello lagoon.

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***, 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, which have increased their cover in the last ten years, whereas there has been a constant decline of macroalgae (de Biasi et al., 2003; Lenzi et al., 2003). The correlation between nitrogen 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 for nitrogen and macroalgae can be found in the previous paper (Marsili-Libelli and Giusti, 2004).

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

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

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

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

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

depending on photoperiod d

$$g(d) = 1 - \frac{1}{1 + b \cdot e^{a(d - f_0)}}, \tag{4}$$

temperature T

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

density function R

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

and internal nitrogen quota N_{int}^R

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

whereas the decay is a function of temperature.

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

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

4.2 Cellular automata for seed dynamics

An improvement to this basic model is presented here, consisting of:

1. Seed production and propagation;
2. A set of rules describing seeds dispersal, burial and germination, as a function of environmental conditions, to produce new plants on the following year.

The cellular automata approach is particularly suited to model the year-to-year evolution, rather than just the seasonal bloom which is less important in the case of seagrass which tend to form long-term, rather compact colonies. To describe the seed propagation the scheme of Figure 3 defines the reference directions of water movements along the horizontal (W-E) direction *u*, and the vertical (N-S) direction *v*.

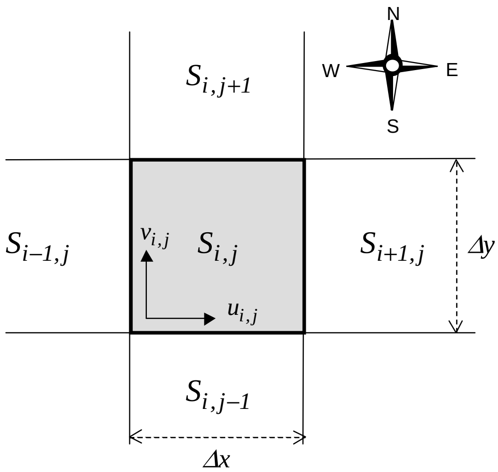

Fig. 3. Cell interactions through advection and diffusion in the spatial discretization. *S* represents the seed concentration in each cell.

It is supposed that as far as sexual reproduction is concerned, the scheme of Figure 4 represents the relationship between adult plants and seeds. The adult plants generate seeds with rate Ps, 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 4. 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.

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 0.4 m s^{-1} (McGinty and Wazniak, 2002).

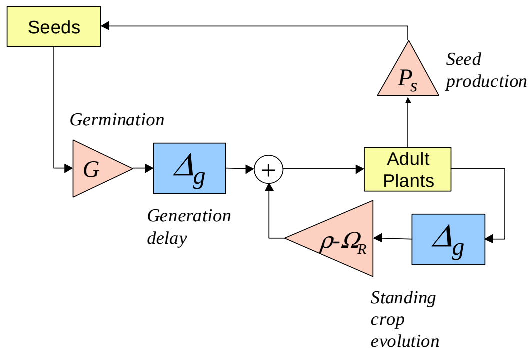

Fig. 4. Interaction between seeds and adult plants, including the generation delay Δ_g .

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

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 the first flowering. From the modelling viewpoint, it is therefore assumed that Eq. (9) is activate when the total biomass is below 10% of the maximum vegetative peak and runs only for a limited number of days. 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 sediment composition in terms of organic content, Oxido-Reduction Potential (ORP) and pH represent important factors for the germination of seeds and the expansion of the meadow. These facts 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 actual germination percentage of sowed seeds, using the Fuzzy Logic Toolbox (Gulley and Jang, 1995) in the Matlab programming environment.

Table 1
Fuzzy rules for seed germination.

R_1: if pH is medium and ORP is high then G is high
R_2: if pH is high and ORP is high then G is low
R_3: if pH is low and ORP is low then G is low
R_4: if pH is medium and ORP is medium then G is medium

The fuzzy qualifiers (low, medium, high) for the two variables *(pH, ORP)* were defined as shown in Figure 5.

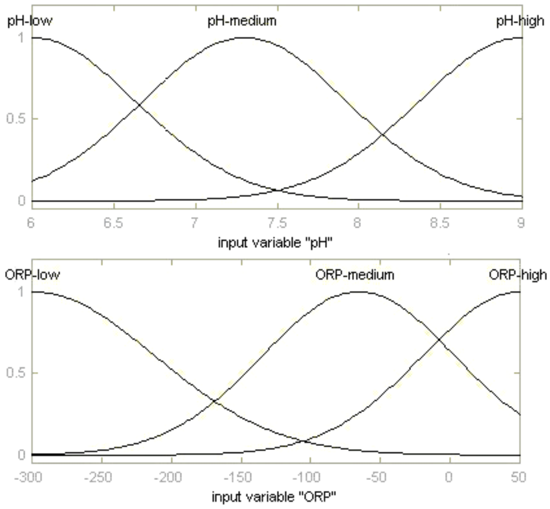

Fig. 5. Fuzzy membership for pH and ORP used in the fuzzy rules of Table 1.

The implication surface resulting from the fuzzy rules of Table 1 as a function of pH and ORP has the form shown in Figure 6. 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.

