Introduction

> "and what is the use of a book," thought Alice,
> "without pictures or conversations?"
>
> —Lewis Carroll[1]

Modeling, ...

Our environment with its dynamic and spatial processes is recognized as complex, highly interacting and spatially distributed. These properties make analyzing, describing, modeling and even simulating our environment a challenging task. A framework that enables us to study, for example, the consequences of human influences on ecological systems without even disturbing these is a valuable and important tool for environmental management. Models are therefore identified as important and necessary tools for studying and understanding ecological processes, testing hypotheses of the functioning of ecosystems in a systematic manner and for investigating environmental response to human impact.

This makes modeling an important part of the interdisciplinary research field of environmental science. Ecological modeling however is done less and less by mathematicians and more and more by practicing ecologists and environmental scientists.

[1]see p. 280 for references of quotations.

The present state of environmental modeling is characterized by a number of model developments. Several authors state that a general concept is missing in ecological or environmental modeling. Recent development of environmental models has shown that a multitude of possible approaches and theories have been developed. Some authors complain that *we have produced an enormous redundancy*. This multitude of different approaches refers to the considered temporal scale, the considered mathematical languages — such as differential equations (partial or ordinary), matrix models, fuzzy systems etc. — and the chosen concept of regionalization and spatial extent. The incorporation of spatial attributes into the modeling process causes a mismatch between the scale at which attributes are obtained, and the scale at which the processes occur.

The first part of the book (Chapters 1 to 3) gives a synthesis of model development concepts. Compiling mathematical equations and setting up simulation models is a complex and challenging task. Setting up ecological models requires a detailed system analysis of the processes of interest. A systematic way to achieve a concise and valid simulation model is to start with a conceptual model, which every scientist usually has in mind when investigating a process. Chapter 1 traces the path from conceptual models to validated regionalized environmental simulation models. The step of translating conceptual models into computer models is assisted by several development platforms. These platforms translate conceptual models into mathematical equations of a certain mathematical "dialect".

Focusing on processes of the abiotic environment as well as the first two trophic levels of the biotic environment, several different translations of conceptual diagrams into mathematical models are studied in Chapters 2 and 3. The first focuses on the dynamic patterns on different temporal scales such as nutrient flow, water transport, growth of crops and weed, population dynamics, competition, etc. Migration of species, vertical and horizontal fluxes of matter and information through a landscape are the characteristic properties of ecosystems. In Chapter 3 spatial interactions are discussed and the possible mathematical modeling concepts are presented, starting from highly aggregated mathematical models given by partial differential equation systems, we end up with with a discussion of cellular automata. For comparison, different mathematical "dialects" are used for modeling the same process to analyze and compare different methodologies.

Integration, . . .

Although there is consensus on a general methodology of model development, one needs to consider that environmental modeling is a diverse field of research. First of all because it is an interdisciplinary issue. Biologists, ecologists, computer scientists, mathematicians, physicists have to work together and to integrate their methodology to solve ecological problems of the 21^{st} century. This diversity leads to a multitude of approaches solving similar or even identical tasks. Several scientists complain of a lack of theoretical foundation of environmental modeling.

For example, conceptual difficulties stem from the fact that processes of different dynamic quality interact. The dynamics of technical systems are mostly time discrete and their dynamics are closely related to discrete spatial structures, whereas many environmental processes are continuous in time and space. The whole system can be characterized as structured time discrete and time continuous. One is faced with a problem that can be summarized as mathematical heterogeneity. It is not feasible to model integrated systems in the framework of one mathematical "dialect".

An environmental model requires the integration of all these approaches. This requires a general theoretical framework. The subject of Part II of the book is to bring together modern mathematical methodologies to solve the task of integration. These concepts are used to assess the anthropogenic impacts of production and the use of goods and services on the environment. This life cycle impact assessment methodology comprises a system-wide analysis of mass- and energy flows, performed within the step of life cycle inventory. Distributions of emissions are estimated within an environmental fate model including dispersion–reaction modeling and impact assessment has to be performed for different impact categories. The product is a hybrid model which integrates different environmental techniques and demonstrates how these effects can be addressed in environmental assessment.

