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MULTI-OBJECTIVE MODELLING

OF ECONOMIC-ECOLOGICAL INTERACTIONS AND CONFLICTS

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ABSTRACT

This paper presents examples of modelling developments in various policy fields where economics and ecology meet, often in conflicting situations, i.e. with conflicting objectives. An overview of nature conservation and economic objectives and policy issues is given and a series of policy fields in which practical applications of economic-ecological modelling exist. This is illustrated by a selection of examples of such applications. One of the emergent conclusions from the paper is that economic-ecological models have rarely been used for explicit trade-off of conflicting objectives, although the resource and environmental policy issues for which they are built generally imply multiple objectives. Most economic-ecological models reviewed in this paper rather analyze the impacts of conflicting objectives on the economic and ecological systems respectively.

1. INTRODUCTION

During the past few decades both policy-makers and scientists realized increasingly that real world problems are very complex and difficult to solve without a careful analysis. To that end, quantitative modelling approaches have become important in many disciplines. Mathematical models were introduced for research and understanding of situations and developments in the real world. This was done primarily however, to describe and analyze structures and mechanisms in monodisciplinary contexts. The resulting models externalize all factors other than those belonging to the pertinent discipline. With these efforts focused on monodisciplinary instruments the practibility of applying them in real world policy making and planning had to take - at least temporarily - a back seat.

More and more researchers, planners and policy analysts have, however, become aware of the limitations of monodisciplinary modelling for understanding developments in the real world. Real world problems do not follow the boundaries of scientific disciplines. Purely economic models proved often to be inadequate and ineffective in explaining actual economic development, while purely ecological models also were found to be rather useless in explaining and predicting the state and behaviour of ecosystems influenced and managed by man. A series of attempts started in which monodisciplinary models were extended with variables from other disciplines and later fully multidisciplinary models began to appear. In this paper we give some examples from various policy fields of developments where economics and ecology meet, often in conflicting situations, i.e. with conflicting goals. Section 2 presents an overview of economic-ecological objectives and policy issues and a series of policy fields in which practical applications of economic-ecological modelling have been attempted so-far. In Section 3 a selection of examples of such applications has been reviewed. Some concluding remarks are presented in Section 4. A more extensive introduction into economic-ecological modelling can be found in Braat and van Lierop, 1985 and 1986.

2. GOALS, POLICY ISSUES AND SCIENTIFIC DISCIPLINES

To live and grow, living systems need energy and matter in utilizable forms. When the state and development of the environment do not meet the requirements or needs for energy and matter of individuals, special interest groups or society, they constitute a 'problem' and sooner or later will be referred to as such. Such problems can be identified as conflicts between the natural system (the part of the earth's environment not designed or built by man) and the socio-economic system (comprising humans, their built environment and their social organization). Environmental and resource issues are real world phenomena observed and felt by the general public, academic scientists, policy-analysts and decision-makers. Essential information in the analysis of such issues is the set of feasible policy options and their consequences for the socio-economic and ecological systems involved. This requires information about the state of these systems, their general behaviour and the position and specific linkages (interrelations) of relevant issues. In many of these issues political aspects play a role. The final policy is either influenced by a single objective or by multiple objectives. In environmental and resource policy making, three main types of *policy objectives* can be distinguished:

(1) ecological (or nature conservation) objectives, aiming at a minimum exploitation of and damage to natural systems. In general, these objectives concentrate explicitly on limited areas only, sometimes with the implicit purpose of saving resources for later use. Another aspect is the protection of natural systems from consumptive use for the non-consumptive forms of use, such as recreation, aesthetics and scientific research;

(2) economic objectives, sharing the characteristic of maximum production of goods and services at minimum cost. The satisfaction of present needs is predominant. These needs may be very basic such as food and shelter, or less generally accepted such as marginal increase of personal wealth;

(3) mixed objectives, i.e. economic and nature-conservation objectives are considered at the same time. These objectives are not as common as the beforementioned ones. They can be characterized as maximum sustainable use of resources and environmental services at minimum ecological damage and minimum costs. The crucial concepts are sustainability and multifunctional use. This means that the various forms of

use are compatible with the productive and carrying capacity of the natural systems involved. It implies that this compatibility extends over an unlimited period of time.

Policy issues are the policy or managerial problems that are addressed with one of these type of objectives in mind. In view of the relationships between the natural system and the socio-economic system, the policy issues can be illustrated by figures 1, 2, and 3. These figures are based on a simple conceptual model of the relationships between the natural and the socio-economic systems in the real world.

