

AN INTEGRATED ECOLOGICAL MODELLING AND DECISION SUPPORT METHODOLOGY

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ABSTRACT

This work presents a methodology for modelling and simulating aquatic ecological systems and an associated methodology and software for creating Decision Support Systems (DSS) for this kind of environment. Both are based on object oriented programming (OOP) and, in the case of the DSS, on Autonomous Intelligent Agents. The modelling software (EcoDynamo) includes several object dynamic link libraries to simulate different physical and biogeochemical ecosystem processes. These libraries were designed to be possible their linkage with different model shells, for the sake of portability and usability. A high level communication language (ECOLANG) was developed to allow the communication between EcoDynamo and the agents. The DSS uses one methodology of discrete multi-criteria, where given a users preference structure (elicited with the Analytic Hierarchy Process methodology - AHP), a priority ranking of the pre-processed scenarios is achieved. To validate the approach, EcoDynamo was used with the DSS to simulate different management scenarios in a coastal lagoon at the South of Portugal – Ria Formosa. The experiments performed showed that these tools may be widely used by people involved in the management of coastal areas to integrate environmental, economic and social issues in the decision process, without an in-depth knowledge of modelling methodologies.

INTRODUCTION

Models of aquatic ecosystems include hydrodynamic and biogeochemical processes, such as photosynthesis, nutrient cycling and grazing. The former are responsible for the transport of pelagic variables across model domain and across model boundaries. The latter are responsible for local changes of state variables, such as concentration of chemical constituents and biomass of different species or groups of species.

Different modelling teams tend to adopt different modelling tools, due to the knowledge of their researchers and the inherited software they use. The most common approaches are the structured programming - e.g. the EMS Dollard (Baretta and Ruardij 1988), COHERENS model (Luyten et al. 1999) - or object oriented programming - e.g. EcoWin, (Ferreira 1995), individual-based modelling (IBM) (Breckling et al. 2006).

Models based on structured programming consist of a main program, where some general state variables are defined and calls are made to several sub-routines, at each model time step. These sub-routines calculate all processes represented in the model and the fluxes that affect each state variable. At the end of each simulation cycle, state variables are updated as a function of the mentioned fluxes. In some cases, sub-routine calculations depend on general scope variables. In these situations, it is difficult to reuse these sub-routines from other source codes. Moreover, depending on the compilers used, it may be difficult to combine sub-routines written in different source codes to build new models (Pereira et al. 2006).

In the case of object-oriented software, it is possible to define objects representing several groups of variables and processes that may correspond roughly to the sub-routines of the previous approach. The elimination of general scope variables helps avoiding programming errors. Furthermore, object properties, such as reusability, inheritance and polymorphism (Meyer 1997; Weiss 2000) make them very useful in ecological modelling (Pereira et al. 2006). For example, one may define a zooplankton object that has a set of parameters and procedures to change its state variables (e.g. biomass) by simulating relevant physiologic processes. However, for the implementation of a particular model it may be necessary to include several zooplankton species, differing in the values of some physiologic parameters, everything else being equal. In this situation, it is not necessary to create code or variables for each new zooplankton species. Using polymorphism, several dynamic instances of the same object may be created, each with their own parameter values and corresponding behaviour. There is no need to create more state variables, as it would be the case in a

structured dynamic model (at least one per species), because each instance of the zooplankton object has pointers to the corresponding state variables. Therefore, using the same objects, it is possible to build models of different complexity. Furthermore, if it becomes necessary to change some calculations, create new variables or parameters, for one of the modelled species, a descendant object may be easily created by overloading only the procedures that have to be changed, everything else being inherited from the ancestor objects.

Objects may interact between each other. For example, a zooplankton object may graze a phytoplankton object after inspecting its properties, such as biomass, and “informing” phytoplankton how much will be grazed. This is done by having methods in each object that are responsible to show “public” properties (e.g. biomass) and methods that are responsible to change them as when phytoplankton is grazed by zooplankton (e.g. Ferreira 1995).

