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Integration of socio-economic and bio-physical models to support sustainable development

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Abstract: The world we live in is complex and ever-changing. With a wide range of driving forces continuously acting within and upon it, causing actions and reactions, it is crucial to adopt a holistic view when trying to understand its behaviour. When modelling parts of our surroundings it is therefore not enough to focus merely on the individual processes affecting a region, but it is necessary to look at the system as a complex integral whole. The MedAction Policy Support System (PSS) aims to do just that by incorporating socio-economic as well as physical processes and paying much detail to the strong interlinkages between them.

The MedAction PSS aims to support policy-makers in arid and semi-arid regions in understanding the impacts of autonomous developments *within* a region (e.g. farmer behaviour, interaction and allocation of different land use functions within the region) as well as the impacts of external influences *on* the region, such as economic and demographic growth or climate change. It enables its users to carry out what-if analyses of various policy alternatives. Impacts can be measured by means of a number of policy relevant indicators, such as profits in the agricultural sector, forested area, water use and availability, land degradation and land use changes.

The system is composed of several sub-modules, integrated into a single model that simulates regional developments up to 30 years into the future. Each process is modelled at the appropriate temporal and geographical resolution, e.g. the land use module calculates on a yearly basis while the hydrology module has a variable time step in the order of minutes. The finest spatial resolution is 100 by 100 meters.

Driving forces in this system are demographic and economic growth as well as climate change. The socio-economic growth is translated into changes in the demand of the different land use functions in the region. The allocation of these land use demands is based on cellular automata interactions, a transport network, zoning, and suitability maps for each land use category. For two of these land use categories, agriculture and natural vegetation, there is a dynamic suitability map, changing every year based on the physical aspects of the system (soil moisture, salinity, slope, temperature) which, in turn, reflect the current state and history of climate and land use. These changing physical aspects are calculated in the climate, hydrology and vegetation modules and are influenced by social processes such as water use and land management practices. Besides a dynamic suitability map for agriculture used in the land use module, there is also a dynamic suitability map for each crop type, which is used in the crop choice module. This module calculates what type of crop will grow on the agricultural cells, based on the dynamic physical suitability, the crop price, the water price and use, and the social aspects that influence farmers in their decision-making.

In this paper we will focus on the integration of the socio-economic and bio-physical processes and discuss a number of problems we encountered. Furthermore we will discuss how the MedAction PSS can be used in sustainability impact assessment (SIA) studies as required by the Commission of the European Communities (2002) and discuss the importance of tightly coupled socio-economic and physical modelling in doing so.

Keywords: *Policy Support System (PSS), model integration, feedback loops, desertification, sustainability impact assessment (SIA)*

1. INTRODUCTION

Land degradation and desertification are important issues in arid, semi-arid and dry sub-humid regions. Climate change in combination with socio-economic processes acting on the land may induce a reduction of resource potential. Looking to mitigate these problems, the European Commission funded among others the research project '*MedAction: Policies to combat desertification in the Northern Mediterranean region*' in which the MedAction Policy Support System (PSS) has been developed. According to the 'Text of the United Nations Convention to Combat Desertification' as provided by the United Nations (1994) 'combating desertification' includes activities which are part of the integrated development of land in arid, semi-arid and dry sub-humid areas for sustainable development which are aimed at:

1. prevention and/or reduction of land degradation;
2. rehabilitation of partly degraded land; and
3. reclamation of desertified land.

In this definition the term 'sustainable' is used. In this paper we follow Papadimitriou's (1998) sustainability definition: 'A rural landscape is defined as sustainable under its contemporary land management and land-use regime if two conditions hold:

1. the landscape is physically viable for the present and the future; and
2. the population acting on and living from the natural resources of the landscape is socio-economically viable in the present and the future.'

The MedAction PSS has been developed with the aim of providing a support tool for policy makers confronted with land degradation and desertification. The aforementioned concepts and definitions have guided us in the initial development of the system to set the context and select the main processes to be incorporated. The system has been developed as a generic system and has been applied to the Marina Baixa and Guadalentín river basin in Spain, the Argolidas in Greece and the Jeffara region in Tunisia (the latter as part of the ongoing EC FP6 DeSurvey project, see also Van Delden, et al., this conference). For the European applications the same model components were applied, but for the Tunisian application some changes had to be made, mainly to the socio-economic components, since the social structure differed from the European context.