. . . and Management

Quantitative and qualitative analysis of environmental processes by computer models is one aspect of ecosystem modeling. Additionally, a very frequent application of ecological models is to study the consequences of anthropogenic impact on the ecosystem with respect to the environmental fate of substances, habitat suitability of species, persistence of populations etc. In this way different management strategies can be compared. The question of the degree of impact which nature can sustain without harm to the environment has already been posed. Ideas like most sustainable yield were introduced in the late 1960s. Ecosystem management has become now an important discipline of scientific research and is an important branch in the political decision-making process. Because ecological models are complex and highly interacting, as stated above, this decision making process requires methodological support. The third part of the book deals with applications of ecological models in the decision-making process: either by the use of scenario analysis technique or by the application of optimum control theory to an ecosystem model. Problems of ecosystem management are solved by the use of numerical optimization. This can be interpreted as the follow up of the most sustainable yield concept by the use of scientific computing.

With increasing complexity of ecosystem models, one becomes aware, that scenario analysis may not be the appropriate tool to vary all required control parameters. Systematically sorting through all possible combinations of control variables yields a desired optimal scenario. This is achieved by the optimization or optimum control approach. Chapter 8 introduces this third part of the book, offers an overview of the approaches “scenario analysis” versus “optimization” and defines the tasks to be solved for optimum control of environmental systems.

Complexity of environmental models leads to an enormous computational effort, if these models are to be used in optimum control theory. Introducing certain hierarchies is one concept which can deal with increasing complexity. In Chapter 9 a framework is proposed for an application of environmental models in optimum control theory. This development focuses on spatially explicit models as well as models with a broad range of temporal patterns and dynamics. The generic code can cope with hybrid models. It requires appropriate numerical procedures, too. This is achieved by a hierarchical approach to the optimization problem and this decreases numerical effort.

Applications of this concept are presented in Chapters 10 to 12. Chapter 10 focuses on optimum temporal patterns of management strategies of an agroecosystem. Different results of optimum fertilizer input, pest management, weed control and crop rotation schemes are presented. Several scenarios of environmental assessment are compared using the tool of optimization. These results are then studied within a regionalized model. Beside the dynamic solution, Chapter 11 focuses on the regionalization of the optimum control problem. The task is solved by the identification of homogeneous units in the observed region by a geographic information system. The second innovative topic, which enables a regionalized solution of the optimum control problem, is the estimation of families of optimum solutions parameterized by spatial properties. The proposed methodology supports the step of decision support in site-specific farming.

In Chapter 12 all these concepts are applied to solve management problems of land use with a spatially explicit model on a landscape scale. Spatially explicit ecosystem models allow the calculation of water and matter dynamics in a landscape as functions of spatial localization of habitat structures and matter input. For a mainly agricultural region the nutrient balance as a function of different management schemes is studied in this chapter. The results are tested using Monte Carlo simulations which are based on different stochastic generators for the independent control variables. Gradient free optimization procedures are used to verify the simplifying assumptions. The framework offers tools for optimization with the computational effort independent of the size of the study area. As a result, important areas with high retention capabilities are identified and fertilizer maps are set up depending on soil properties. This shows that optimization methods can be a useful tool even in complex simulation models for systematic analysis of management strategies for ecosystem use.

Summary: How this Book is structured

Aspects of ecological modeling are of increasing importance in any branch of ecology, biology, landscape ecology, and environmental management. The book focuses on two main issues: the integration of different modeling approaches, together with applications in optimization and optimum control theory. It aims at supporting problems of environmental management and tries to bring together modern mathematical methods with environmental ecological research. The concept of the book is to offer a theoretical and methodological platform for environmental modeling, that can provide a starting point for every environmental scientist to solve a particular modeling problem. This is achieved by using the level of conceptual models as a starting point for model development and explanes the types of models that can be derived from one conceptual diagram.

Recent progress in ecological modeling is presented in a concise way showing results of high standard mathematical methods, such as the use of numerical solutions of partial differential equations for modeling water and matter transport, as well as population dynamics and migration in real landscapes. This provides a foundation for aggregated spatially explicit models using geographic information systems. Finally these high standard mathematics are used to develop concepts of solving optimization and optimum control problems for environmental management.

This structure of the book follows these objectives. Chapter 1 introduces terms and methodologies and presents an overview of environmental modeling concepts. Chapters 2 and 3 can be understood as a toolbox for translating conceptual models into equations. These chapters provide the necessary functions and equations used in most ecological models. It must be noted that all equations presented are illustrated with examples and applications. Chapter 4 discusses the results obtained in the context of meta modeling and scientific theory. Further applications of hybrid models in biology as well as in environmental assessment are reported in Chapters 6 and 7. The focus in Chapters 5 and 9 is on the mathematical foundation of the integrating modeling concept as well as the application of environmental models in optimization. Applications concepts are presented in Chapters 10 through 12, which are understandable without reading Chapters 5 or 9 in detail.