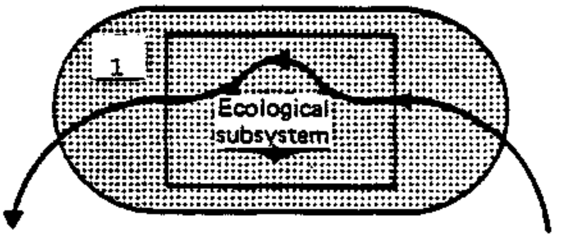
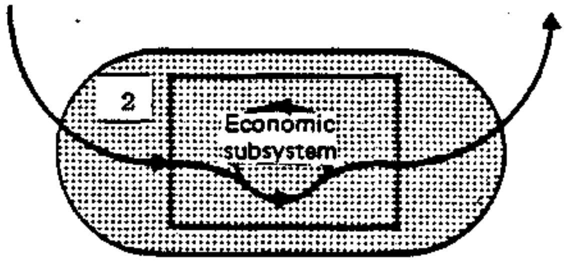


Fig. 1. Ecological policy issues



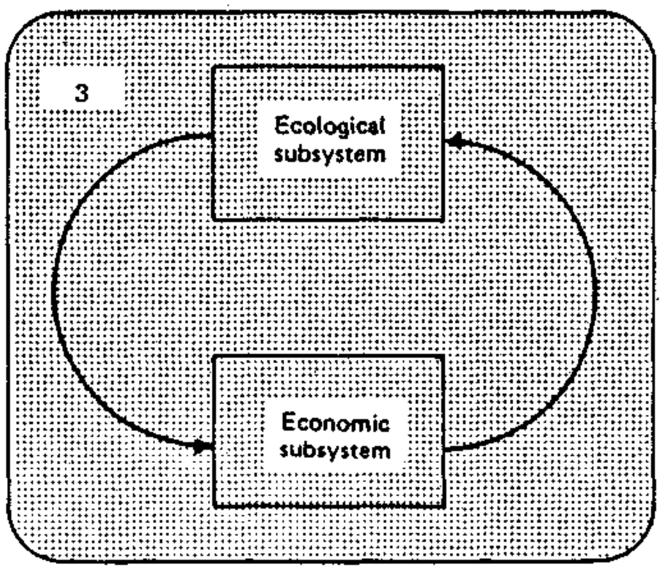


Fig. 2. Economic policy issues

Fig. 3. Economic-Ecological policy-issues

The output (left arrow) from the box representing the ecological system in Fig. 1 indicates policy issues concerning the ecological impacts of resource use. The concern here is: the ecological effects of the extraction of resources from ecosystems (natural and managed) and the policies which might lead to minimization of the impacts. The input (incoming arrow) represents ecological impacts of pollution and disturbance, (e.g. from outdoor recreation and construction) and the policies or control measures at the receiving end. Policy issues concerning ecosystem conservation management or the planning of whole ecosystems focus on both inputs and outputs as well as on the internal functioning of the ecological subsystem (i.e. the total ecosystems throughput).

The input (left arrow) into the economic subsystem in Fig. 2. indicates economic impacts of resource use, i.e. both cost impacts and management of development activity. The output (right arrow) represents economic impacts of pollution and disturbance, e.g. water pollution control costs. In economic system planning and economic management, both inputs and outputs are considered. Policy issues in these cases are, for instance, the optimal allocation of resource input to the economy and the achievement of cost-effective material balances.

Fig. 3. indicates all those policy issues in which both ecological and economic objectives are involved. Simultaneous attention for outputs from the ecological subsystem and inputs into the economic subsystem, as indicated above, refers to multifunctional, sustainable use of resources. The concern is then, evidently, on how to plan and manage resource use and conservation activities (including development) in such a way that a long-term use is guaranteed, considering, e.g., cost aspects and changing demand. The focus on flows from economic systems into ecological systems involves sustainable use of environmental services. Objectives here can be phrased as: optimal use of ecological assimilative capacity with minimal negative impacts. In case the complete cycles of input-throughput-output, as pictured in Fig. 3., are of concern, we speak of total system planning and management. This may involve different geographical scales (e.g. local or regional) and different elements that cycle in (or flow through) the system (pollutants, energy, phosphates, carbon, biomass, etc.).

During the last 60 years a great variety of modelling methods has been developed in economics as well as in ecology to study these policy issues. Real integrated multi-disciplinary models differ from the "extended" monodisciplinary models (developed in, for instance, environmental and resource economics and ecology) in that they include adequate representations of both the economic and the ecological components and processes which are part of the problem situation the models are developed for. Models in which both economic and ecological objectives receive full attention are still rather scarce and still face many theoretical and technical problems. As the underlying mathematical and statistical techniques used in both disciplines are generally the same, one would think that integration of economic and ecological models is basically feasible. This assumption is further supported by the observation that the dynamics of economic and ecological systems can be described by similar equations (see e.g. Odum, 1983), which suggests that interdisciplinary modelling has a definite theoretical basis. Consequently it could be concluded that, as integration is not easily accomplished in practice, that either the mathematical and statistical possibilities are not fully explored, or that problems exist in other aspects of the models, such as data and temporal and spatial dimensions.

