



Remote sensing as a tool for 3D model of ecosystems: an application to lagoon of Venice

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Abstract

Three-dimensional models require a large amount of data for characterising the space and time evolution of the system and for testing the adequacy of the model. Remote sensing can greatly improve the results of these models because makes available space-time series of data hardly obtainable in other ways. Indeed, traditional kind of measurement, while more accurate, cannot provide data sampled as often, and on as a fine mesh, as the ones obtainable by remote sensing technique. Experimental observations derived from remote sensing images, has been coupled with a 3D-water-quality model, to analyse the effects of eutrophication in the lagoon of Venice, namely to define the modality of the spatial expansion of macroalgae community.

The model covers the central part of the lagoon of Venice, that includes the industrial area and the historic town of Venice. It combines transport and tropic processes, describing the seasonal dynamic of the main community of macroalgae (*Ulva r.*), phytoplankton and zooplankton densities, nutrients' concentration in water (NH_4^+ , PO_4^{--} , NO_x), BOD and Dissolved Oxygen. The variation of light and temperature during the year is computed on the basis of meteoroclimatic data combined with an energetic balance. The nutrients loading are interpolated from monthly averaged estimations and immitted as point sources.

Transport processes are simulated by 3-D anisotropic turbulent diffusion, which takes into account the average dispersive effects of the tidal agitation. All the state variables are considered as passive solutes, except for macroalgae colonies, which spread according with an empirical law (diffusive process but with different and empirical constant coefficient) and are always confined only into the bottom layer. Macroalgae surviving in the new colonised area will

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depend both upon rate of macroalgae spreading and bathymetry conditions, as well as hydrodynamic and trophic conditions.

This is in agreement with the experimental observations which show that *Ulva r.* is present only in well defined areas. Comparison of the simulation outputs versus remote experimental observation gives the possibility of estimating the rate of spreading of macroalgae colony.

Even starting from homogeneous initial conditions, the model succeeds in describing the main features of the spatial pattern for *Ulva r.* and the seasonal evolution the other state variables, also as a consequence of the nutrient scenario input and transport phenomena. Results are markedly improved when initial conditions for *Ulva*, in the early spring, are defined according with a map of presence-absence, obtained by treating a remote sensing image. The observed spatial pattern is correctly described yielding sharp gradient of standing crops biomass.

These first results indicate that the simulations appear to be in reasonable agreement with experimental observations in this area, and therefore supports the plausibility of the *Ulva* spreading mechanism.

Introduction

In the last two decades the lagoon of Venice went through such modifications that macroalgae are no longer a negligible component of the ecosystem, but they actually are of major importance in the cycling of matter and energy¹.

Mathematical modelling, besides being an useful tool in planning management and recovering strategies, helps in the synthesis and interpretation of the data, acting as a theoretical framework in which one can fit most of the partial knowledge gathered by experimental scientists.

For this reason an eutrophication model, taking into account both phytoplankton and macroalgae dynamics, have been coupled to a three dimensional diffusion model of the central part of the lagoon of Venice^{2,3,4,5,6,7}.

Remote sensing

Mathematical model requires for a large amount of data, first to understand the physical processes which are going on and actually build a model for them, and then for estimating the parameters used in the formulation, for the calibration and for the validation of the model. This is all the more true for threedimensional model, whose validation goes through a comparison between simulations and experimental spatial distribution of the state variables.

Remote sensing techniques are amongst the more useful tools to this aim, since they are able to make available space-time series of data hardly obtainable in other way. Indeed traditional kind of measurement, while more accurate, cannot provide data sampled as often, and on as a fine mesh, as the ones obtainable by remote sensing technique. Coupling of remote sensing

measurement with mathematical modelling are therefore a necessary step in designing a modern management and recovery strategies.

In this paper we used two different remote sensing images, Landsat-5/TM, referring to April 30th, and July 19th 1990 satellite pass.

Several algorithms are available in the specific literature for derive the presence of chlorophyll and suspended matter from the spectral signature of marine water. Nevertheless, the interpretation of remote sensing information collected for the Lagoon of Venice is by no means trivial, because of the many problems due to the particular environmental conditions, which present an high variability both from a geomorphologic point of view that for the water-quality one.⁸

The methodology here used for the recognition of macroalgae vegetation from Landsat-5/TM images^{9,10} enable one to identify a spectral indicator, SI, based on the TM spectral bands correlated with dominant biochemical parameters of the physiological stages of macroalgae vegetation.

$$SI = (TM4-TM3)/(TM4+TM3) \quad (1)$$



Figure 1. Remote sensing image for April 30 1990. Macroalgae presence is indicated by the white area

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In Figure 1, referring to spectral indicator SI for April 30th 1990, macroalgae presence is associated to the white area in the very centre of the picture, just under the major island on which the city of Venice is built. From this one we have derived a map of presence-absence of ulva biomass, Figure 2, to be used as starting point for our simulations, by identifying the nine pixels of the landsat images corresponding to each node of the model bathymetry and checking whether or not at least half of them presented macroalgae vegetation.

