Integration of multi-scale dynamic spatial models for land use change analysis and assessment of land degradation and socio-economic processes

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Research context

- Two EC–projects: MODULUS and MedAction
- Research questions and aims:
  - Can existing scientific material be integrated and made useful to policy makers?
  - Develop a generic tool for integrated decision and policy–making in the domains of desertification, land degradation, spatial planning and water(shed) management;
  - Build, apply, and test the system as part of a collaborative effort between EU–researchers and regional planners.
Goals of the MedAction PSS

- A generic system for technicians supporting planners and policy-makers at the regional level in the context of desertification

- To be used for problems with a high level of abstraction:
  - Strategic policy plans with time horizon 20–30 year
  - What-if analysis, integrated assessment and communication

- Consists of scientific models from former EU-projects:
  - Integrated assessment not comprehensive
  - Strong interlinkages between all models

- To support decision and policy making:
  - Linking policy themes, measures and indicators
  - User-friendly interface
What is desertification?

The United Nations defines it as:

‘The degradation of arid, semi-arid and dry sub-humid zones resulting from different factors like climate change and human activities.’
The extent of the problem

- Desertification threatens the well-being of +/- 1 billion people worldwide;
- 30% of the land surface of the earth is already affected;
- Each year 10 million hectares of land are permanently degraded.
Desertification

- Overexploitation of land and water resources
- Land management
- Climate change
  - Rainfall
  - Temperature
- Land degradation
- Salinisation
- Erosion
- Deforestation
- Land abandonment
- ...

Possible solutions

- Changing the way the land is managed:
  - Other ways of ploughing;
  - New irrigation methods;
  - Irrigation with less saline water;
  - Changing the crop types;
- Diminish the amount of water used;
- Reforestation.
Problems and conflicts

- It is not always clear what the impacts are and how processes influence one another;

- Difference in goals and values:
  - between different types of farmers;
  - between the tourist sector and the agriculture;
  - between the economy and the nature.

- Policy-makers work in different sectors which results in sectoral decision-making.
Conclusions regarding desertification

- It is a very complex problem with many processes, actors and relations;

- Some problems can be solved through investigation and education;

- But others can only be solved through a consideration of the objectives of the different actors in an integrated planning process.
## Structuring the important elements

<table>
<thead>
<tr>
<th>The mes</th>
<th>Policy measures</th>
<th>Indicators</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Sustainable farming</strong></td>
<td>• Subsidies, taxes</td>
<td>• Profit</td>
</tr>
<tr>
<td>Long term profits</td>
<td>• Water price</td>
<td>• Crop type</td>
</tr>
<tr>
<td>Sustainable land use</td>
<td>• Water availability</td>
<td>• Number and location of abandoned cells</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Dynamic suitability maps</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Irrigation water used from different sources</td>
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<tr>
<td></td>
<td></td>
<td>• Amount and cost of irrigation water</td>
</tr>
<tr>
<td><strong>Water resources</strong></td>
<td>• Water availability and price</td>
<td>• Change in aquifer and reservoir budget</td>
</tr>
<tr>
<td>Availability and price of water</td>
<td>• Amount of water from outside the region</td>
<td>• Natural water input (runoff and recharge)</td>
</tr>
<tr>
<td></td>
<td>• Construction of desalination plants</td>
<td>• Costs and amount of water used</td>
</tr>
<tr>
<td><strong>Land degradation &amp; desertification</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Erosion</td>
<td>• Afforestation</td>
<td>• Fertile soil depth</td>
</tr>
<tr>
<td></td>
<td>• Grazing regulations</td>
<td>• Erosion rates</td>
</tr>
<tr>
<td></td>
<td>• Construction of check dams</td>
<td>• Change in storage capacity of reservoir</td>
</tr>
<tr>
<td></td>
<td>• Dredging</td>
<td>• Total cost of dredging</td>
</tr>
<tr>
<td>Preservation of nature and forests</td>
<td>• Afforestation</td>
<td>• Forested area</td>
</tr>
<tr>
<td></td>
<td>• Zoning</td>
<td>• Changes in natural vegetation type groups</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Dynamic suitability maps</td>
</tr>
<tr>
<td>Salinisation</td>
<td>• Maximum amount of water available from aquifer and desalinated water</td>
<td>• Soil salinity</td>
</tr>
<tr>
<td></td>
<td>• Maximum allowable percentage of salt in water from desalinated</td>
<td>• Salt concentration in the aquifer</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Restricted factor for plant growth (yes/no)</td>
</tr>
<tr>
<td>Sustainable land use in region</td>
<td>• Zoning</td>
<td>• Land use map</td>
</tr>
<tr>
<td></td>
<td>• Construction of infrastructure (dams, roads, channels)</td>
<td>• Dynamic suitability maps</td>
</tr>
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<td></td>
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<td>• ESA</td>
</tr>
</tbody>
</table>
Main characteristics of the MedAction PSS

- Integrates processes in a mutually interlinked manner: Climate, Hydrology, Vegetation, Crop choice, Land use.