Yet, there are definite possibilities to integrate existing economic and ecological models of environmental and resource problems. The most successful attempts sofar have been in connecting so-called physical-economics models (e.g. material-balance models (Kneese et al. 1969)) with ecological "flow" models, designed to assess resource extraction and pollutant input impacts (see Ikeda, 1980, Spofford et al., 1976 and Arntzen et al. 1981). Integration of economics and ecology in a holistic model has been shown to be entirely feasible. Both empirical models (Isard, 1972) and theoretically derived models (e.g. Brown, 1977 and Boynton et al., 1977) have been applied in resource and environmental analysis. The extended economic cost-benefit-models and the so-called ecological-evaluation models do apparently, however, not provide good starting points for integrated economic-ecological modelling.

In many sectors of environmental and resource management modelling approaches that take into account both economic and ecological aspects have been developed and applied. This happened, among others, in forestry, fishery, agriculture, air pollution control, water quality and water resource management, outdoor recreation and regional or national planning. Within such *fields of application*, models may, for instance, be used for identification and description, analysis of complex processes, and prediction of consequences of policies, control, or management. Many models have multiple-use capability in this respect.

In the next section we review a selection of models in these fields for the three types of policy-issues that have been identified above: (1) ecological policy issues, (2) economic policy-issues or (3) mixed ones. The overview claims by no means to be exhaustive or representative, nor fully consistent as to the level of detail. It is a limited presentation of some practical modelling examples (many with multiple objectives) on areas where economics and ecology meet. Fig. 4. summarizes the position of the various examples. The numbers in the figure relate to the sub-sections in the next section. It should be remarked that many of these example-models could, in a technical sense, easily be adopted for model applications in other fields than the ones they were originally developed for.

		Policy Issues	
Fields of Application	Ecological	Economic	Mixed
Agriculture			
Air pollution control		3, 4	
Fishery		5	
Forestry	1	6	
Water management	2	7	8
Combinations (resource and pollution, and total systems models)			9, 10, 11, 12, 13

Fig. 4. Characterization of the example models in the successive sub-sections of section 3 by field of application and policy issue.

3. A HOST OF EXAMPLES FROM APPLIED ECONOMIC-ECOLOGICAL MODELLING

3.1 A MODEL FOR PLANNING THE DEVELOPMENT OF INDUSTRIAL PLANTATIONS, by J.B. Dargavel, *Australian Forestry*, 41 (2), 1978, pp. 95-107.

This study (see also Agren, 1986) focuses on total ecosystems throughput: managing forests in terms of silvicultural methods (thinning, fertilizing, weed control etc.; in other words manupulation of both inputs and outputs as well as the internal structure of the system of forests). A *linear programming model* is applied to solve the optimization problem included in silvicultural methods for the utilization of "Pinus radiata" plantations by an Australian forest company with a planning horizon of 25 years.

The ecological (forest) submodel in this study is formulated as a simulation model. This is applied to 188 relatively homogeneous stands representing a variety of growth conditions into which the relevant area could be subdivided. Intensive data collection had made it possible to develop regression equations for height, basal area, and volume over time for all site conditions of interest (see: Turner et al. 1977). Possible management actions were: (1) fertilization which added to both height and basal area increment over some fixed duration of response; (2) weedicide application which partly was incorporated in fertilizer response and partly resulted in improved planting survival; (3) tree breeding increasing basal area at age 10 by up to 20 percent; (4) a series of thinning and clear-felling options. Evaluation of all possible combinations was not feasible because of the high number of alternatives. Also an optimal (maximum profit) solution for any one stand could not simply be chosen independently because of the need to meet overall objectives and share overall resources. The constrains were that (a) wood supply had to satisfy the capacities of present mills and yet not exceed the possibilities of increasing these capacities, (b) the cost of the forest operation for each selected combination of strategies must not exceed the budget available each year, and (c) the standing stock at the end of the planning period must represent a sustainable yield.

The economic subsystem is represented by an optimization routine describing a manager trying to manipulate the ecological subsystem towards some preset goals.

The overall model has demonstrated that the forcast of future demands can significantly change the tinning method and clear-felling age.

Although in principle this type of model may be suitable to analyze policy-issues as here described, it should be noted that they require large data bases and that they are also very computer-time consuming. Furthermore, the economic part of this study was too much underdeveloped to call it a really integrated multi-disciplinairy multi-objective analysis.

3.2 PROBLEMS OF APPLICATION OF THE ECOLOGICAL MODEL SALMO TO LAKES AND RESERVOIRS OF DIFFERENT TROPHIC STATE, by J. Benndorf and F. Recknagel, in *Ecological Modeling*, 1982.

This water quality study has utilized a dynamic ecological model to analyse the eutrophication of the pelagic zone of reservoirs and lakes. This *simulation model*, SALMO (i.e. Simulation with an Analytical Lake Model), involves only three state variables (two groups of phytoplankton, zooplankton and orthophosphate), but nevertheless a great number of internal control mechanisms is considered.

