New directions and challenges in spatial dynamic modelling of ecosystem functions in heterogeneous landscapes as basis for a better sustainable landscape management

Karl-Otto Wenkel, **Ralf Wieland, Wilfried Mirschel**

Centre for Agricultural Landscape Research (ZALF), Institute of Landscape Systems Analysis, Eberswalder Straße 84, D-15374 Müncheberg, Germany,
wenkel@zalf.de, rwieland@zalf.de, wmirschel@zalf.de

Abstract: The aim of this paper is to discuss scientific challenges and new possibilities for a better modelling of consequences of land use changes in heterogeneous landscapes on ecosystem functions in space and time. The landscape or regional scale means an area of about 100 km^2 up to some 1000 km^2. Main problems on this scale are high complexity, structural diversity, ecological heterogeneity and uncertainty in data, in understanding of the process dynamic and by uncertainty in models.

***Keywords**:* sustainable land, climate change, reduced resources availability, ecosystem models, fuzziness, dynamic processes, software tool boxes, landscape indicators, neural network, genetic algorithms

1. WHY WE NEED BETTER MODELS ON THIS SCALE?

Sustainable development and sustainable land use management together with increased awareness of climate change and reduced resources availability have been received increasing attention around the world (Hurni 2000). Practical tools and models which can be used for a better sustainable landscape management at local and regional levels have emerged however only recently. The development of such models, which can be used for the quantitative or qualitative characterization the sustainability of land use systems therefore is a major challenge for ecological and environmental modelling worldwide.

During the past decades marked progress has been achieved in ecosystem modelling. These developments have stimulated first attempts to put together separate ecosystem models with GIS to first prototypes of integrated landscape models, first in form of coupled comprehensive process models. Process and ecosystem models in ecology traditional are developed for the one-dimensional case (point model), i.e. only for selected points within an area. Examples for such process models are the soil-plant-atmosphere models such as CERES (Ritchie & Godwin, 1993), WOFOST (Supit et al., 1994), DAISY (Hansen et al., 1990), STICS (Brisson et al., 2003), AGROTOOL (Poluektov et al., 2002), HERMES (Kersebaum, 1995) or AGROSIM (Mirschel et al., 2001) with different focuses. An overview on agro-ecosystem and ecological models is given in CAMASE (2005).

These models describe processes in a greater detail and need a lot of information as driving forces or as parameter inputs. In a regional scale it is difficult to provide all this information. Here the available information is characterized usual by a significant fuzziness. The often proposed idea of a nested modelling approach, that means the combination of point models using spatial information and approximation, can be therefore not the optimal solution. Other limitations in the application of such comprehensive ecosystem models arises from the difficult parameterization of comprehensive models and their high computational costs.

On the other hand there are conceptual models, which cannot use for describing of dynamic processes, or models which were developed for the global scale. Examples for the latter are some types of climate models or macroeconomic models. The spatial resolution of climate models is often to broad for regional studies. Macroeconomic models usually do not use a spatial modelling context. As a consequence these models can be used in principle only to describe the boundary conditions for regional models.

In a region there are a lot of processes which are related to different scales. For example, biotic processes described by habitat or population models refer to the regional scale. On the other hand some abiotic processes such as matter flow described by wind or water erosion models, or diffuse fluxes of nitrogen or phosphate to rivers or lakes are strongly influenced by regional sources within their catchments and of the heterogeneity of the land use types. Those water catchments often are in focus of regional policy.

Another example is the regional energy production using by wind or alternatively by energy crops. This new orientation of land use provides new possibilities for a whole region, but it is not free from ecological problems, in particular if the land use structure and intensity is not managed sustainable enough. In all cases it is necessary to investigate the spatial-temporal impacts of different local realized land use activities on the environment and its sustainability at the regional scale.

Landscapes, the subject of landscape management, are complex, spatially and temporally multilayered systems, which change and develop naturally but are also subject to anthropogenic changes (LAUSCH, 2003). To analyse, evaluate and manage them, tools and models are required, which can be used to represent and interpret the variety and complexity of the connections between biotic and abiotic landscape structures and functions and are able to assess the complex impacts of natural and anthropogenic land use and climate changes as reliably as possible.

In spite of substantial progress has been made in the development of more integrated ecosystem models in the last years, integrated space and time-related dynamic landscape models are exceptions up to now. The development of such integrated regional models is a very ambitious task and require an “own inter-methodical approach” (LAUSCH, 2003). And yet this demand seems difficult as the variety and diversity of knowledge of one scientific discipline is increasing on the one hand, and on the other the necessary inter-methodical approach requires a high degree of creativity, versatility and openness in research.