MedAction supports policy-makers having to intervene in a complex human-natural system. It is built from the belief that this kind of intervention requires addressing the system as an integral entity rather than focussing on individual processes affecting a region. For this reason it tries to apply scientific research to the support of policy-making through the construction of an integrated model based on scientific knowledge from previous European research projects, policy measures and policy relevant indicators. MedAction is implemented with the GEONAMICA software environment, which enables a user to develop and run fully coupled multi-scale dynamic spatial models featuring complex feedback loops. Moreover, GEONAMICA provides a user-friendly interface with tools for visualisation and analysis of the outputs generated.

This paper describes the choices made in the development of the system and specifies how the interlinkages between the socio-economic and bio-physical processes have been in incorporated. We discuss the problems we experienced, the solutions found and the remaining challenges. Furthermore, we explain the importance of a tight coupling of socio-economic and bio-physical processes when conducting a sustainability impact assessment study.

2. DYNAMIC SPATIAL MODEL INTEGRATION TO SUPPORT POLICY MAKING

The most important reason for model integration is that it enables to treat the real world system as an integral entity rather than a number of individual processes. Since actions in one policy sector can almost never be taken without having an impact on other sectors it is important to understand what the impacts are of the measures a policy maker can impose and how these actions will interact with (re)actions of the other actors in the system. The understanding of all parts of the system, their interlinkages and the non-linear aspects that arise can be supported by an integrated computer model.

The MedAction PSS incorporates a dynamic spatial integrated model. It integrates 15 individual models with different modelling paradigms and temporal resolutions varying from minutes (for the rainfall and erosion models) to a year (for the land use and crop choice models). It has a finest spatial resolution of 1 ha grid cells.

The choice for dynamic modelling has been made because important driving forces and processes change over time, and actions and developments that have taken place are very often not reversible, indicating a path-dependency of developments. The choice for spatially explicit modelling is twofold. Firstly the characteristics of a specific location are very important for the land use at that location as well as the physical processes that take place on that location - e.g., soil characteristics influence plant growth and steep slopes are not the best locations to build industrial complexes on. A second reason for spatial explicit modelling is that aspects in the surroundings of a specific location are important for the changes occurring on that location: land use functions will attract or repulse each other, natural vegetation types can spread through seed dispersal, economies of scale in agriculture can be reached by farming plots with similar crop types next to each other, and runoff from upstream areas has a major impact on the downstream areas.

Choices about the different scales and resolutions are made based on the scale and resolution regional policy-makers make decisions on and on expert opinions of scientists about the scale and resolution that different processes can best be represented on from a scientific point of view. More information on the choice of temporal and spatial scales and resolutions can be found in Oxley et al. (2004).

3. DEVELOPMENT OF THE INTEGRATED MODEL

The conceptual diagram has been the basis of the development of the quantitative integrated model. It represents all important processes and their relations to each other. The conceptual diagram of MedAction is designed based on three pillars:

- The concepts of combating desertification and sustainable development as described above;
- Scientific literature and models of desertification processes;
- The relations between policy themes and available models.

An important issue in model integration is to have a focus for the integrated model without setting the aim too narrow, risking the final system to be only suitable for one specific policy problem. The important desertification processes found in literature have been discussed with policy makers from the region. This has resulted in the selection of three policy themes, which are highly interconnected: land degradation & desertification, water resources and sustainable agriculture. For each of these themes the main problems, goals, policy options and policy indicators have been collected, structured, and linked to the relevant processes described above. Based on this framework, and the availability of models representing the important desertification processes, the conceptual diagram presented in figure 1 has been developed and used as a basis for the design and development of the integrated quantitative PSS (Van Delden et al., 2004; Van Delden et al, 2007). Details about the models incorporated can be found in Van Delden et al. (2007), a summary of this is provided below.

Drivers are grouped into 1) external factors that cannot be changed by (regional) policy makers, 2) policy options on which they have an influence and 3) management options related to decisions farmer's make for their agricultural practice. Main external drivers are climate change and variability, market prices for crops, occurrence of forest fires and demand for land use based on population and economic developments. Main policy options are decisions related to subsidies, taxes, water pricing, water allocation, maximum extraction of water from the aquifer and reservoirs, construction of infrastructure, zoning and reforestation. Land management options include grazing, ploughing, terracing and choosing spray or drip irrigation.