The applicability of this model to quite different water bodies is checked by comparing simulation results with observations. Four water bodies are used for these comparisons: Lake Stechlin (deep, oligotrophic), Saidenbach reservoir (deep, mesotrophic), Bautzen reservoir (shallow, hypereutrophic) and Bleiloch reservoir (deep, hypereutrophic, high light extinction). In spite of numerous deviations between simulations and observations, the general result of these - rather practical - validations seem to justify the use of SALMO in water quality management. The authors regard the comparison of simulated scenarios to be a most adequate validation method because it minimizes the influence of the inaccuracies of the model. An example of a scenario analysis for decision making in the management of a multi-purpose reservoir is given in detail.

The direct link of this mainly ecological model to the relevant policy issue, i.e. ecological impacts of pollution resulting from opposing economic and ecological objectives, have not really carefully been taken into account in this study. Although a complete economic sub-model may not have been necessary given the purpose of the model, that link could have been made more visible.

3.3 TRIPLE LAYER MODEL: A NATIONAL-REGIONAL ECONOMIC-ENVIRONMENTAL MODEL FOR THE NETHERLANDS, by W.A. Hafkamp, North-Holland Publ., Amsterdam, 1984.

This study aims at showing the potential of *a linear multiple objective decision making model* to analyze conflicts in a spatial-economic-environmental system. To that end normally a reference framework is used, defined by a set of objectives which are influenced by a number of decision variables. A unique optimum solution is generally not found by this method and therefore priorities (in terms of weight functions) have to be assigned to the various solutions in order to obtain a multi-objective optimization solution.

An elaborate national-environmental model for the Netherlands has been developed in this study, which uses a so-called multi-layer projection to describe and explain at a macro level economic, environmental and other developments in a spatial system. The model approach provides a methodology to combine different modules for parts of the analyzed system (e.g.

separate sub-models for the economy, ecology etc.) in an integrated model. It is possible to distinguish between relationships between variables in some layer (intra-layer relationships) and between variables from different layers (inter-layer relationships). The operationalization of the Triple Layer model for the Netherlands uses in an economic module a five-region *input-output model* as well as a *simulation model* to study the effects of various alternative economic policies on the economy. An employment module describes supply and demand of labour in all regions and sectors and the environmental module deals with emission and diffusion of air pollutants. Water pollution and solid wastes are not included into the analysis and only a limited number of pollutants were analysed in. the study. A data advantage of the model is that real world phenomena our allowed to be studied in the seperate layers in their natural units of measurement (including their own time and space dimensions). A disadvantage is that computational reasons forced non-linear parts of the multi-objective model to be linearized. Next these linear functions were estimated with ordinary least squares or with single point-estimates (especially for the input-output model). A shortcoming of the study is that no model validation has been made.

As the environmental module in the model does not include ecological systems and interactions, the model may be reasonably suited to analyze economic policy issues, but for more integrated economic-ecological purposes the environmental part of the model needs, however, to be elaborated.

3.4 A MIXED INTEGER PROGRAMMING MODEL FOR THE INTEGRATION OF AIR QUALITY POLICY INTO LAND-USE PLANNING, by E. Werczberger, Papers of the R.S.A. Vol. 33, 1974, pp. 141-154.

This study considers integration of air quality into land-use planning. This requires two kinds of policies:
(1) air-quality management, i.e. control of the location and quantity of pollutant emissions to ensure maintenance of air quality standards, and
(2) locational policies which prevent pollution-sensitive activities such as housing or hospitals from being located in high-pollution areas.
For an efficient program of action, both types of policies must be considered. Hence land-use planning and air-quality policy cannot be separated.

The point of departure in this paper is the *linear programming* formulation of the urban land-use system as was firstly proposed by Herbert and Stevens. Air-quality policy is introduced by requiring for each urban activity: maintenance of the appropriate air-quality objective at the site at which a unit of the activity is located. The consideration of zoning regulations and of spatially differentiated air-quality objectives results in a *mixed integer programming model*.

A further elaboration in this area is an application of *goal* *programming* to the planning of industrial location in the context of air-pollution policy (see: E. Werczberger, A Goal Programming Model for Industrial Location involving Environmental Consideration; in *Environment and Planning A*, 1976, 8, pp. 173-188). Goal programming is a modification of linear programming that is designed to solve problems characterized by a large number of conflicting objectives. The solution is obtained by expressing all objectives as constraints and minimizing the deviation of the allocation from the respective targets and standards. If lexicographic ordering of objectives prevails, the constraints can be introduced in order of their importance.

The policy issues of these studies have a strong economic orientation as do the respective models. This is probably the reason why a more integrated economic-ecological approach was not really necessary. The models are basically economic with a few ecological elements added to them. It would be interesting to see a full-size empirical application of these so-far apparently mainly theoretical approaches.

3.5 OPTIMAL FISHERIES INVESTMENT: COMPARATIVE DYNAMICS FOR A DETERMINISTIC SEASONAL FISHERY, by A. Charles, Dept. of Economics, Resources Paper No. 85, Vancouver, Canada, 1982.