Ecological models are frequently developed for management purposes. The set up of a model with existing modelling software may be a relatively complex task, where the user must prepare several configuration files that define several ecosystem characteristics, parameters and initial values for the variables – this is usually called a scenario. Model outputs consist of results, regarding several variables that reflect, for example, water and sediment chemical quality and production of several species. Therefore, the usage of such models by non-modellers, involved directly on management issues, may be discouraged by the complexity mentioned above. Moreover, results obtained with different scenarios may be difficult to order according to some quality criteria, unless some decision support rules exist. Accordingly, the purpose of this work is to describe a methodology allowing the linkage of a modelling software – EcoDynamo (Pereira et al. 2006) - through a specific communication language – ECOLANG (Pereira et al. 2005) – with a Decision Support System (DSS) software and to present a practical application of this combined methodology. It is noteworthy that this work presents a first description of a new tool, which is the DSS software, and a first synthesis of tools described elsewhere (e.g. for ECOLANG see (Pereira et al. 2005); for EcoDynamo see (Pereira et al. 2006)).

The rest of the paper is organized as follows. Section 2 describes the system conceptualization with emphasis on our ecological modelling software - EcoDynamo. Section 3 briefly describes ECOLANG – a high-level communication language developed for this type of ecological simulations. Section 4 analyses the Decision Support System developed and is followed by a description of the Analytic Hierarchy Process. The paper ends with an analysis of our case study: Ria Formosa lagoon and some conclusions and future work.

SYSTEM CONCEPTUALIZATION

EcoDynamo - Ecological Modelling Software

EcoDynamo is an example of object oriented modelling software, built in C++ that was designed to simulate thermodynamic, hydrodynamic and biogeochemical processes of aquatic ecosystems. Details about EcoDynamo may be found in (Pereira et al. 2006). One important characteristic of this software is that its objects are compiled as Dynamic Link Libraries (DLLs) with an interface allowing their linkage with other modelling software codes written in FORTRAN or C. This allows different modelling teams to share software for the calculation of specific processes, independently of the programming language preferred, and enabling bidirectional code reutilisation. The EcoDynamo shell (Figure 1) manages the graphical user interface, the communications between classes and the output devices, where the simulation results are saved. Simulated processes include:

- (i) hydrodynamics of aquatic systems - water elevations, current speeds and directions;
- (ii) thermodynamics - energy balances between water and atmosphere and water temperature;
- (iii) biogeochemical - nutrient and biological species dynamics;
- (iv) anthropogenic: e.g. biomass harvesting.

Ecosystem characteristic properties are described in a model database. EcoDynamo has an interface module that enables communications with other programs for external control. For example, the simulations runs can be controlled by commands like start / stop / pause / restart / step simulation. Simulation activity can be monitored with the help of log files, activated before the simulation run.

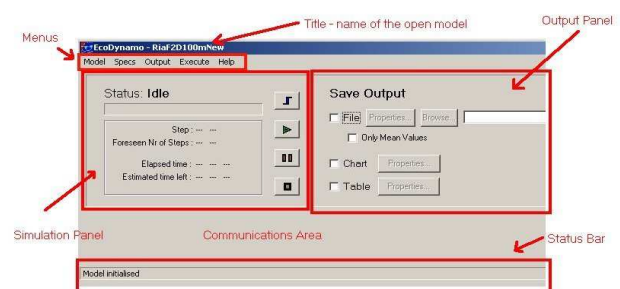


Figure 1: EcoDynamo Shell

Some of the output options provided by EcoDynamo make use of MatLab® functions. The implemented interface DLLs integrate graphics output features and HDF (Hierarchical Data Format) file functionalities.

ECOLANG – A Communication Language For Simulations of Complex Ecological Systems

ECOLANG (Pereira et al. 2005) was developed with the purpose of exchanging information between EcoDynamo and a Decision Support System (DSS) based on Intelligent Agents (IA). It was designed to describe ecological systems in terms of regional characteristics, living agent's perceptions and actions and is independent from any hardware or software platform. Its main characteristics are as follows:

- (i) it is a high-level language easily understood by software agents and humans;
- (ii) it has a simple syntax validation;
- (iii) its ontology is oriented to aquatic ecosystems;
- (iv) it is easily adaptable to new IAs included in the system;
- (v) it is independent from any hardware or software platform, including operating system or programming language.

ECOLANG messages describe regional characteristics of the ecological systems, translate agents' actions and perceptions and enable different levels of communication:

- (i) Execution - commands over the simulation model (initialize, run, pause, step, stop);
- (ii) Configuration - select sub-domain, select classes, change variables and parameters' initial values, select variables for output, simulation period and time step before the model runs;
- (iii) Definitions - aggregate areas into regions according to some common properties, define sub-domains based in the regions;
- (iv) Statistics: collect results from simulation experiments, compare results with previous simulation experiments or observed data and advise the configuration module the expected actions to take;
- (v) Events: spontaneous messages that agents generate to inform some important events or results.