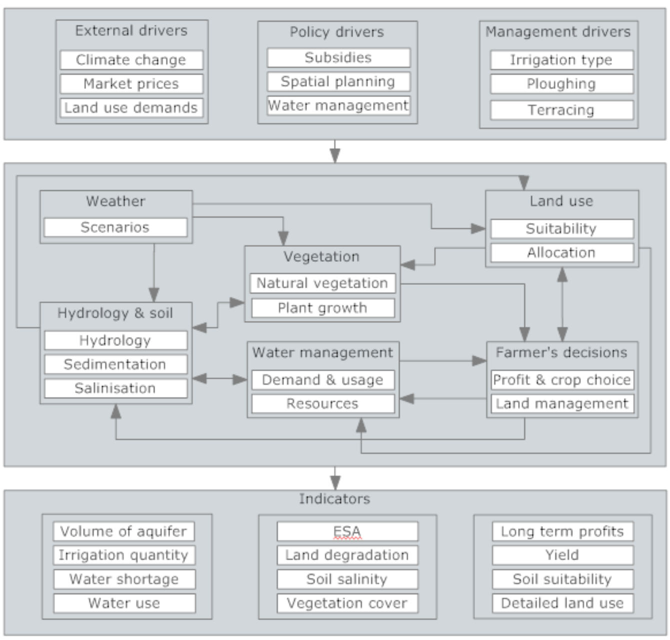

Figure 1: System diagram of the MedAction PSS

Climate processes are represented by means of three regional climate scenarios, derived from global circulation models, as well as a zero change scenario. Based on these climate scenarios, monthly temperature, daily solar radiation and sub-hourly rainfall storms are generated. Using locational characteristics together with information from weather stations in the region, rainfall storms and temperature are spatialised to provide more accurate information. Output from the weather generator is used in the hydrology and soil module to calculate the hydrological cycle including infiltration, run-off, evaporation, soil moisture and aquifer replenishment and in the plant growth module to calculate the changes in biomass, leaf area index and vegetation cover for both natural vegetation and crops types. More information about these biophysical models can be found in Mulligan (2004).

Information from the bio-physical models is used in the suitability component to link the physical suitability of locations to the yield of the farmers and the development of natural vegetation in the natural vegetation model. Dynamic suitability maps represent the changes in (yield) biomass based on stress factors, similar to those mentioned by Yassoglou (2000) and Thornes (1999): soil salinity, fertile soil depth, soil moisture, and temperature. They are recalculated on a yearly basis using up to date model output from the physical sub-models. Response curves for the different plant types, describing the relation between plant growth and the physical variables, are applied to transform the model output into suitability values ranging between 0 and 1 (1 being very suitable, resulting in a maximal possible growth). This is schematised in detail in Figure 2.

The stress factors mentioned for the production of yield are in turn influenced by human behaviour, either in a positive or a negative way. Irrigation plays a major role in the salinity of the soil and terracing and ploughing can have a significant impact on soil erosion. Moreover, crop choices are crucial for the agricultural water demand as well as for the erosion of the soil. A similar concept is followed for the natural areas, although the human drivers are slightly different here. Instead of water extraction and irrigation, grazing and forest fires are important drivers induced by human behaviour.

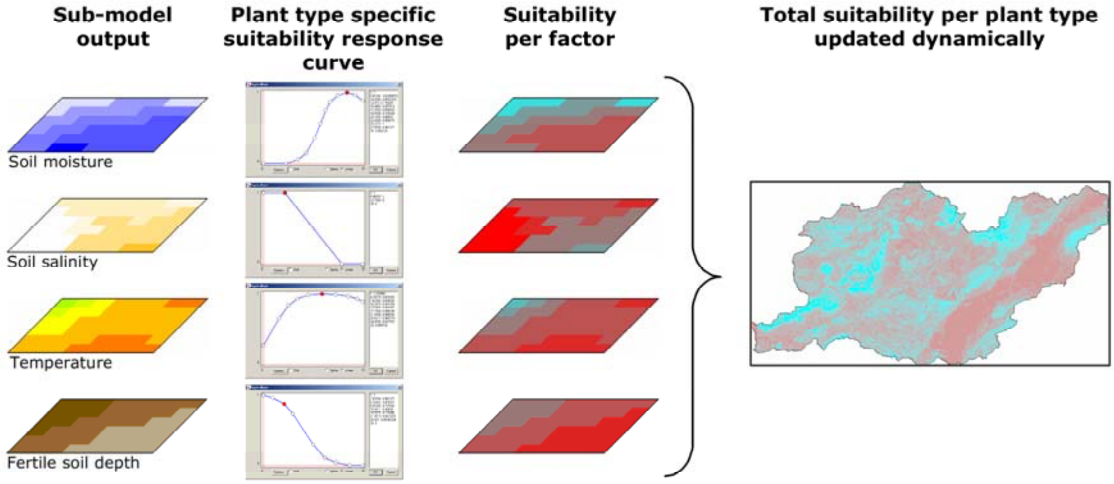

Figure 2: Dynamic suitability maps are updated yearly. Plant-specific suitability response curves (2) are applied to factor maps, which are the output of the physical models (1), and transformed into suitability maps per factor (3). The latter are combined into a suitability map (4) per crop type using a minimisation function.