This model deals with optimal investment planning in fisheries. The problem of determining optimal investment levels and optimal capital stocks is a pervasive one in the economics literature. A major complication in determining such optimal investment strategies is the frequent lack of malleability of capital, a problem which is particularly prevalent in renewable resource industries. Most models of fisheries management problems have so-far concentrated on the dynamics of the resource stock, treating the capital stock as given.

The model in this study:

a. consideres time to be discrete between fishing seasons although continuous within each season,
b. defines end-of-season escapement and yearly investment as decision variables, and
c. allows delays between the time at which investment decisions are made and the time at which these investments come on-line.

A *dynamic programming approach* is utilized which allows to study arbitrary stock-recruitment functions (including the Beverton-Holt and Ricker equations) and to obtain detailed comparative dynamic results. Specifically attention is paid in the paper to the effect on optimal investment/escapement policies of: (1) discrete-time vs. continuous time analysis, (2) investment delays, (3) fecundity and carrying capacity of the stock, (4) fish price, (5) capital cost, (6) discount rate, and (7) depreciation rate.

Obviously the model is basically economic as it concentrates on financial decisions in renewable resource exploitation. Given a policy issue in which the ecology of the fish plays a decisive role (as a dynamic constraint and through indirect feed-backs), a more complete multi-disciplinairy model might have been more appropriate.

A stochasic version of the model is used to study the role of uncertainty in fisheries investment problems (see: A. Charles, Optimal fisheries investment under uncertainty, UBC, Dept. of Economics, Resources Paper No. 86, Vancouver, Canada, 1982)

3.6 PLANNING FUELWOOD PLANTATIONS IN THE DODOMA REGION, TANZANIA: A LINEAR PROGRAMMING APPROACH, by J.C. Allen, Center for Energy Policy Research, RFF, Working Paper, January 1983.

This study describes a forestry model designed for planning and management of fuelwood plantations in a developing country. It consists of a *linear programming model* which aims are
(a) to schedule planting and harvesting of exotic species and regenerating woodland,
(b) to determine how much wood should be burned as fuelwood and how much converted into charcoal, and
(c) to choose for which towns and villages it is possible to collect fuelwood by foot and which should receive truck shipments of charcoal in order to meet the fuel demands as defined by the objectives of a five year planning program.

Two objectives have been identified for this linear programming model: (1) to minimize the tree planting, maintenance and harvest costs, and (2) to minimize the time spent collecting fuelwood and transporting charcoal. The program was solved repeatedly with different criteria for these two objectives, which had been defined under three sets of assumptions:
1. a base case with coefficients corresponding to conservative estimates of currently attainable growth rates of natural woodland and exotic species, and current pit kiln charcoal technology,
2. an efficient kilns scenario which assumes that a doubling of kiln efficiency is attainable, and
3. a fast growth scenario which assumes that a tripling of the growth rate of the exotic species can be achieved.

It will be clear that also this model basically has an economic character, which is not surprising given the policy issue: exploitation of natural resources. Ecological aspects only play a marginal role here as constraints and through slow indirect feed-backs. Given the policy issue at hand the model performs well and a completely integrated economic-ecological model seems not to be necessary in this case.

3.7 DUAL OBJECTIVE CONTROL OF NUTRIENT LOADING INTO A LAKE, by L. Duckstein, I. Bogardi and L. David, in *Water Resources Bulletin*, Vol. 18 (1), 1982, pp. 21-26.

This article reports on a study with a multi-objective viewpoint on the control of nutrient loading into a water body. The example of phosphorus loading (determined by commercial and natural fertilizers) into Lake Balaton, Hungary is used in the article as a case study. Phosphorus is chosen because in this lake - as in many other lakes - it appears to be the limiting factor for eutrophication. About one half of the phosphorus loading in this example originates from so-called non-point sources. This half has been used in the study, while the contribution from point sources (such as domestic or industrial waste) has been excluded from the analysis. It should further be remarked that the dynamics of the system to be modelled were apparently poorly known and that only few observation data were available.

A *multi-objective programming model* and a *simulation method* for eutrophication control are introduced to study minimization of the phosphorus loading in the lake and maximization of the agricultural revenue in the area around it. These two, ecological resp. economic, objectives appear to be in conflict: economic growth (in terms of an increase of agricultural benefits) may accelerate phosphorus loading because of an increased use of fertilizers, while a reduction of phosphorus loading leads to higher costs of water quality control to diminish economic benefits. A discrete set of alternative control methods is defined, consisting of control of a mix of the following elements: point sources, runoff, fertilizer type and application, cropping management, erosion and sedimentation. The system dynamics are provided by a previously developed stochastic model with as output an empirical probability density function of phosphorous-loading reflecting the control policy. A compromise solution of "satisfactum" can then be chosen as a mix of the best ranked policies. This trade off between mono-disciplinary defined objectives is defined in the multi-objective approach by the shortest distance between the ideal solution and a set of feasible solutions.

In this elaborate model for descriptive and explanatory purposes, not more than an indirect relationship exists between economics and ecology. Also, lake eutrophication has not been modelled and has only been used as a background variable which follows directly from phosphorus loading. Consequently the model seems to contain more economics than ecology and will therefore in an actual application probably be mainly satisfactory for the economic policy issue.