DSS - Decision Support System

“An important aspect of any decision support system (DSS) is its intended audience and users. An important part of successful application is not so much the question of how, but why, for whom? Actors and stakeholders are important, their identification and early, and in fact continuous, involvement on a formal basis are important requirements for any DSS project” (Fedra 2005).

The DSS includes several graphical facilities allowing the user to reconfigure several aspects of the model set up, to simulate different management scenarios and to

run the model accordingly. Model results obtained under different scenarios are analysed with the Analytic Hierarchical Process (AHP) methodology (Saaty 1980), using a MatLab® routine developed at Siena University (Siena 2006).

Manipulation of the DSS is very intuitive. The user must select the desired model enabling the “World View” window to visualize a 2D image of model's domain, with the distribution areas of different species represented in different colours (Figure 2) and zooming possibilities.

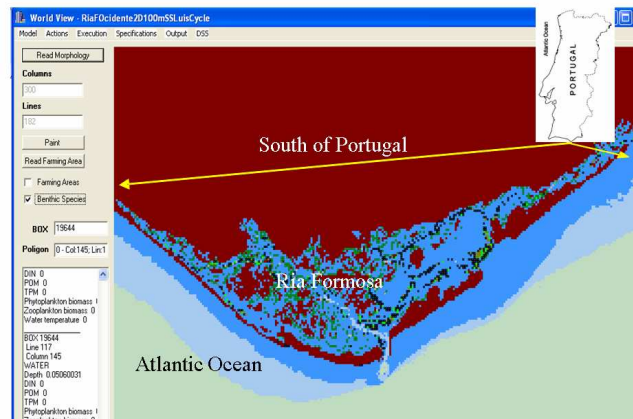


Figure 2: Partial view of Ria Formosa Coastal Lagoon (South of Portugal) with the DSS

On the left of the Figure there are several informations and buttons. The most important ones are: “Columns” and “Lines” indicating the cursor position in the model domain (grid); checkboxes “Farming areas” and “Benthic Species” allowing the visualisation of aquaculture areas, in white, and benthic species, in green and black; “Polygon” indicating the coordinates that define a polygon drawn by the user. Polygons may be used to define particular areas, where virtual changes may be introduced regarding water depth, distribution and abundance of species, etc. These changes may reflect some hypothetical management scenario and are assumed by the model in the next simulation that may be started directly from the DSS interface

Application menus enable the user to act over EcoDynamo. Figure 3 shows some of the menus and submenus of the application. For instance, the user can see the available classes configured in the model selecting the command “Classes Available” in the Specifications menu. The command is translated to the corresponding ECOLANG message and sent to the EcoDynamo application; EcoDynamo answers with the names of the available classes in another message and the result is shown in the “Classes Available” window.

AHP – Analytic Hierarchy Process

The multicriteria analysis tool used by the DSS is the Analytic Hierarchy Process (AHP) (Saaty 1980). It provides a powerful and flexible tool that may be used to make decisions in situations when multiple and

conflicting objectives/criteria are present, and both qualitative and quantitative aspects of a decision need to be considered. Since some of the objectives could be contrasting (e.g. socio-economic interests and environment preservation), it is not true in general that the best option is the one that maximizes each single criterion, rather the one which achieves the most suitable trade-off among the different criteria.

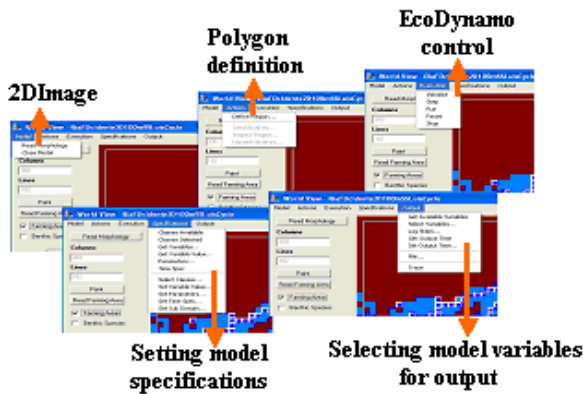


Figure 3: DSS Menus to Act over EcoDynamo and Setting up Simulations

The AHP generates a weight for each evaluation criterion according to the information provided by the user (decision maker). The higher the weight, the more important the objective. Next, the AHP evaluates all the scenarios on each criterion using the information provided by the user. Finally, the AHP combines the objective weights and the scenarios evaluations, thus determining a global score for each scenario and a subsequent ranking. The global score for a given scenario is a weighted sum of the scores it obtained on the single criteria.