Integration between socio-economic and bio-physical processes mainly takes place through land and water resources. Between the different land uses there is a competition to obtain the best locations. The land use allocation model simulates this process using a constrained cellular automata approach that includes the physical suitability of a location, its zoning regulations, the accessibility and the impact of the surrounding land uses (White & Engelen, 1997). Since this model is very well suited to distinguish between main land use classes, but less for simulating crop choice decisions and changes in the natural vegetation, this model is complemented with a utility based crop choice model and a rule-based model that simulates transitions in natural vegetation groups. Decisions on the selected crop types are based on financial (subsidies, market prices, costs), physical (expected yield based on water availability and land suitability) and social aspects (combined in a willingness to change).

Land use allocation, together with land management decisions (irrigation, terracing and ploughing), have an impact on the suitability of the land, which has in turn an impact on the land use. If, for example, a farmer decides for irrigated agriculture and irrigates with water with a high salt concentration, this will have an impact on the suitability of the soil. In a few years, this might results in a degradation of the soil that might result in a decision of the farmer to grow another, more salt resistant crop, or even abandon the land. Land abandonment is an important process in Mediterranean regions, as is mentioned by among others in Papadimitrou & Mairota (1998). In the PSS the process of land abandonment is incorporated by allowing non-profitable agricultural land to be taken over by natural vegetation. On the other hand, urban expansion is also an important driver in the conversion of natural and agricultural land to land for residential, commercial, recreational and industrial uses.

In reality numerous drivers lead to an emphasis on land-use conflicts ultimately linked to the problem of water: improved standards of living, the rise of tourism, the intensification of agriculture, the shift to irrigated agricultural production for export, and the continued drift to an urban society, accompanied by rural depopulation (Grenon and Batisse, 1989). Margaris et al (1998) adds to this that the main driving forces for the Mediterranean primary sector are socio-economic trends related to consumer characteristics. The PSS includes the main drivers of water use and supply. Assumptions on the increased use of water per resident or tourist can be included to represent the improved standards of living. Furthermore the user is able to investigate the impact of a growth in the tourism sector by raising the demand for tourism. Including higher market prices for irrigated crops in the crop choice component reflects the higher demand for agricultural production for export.

The water management model calculates the water budget of the different sources based on extraction by socio-economic functions and replenishment through hydrological processes. The model allows policy makers to manage the available resources in a sustainable manner, because as Llamas (1997) has pointed out, the so-called crises of water is really a crisis of water management rather than a simple crisis of overexploitation and physical depletion, as is often claimed. Recent developments have brought the rural areas of Mediterranean Europe into a more rather than a less marginal condition, especially with respect to water, largely because of the higher level of dependency.

Rainfall from the weather generator and hydrology model takes care of the replenishment of the aquifer and the reservoir. In addition to this supply, there is a policy option to replenish the reservoir through inflow from water outside of the region (e.g. in the Guadalentin river basin the Tajo channel transport water from the Ebro in the north of Spain to the southern Guadalintin river basin. Water is used by the different land use functions. Dryland crops and natural vegetation obtain of their water requirements through transpiration which is based on amongst others the soil moisture. For irrigated crops irrigation takes place when the soil moisture is not sufficient for crop growth. All socio-economic land uses are in competition with each other for the water resources and decisions on the extraction and the allocation can be set as policy options.

4. DIFFICULTIES EXPERIENCED IN MODEL INTEGRATION

A first problem that arose when trying to integrate the socio-economic processes with the bio-physical processes was the delineation of the spatial boundaries of the system. All bio-physical data and models were available at a catchment or sub-catchment scale, while most socio-economic data and models were available for administrative regions. For this application the Guadalentín catchment is defined as the spatial boundary. This catchment contains parts of two administrative regions: Murcia and Almeria. We have downscaled socio-economic data (population, jobs) from the regional level of both provinces to the cellular level using a land use map, and subsequently derived the required socio-economic information by an aggregation of the cellular information within the catchment.

We also experienced difficulties in getting together the data to set-up, calibrate and validate the system. Data availability varied amongst the different components and very often data for different models was available for different points in time. In the end we decided to take 2000 as the initial year of the simulation, because we had a land use map available for 2000. All other initial data was converted to data for the year 2000. For the calibration process we decided to first calibrate all individual models separately, in a second step we grouped the models and finally we tested and calibrated the complete integrated model. For most of the models, data for calibration was available. Data and time for validation were lacking and therefore a validation has not yet been carried out.