3.8 ENVIRONMENTAL QUALITY MANAGEMENT: AN APPLICATION TO THE LOWER DELAWARE VALLEY, by W.O.Spofford Jr., C.S. Russell and R.A. Kelly, Resources for the Future, Washington, D.C., 1976.

In this study a nonlinear ecosystem model is constructed for the Lower Delaware River Valley Region (divided into 57 subregions) and linked with an economic management model within an optimization framework. Aim of the analysis is to provide decision-makers with information on the impacts of various actions (in terms of costs and environmental disturbance). The resulting regional residuals management model for environmental quality assessment consists of the following components:

a. an economic management module, with *linear and non-linear programming models* that analyse the factors influencing the generation, modification (e.g. treatment), and final discharge to the environment of residuals - gaseous, liquid and solid - from individual production and consumption activities. This is done in terms of both costs and physical dimensions.
b. an environmental quality (ecosystem) module with a set of *simulation models with differential equations* which translate the time and spatial patterns of residuals discharges into time and spatial patterns of the resulting ambient residuals concentrations and population sizes of biological species of interest. In connecting a. to b. damage functions are relevant, which relate time and spatial patterns of ambient residuals concentrations to the resulting impacts on receptors - man, animals, plants and structures - in physical, biological and economic terms.
c. an environmental evaluation (modification) module, consisting of *an iterative non-linear programming model* that analyses alternative waste management strategies and the costs of the various options.

This is a really fully integrated economic-ecological modelling approach and it should be remarked that its idea of incorparating an ecological simulation model into management models within an optimization framework seems in principle to be very adequate and effective for policy issues of sustainable use of environmental services. Of course there are still a few problems with the practical application of this complex model. As the modellers state themselves (see: Kelly and Spofford, 1977, p. 442): "lack of appropriate data remains the major limiting factor in constructing and validating ecological models to be used for management purposes". To this could be added that the lack of economic dynamics in the model causes a problem which is only partly overcome by the followed procedure of comparing completely different situations (because of different regional developments) with each other.

See also:

1. W.O. Spofford Jr., Total Environmental Quality Management Models. In: R.A. Deininger (ed.), *Models for Environmental Pollution Control*, Ann Arbor, Mich., Ann Arbor Science Publishers, Inc. (Resources for the Future Reprint No. 130), 1976.
2. R.A. Kelly and W.O. Spofford Jr., Application of an Ecosystem Model to Water Quality Management: The Delaware Estuary. In: C.A.S. Hall and J.W. Day Jr. (eds.), *Ecosystem Modeling in Theory and Practice: An Introduction with Case Histories*, John Wiley and Sons, New York, 1977.
3. C.S. Russell and W.O. Spofford Jr., A Regional Environmental Quality Management Model: An Assessment. In: *J. of Environmental Economics and Management*, Vol. 4, No 2, 1977, pp. 89-110.

3.9 ECONOMIC-ECOLOGICAL IMPACTS OF AIR POLLUTION CONTROL POLICIES, by L.C. Braat, W.A. Hafkamp and S.W.F. van der Ploeg, Papers of the Regional Science Association, 1986.

RIM-RINAL is an economic-ecological *simulation model* for environmental policy analysis, developed at the Institute for Environmental Studies, Free University, Amsterdam. The RIM-submodel aims at analyzing the impacts of alternative environmental policy scenario's on emission levels in the Netherlands from a long term perspective. The model has significant advances over earlier approaches applied in relation with *input-output* based economic-environmental modelling, because it relates emission levels to sectoral activity levels measured in physical terms (e.g. energy use in pJ).

The RINAL-*simulation* model contains modules for various ecological systems. It accepts RIM-output (emission data) and additional scenarios and generates projections for environmental and ecological variables for 10 regions in the Netherlands. The main state variables of the RINAL-model are: the ambient air concentrations and depositions of SO_x, NO_x and NH_x, soil pH (which is subsequently combined with the air concentrations into physical damage functions), three tree species, which together dominate the Dutch forests and timber production sector and two competing heathland vegetation types.

The case study model of RIM-RINAL is basically designed to mimic systems behaviour. Its modular structure allows for easy replacement with more adequate submodels, as soon as data have come available. The RIM-RINAL simulation model in its present state

1) gives contrasting projections of environmental, economic and ecological impacts of alternative air pollution control policies, and
2) allows for the generation of hypotheses about the most crucial system processes, interactions, feedbacks and non-linearities in the system, and thereby offers useful suggestions for directed research.

Sensitivity analyses have indicated that the growth functions of the tree species are sensitive for changes in the damage function. They are also sensitive for the relative weight of direct and indirect effects. The sensitivity leads to a difference of 20% in quantitity of the gross productivity. Other parameter values do not, however, change the direction of the projections generated.