Because the AHP tool is embedded in the DSS software, the user only concentrates its attention in how to compare the criteria. The relative importance between two criteria translates the evaluation (qualitative or quantitative) made by the user to relate the criteria pair and is measured according to a numerical scale that may range from 1 to 9 (the larger value the more important is first criterion compared to the second). The relation between the second and the first criterion is the inverse quantity. Each criterion is compared against all the others criteria resulting the pair-wise comparison (PCM).

With the DSS application it's possible, in runtime:

- (i) to define and modify the relative importance of different criteria used by the decision maker, such as water quality variables, production of some important species, etc., and save them in different PCM files (Figure 4);
- (ii) to receive and save results obtained by EcoDynamo for each different scenario, corresponding to the mentioned criteria;

- (iii) to rank various scenarios, after running the AHP module with the proper PCM matrices.

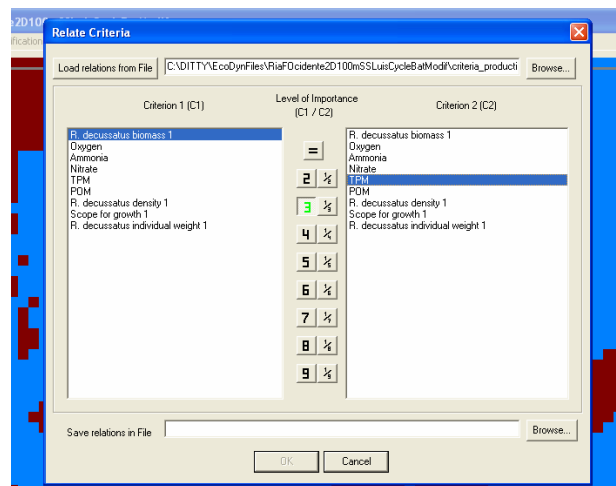


Figure 4: Pairwise Comparison Matrix for Selected Criteria

One important feature of this method is that the relative importance between criteria and scenarios, used by AHP analysis, can be changed between model runs. The data from several scenarios can be collected and saved to be used in a deferred decision process. With this tool the users are involved in the decision process and committed to the alternative proposed as the best scenario for sustainable management of the ecological system. The AHP methodology offers the data for plausible explanation of the best decision.

RIA FORMOSA CASE STUDY

Ria Formosa is a shallow meso-tidal lagoon located at the south of Portugal (Algarve coast) with a wet area of 10500 ha (Figure 2). EcoDynamo and the DSS described above were applied to test several management scenarios of clam farming in Ria Formosa.

The ecological model applied to Ria Formosa is described elsewhere (Duarte et al. in press b). It is a two dimensional vertically integrated model, including thermodynamic, hydrodynamic and biogeochemical processes, both in the water column and the sediments. It also simulates the growth and production of cultivated clams.

The application described herein is based on the analysis of three possible management scenarios, consisting of increasing clam (*Ruditapes decussatus*) biomass density – an important economic resource in Ria Formosa. This first application is based on some simplifying assumptions, just to test the whole system:

- (i) the inverse of average ammonia concentration, over the cultivation areas, is used as a surrogate for water quality. The rationale is that increasing bivalve density should contribute to an increase in ammonium concentration, through excretion, and a decrease in water quality;

- (ii) Chlorophyll concentration, over the cultivation areas, is used as a surrogate for ecosystem sustainability. Increasing bivalve density leads to a decrease in phytoplankton biomass (already relatively low in Ria Formosa), through filtration by the bivalves, and this may reduce food availability for other suspension feeders. Therefore, it is assumed that any decrease in chlorophyll may be viewed as a negative impact for the ecosystem;
- (iii) Total value (calculated from the price per kg – c.a. 5.00€) of average clams (*Ruditapes decussates*) biomass per m² is used as an economic indicator.

Table 1 shows simulation results for the three different bivalve biomass densities. These results were integrated over a simulation of one year and show that when clam biomass is cultivated at increasing densities (from 1 till 3 kg (Dry Weight) m⁻²), bivalve production increases, chlorophyll concentration decreases, being used as food by the clams, and ammonia concentration increases, as a result of clam excretion.