2 The way forward

The raising need to sustainable resource management under condition of global change point out the need and importance of developing and using integrated dynamic landscape models in addressing resource management at regional scale. The development of such models and its use for sustainable landscape management is one of the most important challenges for the landscape ecology and landscape sciences for the next decade. If we have seen above, during the past decades marked progress has been achieved in ecosystem modelling. On the other hand up to now there is a lack of integrated dynamic landscape models, usable for sustainable resource management at regional or landscape scale.

To bridge the gap analogue to earth-system modelling new ways and methods are necessary in the landscape or environmental modelling also.

From the scientific point of view we are confronted with the following problems:

- How to reduce the high complexity of landscape processes within models?
- Are models of intermediate complexity a possible methodological way for the future? How we can adequate capture the functional consequences of structural diversity and spatial heterogeneity in the landscape models?
- How we can ecological process feedbacks and long term developments adequate capture in landscape models?
  What means “ adequate “ ?
- Fuzziness in ecological functions and data and dynamic of processes- which model types and tools are best suitable for landscape modelling?
- How we can bring together conceptual different ecological and economic models?
- How much spatial resolution is required to appropriately capture processes with regional significance?
- How we can adequate include the spatially ecological heterogeneity and its influences on the ecosystem function?
- How many detail of process dynamic we can include into the regional models and what is to do for adequate modelling the interconnected feedback loops in regional landscape systems?

To find answers on this problems we need new ideas, new thinking and a shift in paradigm in integrated regional modelling.

We propose to go the following way:

- Selection and broad discussion of a set of landscape indicators usable for assessment the sustainability of land use systems and landscape development at regional scale.
- Development of new generations of integrated REgional Models Intermediate Complexity (REMICs), following the concepts of the climate modelling community.

- Intelligent combinations of simplified or aggregated process oriented dynamic models with statistical, fuzziness and other model types to new hybrid models
- Development and use of new software tool boxes for rational development and simulation of dynamic landscape simulation models
- Changeover to open source code in program development
- Development of new generations of tools for multi-criteria evaluation and visualization
- Improved validation of regional models through use of long term monitoring data of landscape study areas around the world

3 Choice of landscape indicators

Because landscapes are high complex systems, the first that is necessary is a carefully selected set of landscape indicators, which describe the landscape as a system and the complex long term consequences of land use in a more aggregated way. This implies that these indicators are related to different disciplines such as geology, economy, ecology or soil science. Additionally the modeller has to take into account that all this processes are interacting in space and time. The selection of problem and scale oriented indicator systems can not be completely free from subjectivism. To describe a region by indicators derived from the main regional processes, the indicator selection should be done in participative discussions together with stakeholders. In this process the choose indicators and there limitations should be critical evaluated and determined. The scientists have to develop models and approaches for a quantitative description, i.e. for the calculation of these landscape indicators in dependence on driving forces. These models have to be spatially precise so that they can be used for simulation runs as prerequisite for deducing possible future developments of the region which guarantee sustainability for the entire region.

3.1 REMICs

Currently an open question is, how much details in process dynamic and how much spatial resolution is required to get adequate precise answers on the socio-ecological impacts of land use changes at regional scale, which can be used to decision support in landscape management. Neither conceptual models on the one extreme nor three-dimensional comprehensive models at the other extreme seem to be the optimal solution for the future. **Re**gional **M**odels **I**ntermediate **C**omplexity (REMICs) could be an alternative. REMICs describe most of the processes implicit in comprehensive models, albeit analogue to climate models in a more simplified, reduced form. They explicit simulate the interactions among different components of the landscape system in a adequate way, including the feedback loops (Claussen et al., 2002). They are simple enough to allow long-term simulations at the landscape scale. An important feature of REMICs is, that they are characterized by a lower degree of details in description of process dynamic, but a higher number of interacting components.

3.2 Hybrid models

On the one hand in the landscape there are acting a lot of processes directly or with interactions or with feedback loops. All these processes are not only different in their content but also different in their time and spatial resolution. On the other hand within landscapes there are not enough information available or the available information are connected with more or less high uncertainty. In dependence on process detail and spatial data availability there it is necessary to have a large model base for description of landscape indicators with models different in type and complexity and different in input data demand and output data type. In most cases for describing landscape indicators new hybrid models are necessary, i.e. an intelligent combination of simplified and/or aggregated process oriented robust dynamic models with static and/or stochastic simulation models (empiric model, statistic model, regression model, neural network, fuzzy model ….). The new hybrid models also have to organize and manage the data interexchange between the submodels via model-own data interfaces on the base of maps or data bases.