The RINAL-submodel may be improved and needs to be tested against real field data. However, by desaggregation (to a regional scale) and interpolation (to consecutive 1-year time steps) of national emission projections of RIM, the basis for adequate economic-ecological impact modelling has been established. And although the RIM-RINAL model is not complete yet, it does include the most important cumulative, interactive, feedback and spatial extension aspects of air pollution impacts necessary for adequate economic-ecological modelling. Therefore, it can be concluded that this model has the potential to become an effective tool for general scoping and scanning of alternative, multi-objective policies.

3.10 AN ECOLOGIC-ECONOMIC MODEL FOR SUPPORTING LAND-MARINE INTEGRATED DEVELOPMENT - THE CASE OF THE EAST SETO INLAND SEA, by Y. Nishikawa, S. Ikeda, N. Adachi, A. Udo and H. Yukawa. In: Y Haimes and J. Kindler (eds.), *Water and Related Land Resource Systems* Pergamon Press, Oxford, 1980, pp. 141-149.

The goal of this study was to develop an ecologic-economic model for the eastern part of the Seto Inland Sea, which is surrounded by the second largest industrial base in Japan, comprising Osaka and Hyogo. The aim of this model was to analyze interactions between land-development and marine-resources-use plans to make both plans integrated and consistent with each other. Because of the industrial and urbanization developments in regions close to the Seto-Inland area, it suffers from inflows of nutrients such as nitrogen and phosphorus which causes eutrophication. In the study the area of concern has been divided into coastal and inland-sea zones. Each zone included economic activities such as land cultivation, light and heavy (secondary) industries, fishery and marine/aqua culture, transportation, recreation (swimming, sports, fishing,...), as well as ecologic behavior of chemical substances, plankton, fish and so on.

The overall modelstructure consists of a socio-economic model which has been linked to a marine-ecologic model by means of two auxiliary models, viz. a pollutant emission model and a coastal resources demand model. The study considers the dynamics of the eutrophication process and socio-economic change and makes use of non-linearity characteristics of the systems. The relevant figures have been measured in monetary terms or in their natural units (e.g., fish population in weight terms). In the socio-economic model *multi-objective modelling* is formalized in a *linear-programming approach* as well as in an *input-output model* for the regional economy. A *non-linear differential equations model* is used for the marine-ecological model.

For only parts of the model numerical simulations could be run so-far, basically due to lack of appropriate data at the regional level. Consequently this elaborate integrated systems model for multi-objective analysis has not been used yet for actual policy formulation.

See also:
S. Ikeda, Economic-Ecological Models in Regional Total Systems. In: Braat, L.C. and W.F.J. van Lierop (eds.) (1986) *Economic-Ecological Modeling for Environmental and Resource Management*, North-Holland, Amsterdam, chapter 12 (in press).

3.11 MANAGING SUBURBAN GROWTH: A MODELING APPROACH, by C. Steinitz, H.J. Brown and P. Goodale, Research paper of the Landscape Architecture Research Office, Grad. School of Design, Harvard Univ., Cambridge, Mass., 1976.

This research has produced a complex yet easily used system for analyzing the effectiveness and consequences of different environmental planning strategies. It is based on *trend scenario analysis* through *simulation*, with future developments based on current policies. The south-eastern part of the Boston area was chosen for a first application. This area is characterized by a rapid suburbanization of the major cities ever since 1965.

To provide the information needed to make planning choices, it was necessary to understand the physical, environmental and demographic systems that cause and react to the suburban growth process. To that end 28 computer models were developed to describe collectively the pressures and consequences of suburban growth.

The methodology chosen is extremely flexible to insure the applicability of the research to the greatest number of purposes and users. The individual models may be operated seperately to address specific tasks, or linked in a variety of ways to respond to more complex questions beyond the scope of any single model. When linked together the models exchange information through a *shared computer programming system* and a *common data base.*

In standard operation, the models describe projected conditions in the study area that are likely to exist at various times in the future. By imposing constraints, users of the system can test the consequences of alternative strategies specified as plans, programs, policies, purchases, new capital facilities, new legislation, changes in basic assumptions and priorities or any combination of these. The efficiency and cost-effectiveness of the analysis system allow the models to cycle quickly through alternative strategies and to produce detailed sets of evaluations for purposes of comparison. The analysis can be performed at various levels of spatial aggregation, i.e., the region, a town, a watershed and other functional zones as determined by users' needs.

This type of integrated systems-analysis has been used frequently in applied work. It is not an example of traditional multi-objective modelling. Its flexibility will, however, still guarantee a long-term appearance of this kind of approaches.

3.12 ENERGY, ECONOMIC AND ECOLOGICAL RELATIONSHIPS FOR GOTLAND, SWEDEN. A Regional Systems Study, by A.M. Jansson and J. Zucchetto, Ecological Bulletins 28, Stockholm, Sweden, 1977.