Three successive years have been simulated using the weather data of 2002. The results are shown in Figure 7, showing the maximum and minimum extent of the wigeongrass meadow, with a clear expanding trend superimposed to seasonal fluctuations. The meadow tends to spread in the direction of the prevailing winds from NW and germinate where currents are slower.

The second summer is the time when the highest growth is observed, with the greatest in-meadow heterogeneity. After that, more regular growth development ensues and produces a further expansion in the third growing season.

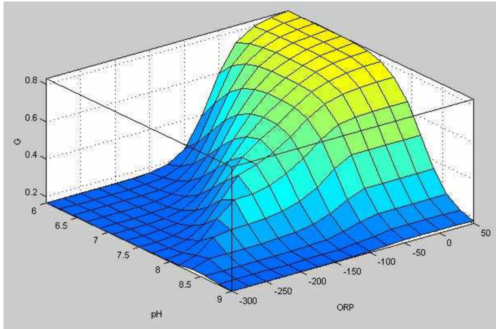

Fig. 6. Implication surface of seed germination rules of Table 1 as a function of pH and ORP.

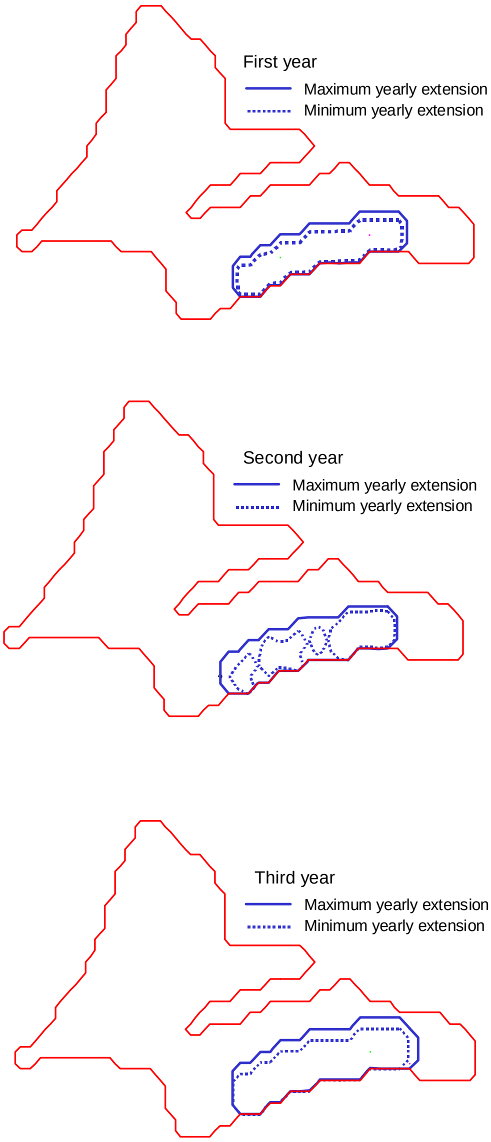

Fig. 7. Yearly fluctuations and long term expansion of the wigeongrass meadow during three consecutive years.

As a concluding remark, Figure 8 shows the general layout of the model, from the software engineering point of view.

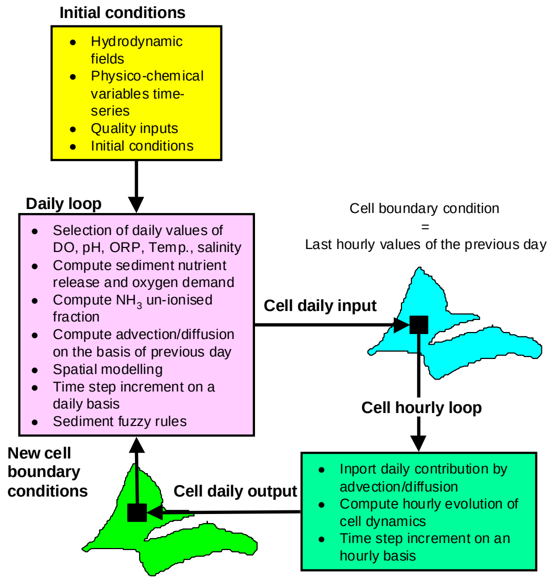

Fig. 8. Software engineering of the ecological model for the Orbetello lagoon.

5. CONCLUSION

This paper has presented an improvement to a previous model describing the evolution of the wigeongrass (*Ruppia maritima*) in the Orbetello lagoon in the context of an ecological model including the dynamics of nutrients and competing groups of submerged vegetation. The previous growth dynamics of wigeongrass has been augmented with the seed model, which consists of a dynamical equation, in the form of a cellular automata and a set of knowledge-based rules defining the favourable conditions for seed spreading and germination. These rules have been implemented as a fuzzy inferential engine. The augmented dynamical model has been integrated into the existing model, which is now capable of describing the observed spread of the *Ruppia* meadows in the Orbetello lagoon over a time horizon of several successive years. The model results are in agreement with the observed behaviour of the existing wigeongrass meadows, which expand slowly but steadily wherever favourable conditions are met.

6. ACKNOWLEDGEMENT

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