When linking the bio-physical and socio-economic processes we faced the problem of integrating daily (or sub-daily) models for hydrology, erosion, salinisation and plant growth with yearly models for land use change and farmer's decisions on crop choice. We decided to let the process guide the aggregation. For soil salinity and fertile soil depth we have chosen the latest values, since they represent the current state of these factors. For soil moisture and temperature the average is taken over the representative period for the growth of the specific plant; e.g. given that for plant type Y the temperature in April and May is crucial, only the average of these two months is taken into account. To compensate for climate variability we have used 3 to 5 year averages.

The MedAction PSS links a process model for plant growth with a rule based model for simulating transitions in natural vegetation type groups. Transitions from one natural vegetation type group to another are amongst others based on the height of the vegetation and the vegetation cover, both calculated in the plant growth model. However, when a transition takes place all new characteristics of the new vegetation type group are adopted which caused some shocks in the system. By creating a more gradual transition we were able to overcome some of the problems, but we feel that there are still remaining challenges in linking models that simulate a continuous process and models that simulate transitions.

5. SUPPORT FOR SUSTAINABILITY IMPACT ASSESSMENT

The MedAction PSS is developed under the assumption that simulation models can assist in decision-making by improving the understanding of the system. The system tries to *represent* processes happening in reality. It is not meant for *normative* optimisation; rather it should be used for *exploration* of different options. The system is developed to provide support in a policy context and therefore has time horizon similar to a strategic policy horizon: 30 years.

In 2002 the Commission of the European Communities has sent out a communication stating that gradually from 2003 the process of impact assessment will be implemented in the Commission for all major initiatives (Commission of the European Communities, 2002). The impact assessment should identify the likely positive and negative impacts of proposed policy actions, enabling informed political judgements to be made about the proposal and identify trade-offs in achieving competing objectives. The MedAction PSS aims to support this process by analyzing the impacts of a wide range of policy options (e.g. reforestation, zoning regulations, construction of infrastructure, restrictions on aquifer extraction, water pricing, subsidies and taxes) on a range of social, economic and environmental indicators. Furthermore, the user is able to assess the impact under a range of external factors which enables him or her to explore the sensitivity of the proposed measures under different external conditions. Since the MedAction PSS has strong interactions between the different processes incorporated, it is able to provide information on (unwanted) side effects, trade-offs that need to be made and win-win situations that can be created.

As part of the MedAction project a scenario study was conducted with the MedAction PSS. In this study regional policy-makers, farmers, farmer corporations, tourist agencies, residents, scientists and ‘free thinkers’ were selected as stakeholders. This exercise showed that the MedAction system could deal with the range of drivers and indicators that were found important in the scenarios (Kok and Van Delden, 2007).

6. DISCUSSION AND CONCLUSIONS

In carrying out impact assessment studies it is important to understand the interrelation between the different disciplines. Integrated models that capture the interconnectedness of real-world systems can improve the understanding of the impact of different policy options on social, economic and environmental indicators.

In the MedAction PSS there is a tight coupling between socio-economic and bio-physical processes. The reciprocal nature of land use & management and land suitability is modelled through feedback loops between the respective model components. Land suitability is composed of a number of bio-physical factors that can be impacted by the choice of land use and management, while the choice of land use and management depends on the underlying conditions of the location. Another important link between socio-economic and bio-physical processes can be found in issues related to water management. Where the bio-physical processes are the main source for replenishment of the aquifers and reservoirs, the socio-economic functions are the main uses of water, being it irrigation, cooling water, drinking water or water for recreation. However, also human interventions can play a role in the water management and supply. Political decisions to transfer water from one region to the other or technological developments to desalinise water from the sea have an impact on the water supply. On the other hand, decisions to farm a crop with less water requirements impact the water demand.

The MedAction PSS helps to support an in-depth analysis of the potential impacts of (a combination of) policy options and external factors on the economy, on society and on the environment. Because the MedAction PSS has strong interactions between the different processes incorporated, it informs on (unwanted) side effects, exposes trade-offs and enables win-win situations.

In integrating models from different disciplines, with different spatial and temporal resolutions and developed based on different modelling paradigms, we faced a number of challenges. We feel we have made good progress in linking socio-economic and bio-physical processes and in coupling models with various temporal and spatial resolutions, but still see major challenges in creating feedback loops between models developed on different modelling paradigms.

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