This study focuses on the interrelationships between human activities and the natural environment on the island of Gotland (Sweden). It presents a general methodology for tying together a regional complex of systems of man and nature in a coherent, systematic and quantitative fashion. Using this methodology, the island was modelled as a number of ecological and economic subsectors, like industry, agriculture, fishery and forestry which consume natural resources, produce economic output and have impacts on the environment. In the terminology of the study: the subsectors contain storages of matter, energy and money, and they exchange these quantities with one another and with the outside world. In particular, the study focuses on the flows of energy in the region as one measure common to both the economic and the ecological system. The feedbacks between the economic activities and the natural environment are linked to each other by an *optimization procedure*. Firstly the economic activities are linked by means of an *input-output approach* consisting of variables measured in monetary terms and next the optimization procedure maximizes the sum of values added for the economic and ecological subsectors, subject to economic and environmental constraints. Also, different *scenarios* (with a time horizon of 10 years) for price developments of various types of energy and substitution of energy types were considered. *Simulation techniques* for trying to predict future impacts on the system are illustrated in terms of a water-nitrogen model and a fisheries model.

The model in this study in which both the economic and the ecological system, plus the relationships between them receive extensive attention, offers a good example of how multi-objective, multidisciplinairy modelling can be done in case the policy issue is total systems planning and management.

See also:
J. Zucchetto and A.M. Jansson, 1985: *Resources and Society: A Systems Ecology Study of the Island of Gotland, Sweden*. Ecological Studies, Analysis and Synthesis, Vol. 56, Springer-Verlag, Berlin.

3.13 A MODELING "APPROACH" TO REGIONAL PLANNING IN FRANKLIN COUNTY AND APALACHICOLA BAY, FLORIDA, by W.R. Boynton, D.E. Hawkins and C. Gray. In: C.A.S. Hall and J.W. Day Jr. (eds.), *Ecosystem Modeling in Theory and Practice: an Introduction with Case Histories*, John Wiley and Sons, New York, 1977, pp. 478-505.

The region analyzed in this study - Franklin county in Florida - consists of a coastal area with a local economy that is traditionally dependent on water-resource based activities with emphasis on the oyster fishery activities in Apolachicola Bay. The project aimed at determining whether a balance was possible between this fishery-based economy and new economic activities to be introduced into sub-sectors of the area. The focus was particularly on evaluating the sensitivity of the local oyster fishery to additional developments of the tourist, retirement, shipping, and cattle industries.

The study represents *corollaries of Lotka's principle* in models which show all important regional aspects in terms of energy, materials and money sources available to a sub-sector. Especially for those that are dominant and/or expected to change. Interaction processes that degrade part of the incoming flows to build higher quality flows and structures are also shown. By means of a series of diagrams *pathways* are emphasized that recycle materials suspected of limiting major processes. Both energy models (conform Odum, e.g. 1983) and economic models have been developed from these diagrams.

The model describing the economic development of the county has been defined one level of aggregation higher than the fishery, to be sure that all important interactions and storages were included. The overall approach combines all component processes of interest. A final diagram is both an easily understood synthesis of the processes in the study area and a visual picture of *a system of nonlinear differential equations* describing the behavior of each state variable (including the feedback relationships between the economy and the ecology). Data needed to evaluate flow rates, initial conditions, transfer coefficients, and some validation graphs were obtained from literature sources as well as fieldwork conducted in the area. The model was tested against field observations to determine if the factors chosen for inclusion in the model were the important ones and whether the coefficients were approximately correct. A sensitivity analysis to evaluate the various options was, however, not conducted.

Simulations were run on an annual bases for the period 1970-2000 (with an extended simulation for 2120) to explore the consequences of alternative management decisions (it should be remarked that the inflows for these forecasts were assumed to be constant at the 1970-level). Some of the results have already been actually used planning decisions of the county.

Also this study with its complex interrelated economic and ecological sub-models is a fine example of how modelling for total system planning and management (in which multi-objectives exist by definition) can be done.

4. CONCLUDING REMARKS

The examples in the previous section illustrate that:

a. where it comes to application of models for environmental and resource management, a tendency still exists to study the economic and ecological aspects seperately. Economic-ecological modelling is in many respects still in the phase of experimentation and first practical applications;
b. certainly not all policy-issues listed in section 2 need to be analyzed by a model in which economics and ecology are fully integrated;
c. most practical models have an extended monodisciplinary

character, whereas integrated economic-ecological attempts are usually fairly academic in nature. These attempts have achieved results in fields with rather "controlled" situations, in which the engineering approach is very important (agriculture and water control);

d. many so-called fully integrated economic-ecological modelling approaches apparently have a monodisciplinairy history. Often external aspects (variables describing elements of the "other" discipline) have only been added in a very late stage of the modelling approach and show to be of just marginal importance in the entire modelling approach;

e. economic-ecological models have rarely been used for explicit trade-off of conflicting objectives, although the resource and environmental policy issues for which they are built generally imply multiple objectives. Most of the economic-ecological models reviewed in this paper as well as those in Braat and van Lierop 1985 and 1986 rather analyze the impacts of conflicting objectives on the economic and ecological systems respectively.

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