Figure 3 refers again to the spectral indicator SI, but for July 19th 1990, and only for the area covered by the model.

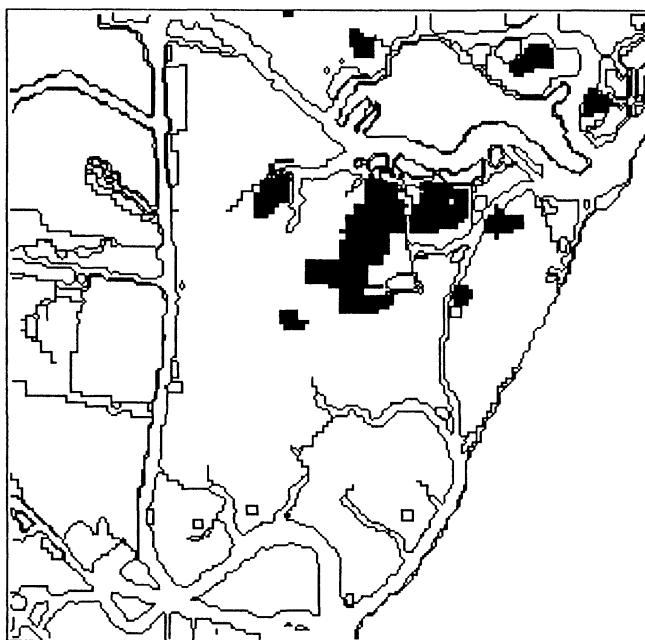


Figure 2. Spatial distribution of macroalgae derived from figure 1 and used as initial condition for our simulations.

Model of Ulva

In the venetian ecosystem *Ulva rigida* is, by far, the most abundant macroalgae species¹. It colonises shallow environments because of its capacity to survive in adverse external condition like low irradiance or nutrient level. Nutrients are not assimilated from the sediment but from the water medium and there is the possibility for the algae to store part of the nitrogen but not immediately metabolised nitrogen, and to use it in a second time.



Figure 3. Remote sensing image for July 29 1990. Macroalgae presence is indicated by the white area.

Therefore *Ulva* can survive for quite a long periods under limiting nitrogen condition as well as in absence of nutrients¹¹.

Ulva dynamics is described by the general equation

$$dB/dt = \nabla k \nabla B + f(x, t) \quad (2)$$

the first term describes transport phenomena and second one represents the biological transformations.

The equations of the model for *Ulva* are summarised in the Table 1. Growth of *Ulva* follows a two steps kinetic, uncoupling growth from assimilation. Asymptotic formulations describe the influence of light and temperature, as well as respiration. Shading from phytoplankton and water, as well as selfshading, is considered.

A multiplicative model is used also for describing phytoplankton dynamic: nutrients limitation is modelled by Monod type kinetic while influences of the forcing functions are respectively simulated by the Steel function (for light influence) and a modified Lassiter-Kearns function for temperature. Steel formulation takes into account shading effects of water and phytoplankton

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itself along the water column. Zooplankton grazing follows a type II functional response, while linear terms described mortality losses.

Mortality losses go into the detritus compartment (labile fraction of dead organic matter), where the bacterial mediate demineralisation replenishes nutrients to the water medium. Detritus sinks at a constant rate and, eventually, reaches and accumulates on the bottom, where it is labelled as superficial sediment. The equations are described in more details in [4]

This model succeeds in describing the main features of the spatial pattern for *Ulva r.* and the seasonal evolution the other state variables: and differentiate the initially homogeneous spatial distribution of macroalgae density, giving rise to sharp gradient of biomass².

The second term of equation 1 accounts for the transport phenomena. Since macroalgae have a pretty large size and, even if weakly, are rooted to the bottom they can certainly not be treated as a passive tracer subjected to the eddy diffusion process, as is done for the other state variables. Nonetheless they do spread and give rise to a spatial distribution of the colonies which present also sharp gradient of density of biomass.