- Processes are represented at the appropriate temporal scale: Daily, Monthly or Yearly;

- Processes are represented at the appropriate spatial scale: Catchment, Sub-cathment or Cellular entity: 1ha.
Problems to be solved

- Integrating models with different:
  - modelling paradigms
  - temporal resolutions
  - spatial resolutions

- Linking science to policy-making
  - policy themes:
    - external factors, policy options, indicators
  - usefulness, practicality, willingness
Physical drivers: Changing precipitation and temperature
The integrated model: Climate & weather

**Stochastic weather generator based on climate scenarios and calibrated on information available from weather stations**

- solar radiation \(f(\text{slope, aspect, time, cloud cover})\)
- net radiation \(f(\text{cover, solar radiation})\)
- PAR radiation \(f(\text{solar radiation})\)
- rainfall and temperature distribution \(f(\text{location, altitude})\)
The integrated model: Hydrology

Process model representing the soil hydraulic processes, water budget, river flow, erosion and soil salinity
Hydrology and soil: sub-modules

- Canopy interception $f$(LAI, vegetation cover, leaf type)
- Evapotranspiration $f$(soil water, vegetation cover, LAI, solar radiation, canopy storage, stone contents)
- Infiltration $f$(rainfall, runoff, infiltration capacity)
- Recharge $f$(soil moisture, K, stoniness)
- Soil moisture $f$(runon, infiltration, evapotranspiration, recharge, pore space)
- Runoff $f$(precipitation, slope angle, infiltration),
- Transmission loss $f$(size of channel, geology)
- Groundwater budget $f$(recharge, pumping)
- Groundwater salinisation $f$(recharge, soil salinity, water sources)
- Soil salinisation $f$(precipitation, irrigation, soil properties, evapotranspiration)
- Soil erosion, $f$(slope, runoff, vegetation, soil properties)
Hydrology & soil
Hillslope hydrology
Erosion
Salinisation
Integrating physical and socio-economic processes

Dynamic suitability maps based on temperature, soil moisture, soil salinity, soil depth, slope and plant properties

Temporal resolution:
- Daily
- Rainfall storms

Temporal resolution:
- Year
Construction of dynamic suitability maps

Sub-model output:
- Plant specific suitability response curve

Integration:
- Average over defined period

Soil moisture
Integration:
- Latest values

Soil salinity
Integration:
- Average over defined period

Temperature
Integration:
- Latest values

Slope & soil depth

Total suitability changing every year affects land & crop choice

Land suitability allocation

Integration:
- Average over defined period

Integration:
- Latest values

Integration:
- Latest values

Rules of combination:
Max:
\[ s = \max_i (s_i) \]

Min:
\[ s = \min_i (s_i) \]

Weighted sum:
\[ s = \frac{\sum_i w_i \cdot s_i}{\sum_i w_i} \]

Weighted product:
\[ s = \left( \prod_i s_i^{w_i} \right)^{1/\sum_i w_i} \]

Inverse weighted product:
\[ s = 1 - \left( \prod_i (1 - s_i)^{w_i} \right)^{1/\sum_i w_i} \]
Socio-economic drivers: Changing land claims, prices and markets
Two step land use allocation

System diagram

- Climate & weather
  - Scenarios
- Hydrology & soil
  - Hillslope hydrology
  - Erosion
  - Salinisation
- Water management
  - Demands
  - Resources
- Farmer's decisions
  - Profit & crop choice
  - Land management
- Vegetation
  - Natural vegetation
  - Plant growth
- Land use
  - Demands
  - Suitability
  - Allocation
Two step land use allocation

Dynamic cellular automata model based on:
- physical suitability
- zoning
- accessibility
- spatial interaction

Constrained by:
- Economic and demographic scenarios based on statistics
Two step land use allocation

Utility function based on:
- physical aspects: yield, suitability, water resources
- financial aspects: crop price, costs, subsidies, ...

In combination with:
- social aspects: willingness to change
Two step land use allocation

Rule based transition model based on
- height,
- vegetation cover,
- seed dispersal,
- fire prevalence, and
- grazing

Land use allocation

Natural vegetation
Two step land use allocation

1. Land use allocation
   - Demands
   - Suitability
   - Allocation

2. Farmer's decisions
   - Profit & crop choice
   - Land management

3. Land use allocation
   - Natural vegetation
   - Plant growth

4. Profit & crop choice
   - Micro-scale dynamics
The integrated model: Plant growth

Plant growth module represents the process of growth of crops and natural vegetation