4 Open source code

Open source software is software whose source code is published and made available to the public, enabling anyone to copy, modify and redistribute the source code without paying royalties or fees. Open source code evolves through community cooperation. For scientific open source software means, that everybody can understand the algorithms behind the program, is able to enhance it and give it back to the community. This leads to a fast error elimination, to the possibility to include new scientific methods and algorithms and at last to a high software quality. Another advantage of this strategy is that the data format specifications are available, this is a indispensable precondition for combining different models.

4.1 New tool boxes for development of landscape simulation models

Simulation systems, like Matlab for example, can handle simulation quite well but have shortcomings in spatial data handling. Geographic information systems (GIS), like ARCGIS, can handle spatial data well, but are not so suitable to perform simulations. What we need is a open source toolbox which is able to do both run simulations and handle spatial datasets. This toolbox should include:

- an interface to the GIS especially to read and write grids in ASCII ARCGIS format,
- a spatial data management system to store and load big spatial data sets with high speed (HDF-Format for example) and to exchange data with other simulation software,
- a connection to a database management system like MySQL to store all information (specific model parameters, parameters of the simulation, measured values to validate the models etc.) in a flexible way,
- a basic set of grid operations (normalize grids, multiply grids, add grids, etc.),
- a basic set of analysis functions, like histograms, statistical routines, etc. ,
- tools to handle expert knowledge (e.g. fuzzy models) and to build models from data sets (e.g. neural networks),
- a framework to include models or other open source software in the toolbox and
- a graphical user interface to control the simulation and write reports, visualize results as maps, charts or in a three dimensional form and include methods to handle multi-criterial results.

4.2 New methods formulti-criteria evaluation

To handle multi-criteria simulation results two problems must be solved. Firstly the Pareto optimality has to be determined.
Pareto optimality, is a central theory in economics with broad applications in game theory, engineering and the social sciences. Given a set of alternative allocations and a set of individuals, a movement from one alternative allocation to another that can make at least one individual better off, without making any other individual worse off, is called a Pareto improvement or Pareto optimization. An allocation of resources is Pareto efficient or Pareto optimal when no further Pareto improvements can be made. To determine the Pareto optimality is difficult and time consuming. A promising approach are genetic algorithms to control the search procedure for optimizing.
The second step is to build a decision support system from the Pareto optimized data sets. Methods for this step are partially ordered set or fuzzy approaches for example.

4.3 Improved validation of regional models

How we have seen, the development of dynamic landscape models, usable to support sustainable resources management at regional scale, is a great challenge for the landscape research in the next decade. There are to solve many complicated tasks. The need of improved validation of dynamic landscape simulation models is one of the most important tasks within the near future. A basic prerequisite for scientific demanding validation of complex integrated landscape simulation models is a network of long term experimental study areas or landscape experiments around the world, if possible. The core research areas within the **L**ong **T**erm **E**cological **R**esearch Network (LTER), (LTERNET, 2006) could be the basis for such study areas.

5 Conclusions

1. Temporal scales of ecological processes and models are highly variable. Because most environmental management decisions are considered over years to decades, landscape models for assessment the impacts of land use systems for sustainability should run over that time period in first line. In any case, the time scale of the models needs to relate to the time scale of the management questions and their implications.

2. Model results always contain uncertainties because they are based on (1) current understanding of interactions and (2) field and laboratory studies (Dale, 2003).

3. That is, why model results are projections (i.e., estimates of future possibilities) rather than predictions, something that is declared in advance (Dale and Van Winkle, 1998). Models produce approximations to real situations and are only as good as the assumptions upon which they are based. Model results therefore should be considered with caution, they are the logical extension of existing data produced via a process that assimilates and applies current understanding. Current understanding of complex environmental systems, as reflected in models, will rarely be adequate alone to provide simple answers to environmental questions.

4. Often incomplete information must be accepted, and decisions must be made with the

best available information. The absence of full information does not imply that there is no scientific value in developing dynamic landscape models.

5. The process of a group of scientists collaborating and sharing their expertise to develop integrated landscape simulation models can be a worthwhile scientific accomplishment. Development of such sophisticated simulation models is an integrative, interactive, and iterative process. The development of landscape models is a powerful process for the synthesis of data, theories, and opinions over scales of space, time and biological organization. It also is a process for creating new insights and questions for new experimental studies at regional scale.

6. The challenge continues to be to develop and use credible models usable for a sustainable landscape management, that range the gamut from improving ecological understanding to being useful for decision making.

7. Integrating models into decision making requires developing flexible tools for environmental management and making them available und understandable to different stakeholders and resource managers. For such applications, ecological models need to be designed up front to meet the diverse needs.

8. Models need to be validated by comparing projections to field data or historical conditions.. Back-casting and comparing model results to historical conditions sometimes offers a useful way to validate a model. More and more important are case studies or landscape experiments in different landscapes around the world, which are good arranged for instruments and designed for long term measurements.

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