Result and discussion

Spreading rate is an important parameter in regulating the evolution of the colonies of macroalgae. The greater the spreading rate the greater the flux of biomass out of an area and, as a consequence, the loss in biomass for that area, which will therefore reach lower value of standing crop. On the other hand, the greater the spreading rate the larger the colonised area and the higher the amount total biomass globally present all over the lagoon.

There is not a clear idea on the modality following which the colonies of macroalgae expand in the lagoon of Venice, for the lack in experimental measurement from one side and of theoretical studies on the other one.

Our hypothesis is that macroalgae are confined in the bottom layer and that it is possible to model their expansion by the purely empirical assumption that diffusion along both horizontal directions is described by a single diffusivity, constant for all the model. Moreover we assume that a colony spreads only in spring and summer and only if its density is above a preassigned minimum threshold. These coefficients are empirical, and might be estimated by comparing visually the space distribution obtained by the model with the observed ones.

This mechanism does not take into account the possibility that floating algae, no longer anchored to the bottom but driven by the currents, will eventually accumulate in certain area. This phenomenon, which following several authors¹² should not be neglected, seems to be of minor relevance in the part of the lagoon covered by our model. Indeed, the hypothesis that residual current and negligible is the very assumption made on modelling transport phenomena as a eddy diffusion process².

The surviving of macroalgae in the new colonised area will therefore depends on the bathymetry, the trophic state in the new area and also on the spreading coefficients. Experimental observations confirm that *Ulva r.* is present only in well defined areas.

Several simulation have been performed varying the spreading coefficient. Bathymetry affect the spatial distribution of macroalgae, because the presence of channels or large area of 2 meters depth slowed down expansion acting as a natural barrier. On the other hand, the final distribution depends also upon the initial condition supplied to the model, as it has been seen by comparison (Figures 4 and 5).

For this reason an experimental map of presence-absence of ulva biomass, to be used as starting point for our simulation (Figure 2), has been derived from the remote sensing image referring to April, 30th 1990, as it was mentioned above.

Simulations have then be compared with the distribution, obtained by a second remote sensing image, Figure 3, referring to the end of July 1990. In the figure the colonies of macroalgae are coloured in white, and one can see as they are much larger than in the Figure 2. Our simulation, Figure 4, shows for the same day a similar distribution of macroalgae biomass: the area invaded by macroalgae is considerably larger than the starting one and also its shape resemble the experimental observation, as one can see noting, for example, as the simulated distribution presents the same peculiar shape of the left edge of the main colony (check its bottom-left corner) or the lower density level along the channel in the middle of the main colony.

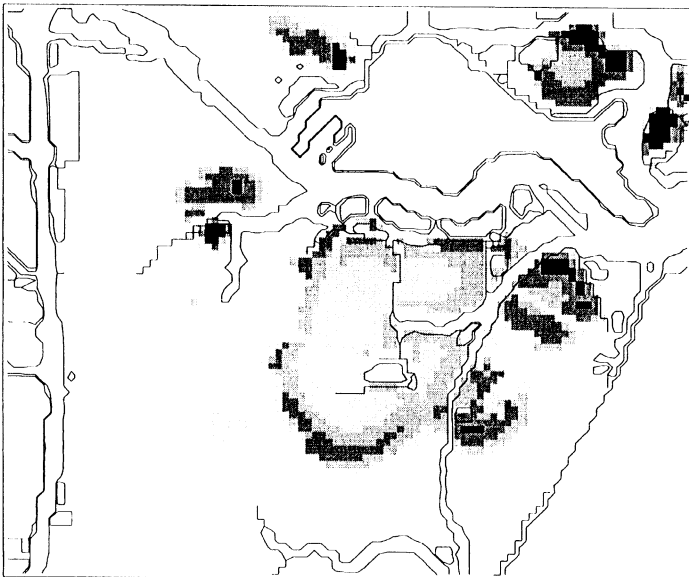


Figure 4. Simulated spatial distribution of biomass

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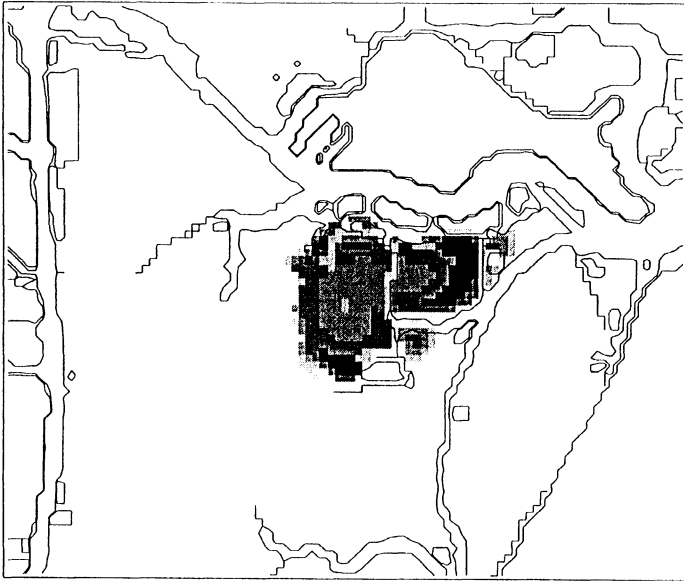