- Plant growth (biomass) and partitioning: $f(PAR, T, \text{soil moisture}, \text{plant characteristics}, \text{soil salt})$
- Cover and leaf area index: $f(\text{plant characteristics, biomass})$
- Strongly interconnected with hydrology model
The integrated model
The integrated model: Farmer’s decisions

- **Profit & Crop choice**
  - Yearly profits $f(yield, crop\ space, costs)$
  - Crop choice $f(expected\ profits: expected\ yield, suitability, water resources, water price, other costs, crop price, social aspects)$
  - Number of years a cells is covered by a certain crop type

- **Land management**
  - Irrigation: spray and drip
  - Ploughing: removing the crust
  - Terracing: leveling and maintaining
The integrated model
The integrated model
### The integrated model: Water management

#### Water budget calculations based on water replenishment from runoff, recharge and Tajo and extraction from different functions

#### Water demands

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Demand per unit (m³/unit)</th>
<th>Demand per sector (m³)</th>
<th>Policy restriction (m³)</th>
<th>Final demand (m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Agriculture</td>
<td>100.00</td>
<td>100.00</td>
<td>100.00</td>
<td>100.00</td>
</tr>
<tr>
<td>Residential</td>
<td>100.00</td>
<td>100.00</td>
<td>100.00</td>
<td>100.00</td>
</tr>
<tr>
<td>Industry and commerce</td>
<td>100.00</td>
<td>100.00</td>
<td>100.00</td>
<td>100.00</td>
</tr>
<tr>
<td>Tourism</td>
<td>100.00</td>
<td>100.00</td>
<td>100.00</td>
<td>100.00</td>
</tr>
</tbody>
</table>

#### Water demands; Division of water

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Aquifer (m³)</th>
<th>Reservoirs (m³)</th>
<th>Desalinated water (m³)</th>
<th>Total (m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Agriculture</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Residential</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
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<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
</tbody>
</table>

#### Water resources

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial volume of water in the aquifer (m³)</td>
<td>10000.00</td>
</tr>
<tr>
<td>Initial volume of water in reservoirs (m³)</td>
<td>1000000.00</td>
</tr>
<tr>
<td>Yearly input from Tajo (m³)</td>
<td>1000000.00</td>
</tr>
<tr>
<td>Yearly capacity of desalinated water (m³)</td>
<td>80000.00</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Policy maximum out (m³)</th>
<th>Price (€)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aquifer</td>
<td>0.00</td>
</tr>
<tr>
<td>Reservoirs</td>
<td>1000000.00</td>
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<tr>
<td>Desalinated water</td>
<td>80000.00</td>
</tr>
</tbody>
</table>

#### Outputs

<table>
<thead>
<tr>
<th>Replenishment (m³)</th>
<th>Extraction (m³)</th>
<th>Current volume (m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aquifer</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Reservoirs</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Desalinated water</td>
<td>0.00</td>
<td>0.00</td>
</tr>
</tbody>
</table>
Using the MedAction PSS

**External factors:**
- Climate change;
- Land use claims;
- Crop price;
- Capacity of desalinisation plants;
- ...

**Policy options:**
- Zoning / Reforestation;
- Subsidies and taxes for different crops;
- Restrictions on water use;
- Allocation of water among users;
- Water price from different sources;
- Construction of infrastructure (dams, roads);
- ...

**Indicators:**
- Land use changes;
- Natural vegetation changes;
- Erosion rates and soil depth;
- Soil salinity;
- Soil moisture;
- Suitability of the land;
- Water resources;
- Water use of different functions;
- Water use from different sources;
- Irrigation water usage;
- Crop type changes;
- Profit for farmers;
- ...

**Diagram:**
- Total reservoir sedimentation chart
- Profit and crop choice table
Compound Dynamic Indicators: Environmentally Sensitive Areas (ESA’s)

Source: C. Kosmas, A. Ferrara, H. Briassoulis and A. Imeson, 1999
Providing integrated policy information

- Land degradation & desertification:
  - ESA

- Water management:
  - Water shortage

- Sustainable agriculture:
  - Farmers’ profit
Conclusions (1)

- Model integration
  - Dynamic suitability maps
  - Two step land use allocation
- Linking science to policy making
  - Connection to *process* as well as *context*
  - Policy-relevant themes, measures, indicators
  - Usefulness, practicality, willingness
- The MedAction PSS
  - Running prototype
  - More calibration and interaction with end-users necessary to bring it to the next level
Conclusions (2)

- Appropriate integrated modelling is a major effort. It requires good scientific knowledge on individual models and model integration as well as teamwork and commitment for the overall product. Communication plays a crucial role.

- Often resources are lacking for a good calibration, validation and uncertainty analysis, and pragmatic choices have to be made.

- A DSS has to answer policy questions in the right context and at the right scale. Therefore end-user interaction is essential!

- To actually use a DSS an implementation plan and training sessions have to be included in the development process.
Thank you for your attention!

More information:
www.riks.nl/Projects/MedAction