Table 1: Simulation Results for Different Bivalves Densities

	Ammonia µmol L ⁻¹	Phytoplankton µg Chl L ⁻¹	Clam Production kg (DW) m ⁻²
Normal density	11.4	0.33	1.4
Double density	17.7	0.29	2.2
Triple density	24.7	0.27	3.0

Different criteria weights are obtained from three different pairwise comparison matrices A1, A2 and A3 (Figure 5). In the first matrix, A1, it is assumed that all criteria have the same importance. In the second one, A2, environmental criterion (inverse of ammonium concentration) is considered the most important. In the third matrix, A3, it is considered that economic criterion (clam yields) is the most important. These three matrices reflect hypothetical views of the relative importance of chosen criteria.

$$A_1 = \begin{bmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{bmatrix} \quad A_2 = \begin{bmatrix} 1 & 2 & 3 \\ 1/2 & 1 & 2 \\ 1/3 & 1/2 & 1 \end{bmatrix} \quad A_3 = \begin{bmatrix} 1 & 1/2 & 1/3 \\ 2 & 1 & 1/2 \\ 3 & 2 & 1 \end{bmatrix}$$

Figure 5: Pairwise Comparison Matrices

Running the AHP analysis combining scenario outputs and pairwise comparison matrices produces the results shown in Table 2, with bold type values corresponding to the highest scores.

Table 2: AHP Scores

	A ₁	A ₂	A ₃
sc1: normal density	0.523	0.642	0.380
sc2: double density	0.194	0.186	0.204
sc3: triple density	0.282	0.172	0.416

If water quality or ecosystem sustainability criteria are considered more important, the normal density farming

is the best option. Increasing bivalve density seems justifiable only when economic criterion is assumed as the most important even degrading the quality of the water in the ecosystem.

More sophisticated analysis and scenarios are being generated using, as criteria, indicators that combine several variables. Among the management scenarios under analysis are:

- (i) bathymetry changes, as those resulting from dredging operations;
- (ii) opening/closing inlets;
- (iii) changes in the location of Waste Water Treatment Plants and
- (iv) creation of new aquaculture areas.

The DSS described in this work is part of a system based on the Intelligent Agents (IA) paradigm (Norvig and Russel 2003; Weiss 1999; Wooldridge 2002; Reis 2003). The general idea is to create several IAs corresponding to the stakeholders involved in exploring/managing the ecosystem under study. Each stakeholder will be “interested” in maximizing some goals, such as clam production, water quality, etc., and will be able to communicate with EcoDynamo in order to analyse different scenarios and to evaluate obtained results with the DSS. One of the stakeholders will be responsible for ecosystem management towards sustainability.

CONCLUSIONS AND FUTURE WORK

In this study, a system combining an ecological modelling software (EcoDynamo) and a DSS using the AHP methodology, communicating with a high-level language (ECOLANG), is described. A simple case study, where this system was used to simulate and evaluate three management scenarios is presented. ECOLANG was described in a previous work (Pereira et al. 2005) and this work presents its first practical usage. ECOLANG makes simulation experiments of complex ecosystems more comprehensible to the humans. It also proved to be a useful tool to interface the model with the DSS and with other applications.

The presented approach makes easy to design and generate alternatives - the first objective a good DSS must provide. The bigger set of alternatives to choose from, the larger the probability that a generally acceptable solution will be included in the set (Fedra 2005).

One step ahead will be the inclusion of feedback from the DSS stage to the scenario generation foreseen to extend the set of possible solutions in response to the users’ preferences structure. This will imply to move from the AHP to the ANP (Analytic Network Process) methodology (Saaty 1996).

The map navigation capabilities of the DSS interface works on a way similar to a Geographical Information System (GIS), in the sense that there is a spatial reference for every pixel in the ecosystem map. However, it would be important to interface this tool with GIS software, to easily import layers with relevant information for model initialisation.

It is expected that the integration of Autonomous Intelligent Agents into this system will improve the realism of decision-making, imposing negotiation between the options and preferences of the different agents, each one with its own decision process. New agents representing entities that influence the ecological simulation may be added in a very natural way. This process makes the simulation realism concerning the human factor an incremental process, enabling the execution of simulations in which humans are modelled by very simple rules but, progressively, introducing human complex reasoning in the simulation process. This will enable the construction of a very realistic multi-agent ecological simulator system that will be a big step for the correct management of environmental resources towards sustainable development.

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