Figure 5. Spatial distribution of macroalgae biomass starting the simulation from unrealistic initial condition

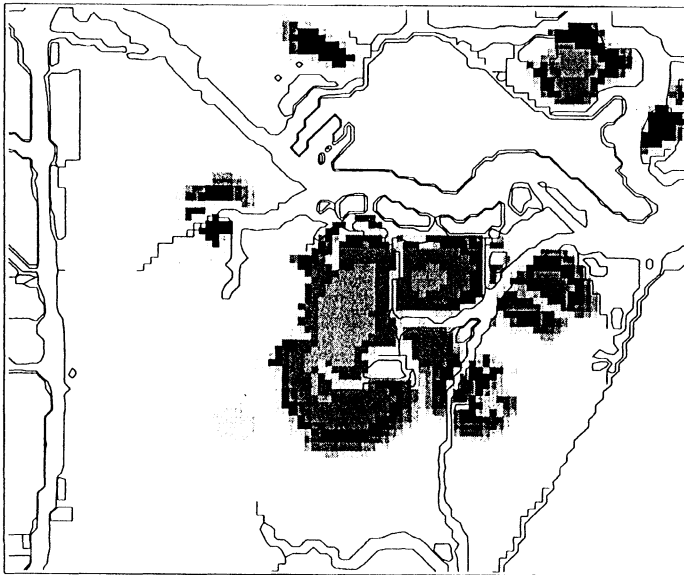


Figure 6. Spatial distribution of macroalgae biomass running the simulation with a lower spreading rate

Figures 5 and 6 respectively illustrate, for comparison, the simulated spatial distribution of biomass obtained starting the simulation from unrealistic initial condition and running the model with a smaller rate of spreading. The differences with the experimental distribution are self evident and indirectly confirm the estimate for spreading parameter used in the previous simulation.

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TABLE 1: MACROALGAE GROWTH MODEL:

Mass Balances

$$\begin{aligned} dB/dt &= (\mu - f_{death}) \cdot B \\ dQ/dt &= (V_{NH} + V_{NO}) - \mu \cdot Q \\ d[DO]/dt &= [\phi - f_{resp}] \cdot B \\ d[NH_4^+]/dt &= -V_{NH} \cdot B \\ d[NO_x^-]/dt &= -V_{NO} \cdot B \\ d[PO_4^{3-}]/dt &= -PCR \cdot \mu \cdot B \end{aligned}$$

Functional Expressions

$$\begin{aligned} \mu &= \mu_{max} \cdot g_1(Q) \cdot g_2(P) \cdot g_3(I) \cdot g_4(T) \\ \phi &= \phi_{max} \cdot g_1(Q) \cdot g_2(P) \cdot g_3(I) \cdot g_4(T) \\ g_1(Q) &= (Q - Q_{min}) / (Q - k_c) \\ g_2([P]) &= [P] / (k_p + [P]) \\ g_3(T) &= \left\{ 1 + \exp[-\zeta_p \cdot (T - \vartheta_p)] \right\}^{-1} \\ g_4(I) &= 1 - \exp(-I / I_0) \quad I = I_{inc} \cdot \exp[-\varepsilon_w - \varepsilon_B \cdot B] \\ V_{NX} &= V_{mNX} \cdot f_1(NX) \cdot f_2(Q) \\ f_1([NO_x^-]) &= [NO_x^-] / (k_{NO} + [NO_x^-]) \\ f_1([NH_4^+]) &= [NH_4^+] / (k_{NH} + [NH_4^+]) \\ f_2(Q) &= (Q_{max} - Q) / (Q_{max} - Q_{min}) \\ f_{death} &= \alpha B^\beta + k_t \cdot \frac{\max[(f_{resp} \cdot B - DO), 0]}{f_{resp} \cdot B} \\ f_{resp} &= k_{resp} \left\{ 1 + \exp[-\zeta_{resp} \cdot (T - \vartheta_{resp})] \right\}^{-1} \end{aligned}$$



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