ECOLOGICAL AND SOCIO-ECOLOGICAL ECONOMIC MODELS

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Summary

The aim of this chapter is to review common foundations and recent developments in the area of socio-ecological economic modeling. The focus is on dynamical mathematical systems.

Central to all modeling in this area is the need for a multidisciplinary approach that describes the dynamics of the economic system, the ecosystem, and the interaction between the two. By identifying variables and parameters that may be under the control of public policy makers, models may by used for assessing the consequences of policy experiments. Alternatively, simulation models may be useful for scenario formulation and forecasting.

Given single or multiple objectives, optimal paths in simulation models can be calculated by means of dynamic optimization techniques. In the case of multiple objectives, or multiple agents having competing objectives, dynamic game theory has become a fruitful means of operationalizing such dynamical systems.

Ecological-economic models may range from those describing the interaction between human activity and the natural environment at an extremely local level (e.g. a pond), to models studying simple closed systems (e.g. population dynamics on Easter Island), to national systems (e.g. multi-sectoral computable general equilibrium models), to international and global models (e.g. modeling trade and environmental change, or global climate change).

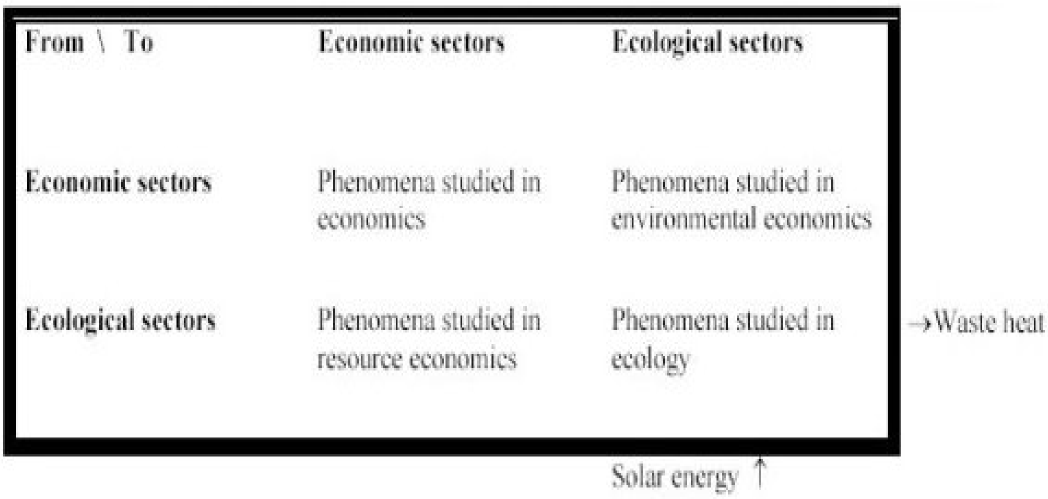
At the theoretical level, there is an increasing emphasis on nonlinear dynamical systems that can mimic complex patterns in ecological economic systems, such as cycles, turbulence, resilience, chaos and catastrophic discontinuities. In simulation, the speed and power of computers continues to increase and permit micro simulation in which macro patterns are derived by aggregation of many micro decision making units. However, empirical estimation or calibration of models and methods of valuation commonly adopted in cost-benefit analysis, such as revealed preference models and contingent valuation, will not be addressed in this chapter.

1. Introduction

Ever since environmental degradation became a core policy issue in developed economies in the 1970s, researchers have devoted increasing attention to the building of analytical models that can aid the formulation and implementation of environmental policies. Initially, economists and ecologists proceeded along rather different paths, but more recently it has become clear that a multi-disciplinary approach is essential for effective modeling of environmental issues and this has led to the field of ecological economics. This chapter introduces the reader to various methodologies for ecological-economic modeling in order to demonstrate how such models can be an effective tool for achieving sustainability of natural resource exploitation and preservation of environmental quality.

Ecological-economic and socio-ecological economic models make explicit the *two-way interaction* between the socio-economic system and the ecosystem, with the latter defined as the complex of living organisms, their physical environment and their interrelationships in a defined space. There are many ways in which human actions influence the environment (e.g., production depletes natural resources and can cause pollution, while consumption creates waste). On the other hand, environmental changes may influence the socio-economic system in a variety of ways (e.g. the cost of resource extraction depends on the availability of the resource; pollution may affect human health and productivity, global environmental change such as the *greenhouse* effect may influence agricultural production). Because the environmental impact of socio-economic activity and the socio-economic impact of the ecosystem are processes that evolve over time, it is clear that the study of economic-ecological interaction requires dynamic modeling that makes the feedback between the two systems explicit. The difference between ecological-economic and socio-ecological economic models in this context is that *behavior* (i.e. the set of preferences of agents) is given in the former, while behavior may evolve in the latter in response to economic and ecological changes.

The need for multi-disciplinary modeling of the ecological-economic interactions is clearly demonstrated by the input-output framework depicted in Figure 1. This figure also illustrates the *materials' balance* idea in ecological economics. The materials' balance is due to the two basic laws of thermodynamics that affect the ecosystem. The *first law of thermodynamics* says that energy and matter cannot be created or destroyed in a closed system. Resources get transformed into products, which after consumption return to the environment as waste. The *second law of thermodynamics* states that entropy has the tendency to increase. *Entropy* is the amount of unavailable energy, or alternatively referred to as the degree of disorder in a system. A closed physical system tends towards an arrangement with maximum disorder, i.e. maximum entropy. Consumption of resources raises entropy. However, it can be seen from Figure 1, that the earth is an open system, as there is an inflow of solar energy and an outflow of waste heat. The energy from the sun puts an upper limit on the consumption that can be sustained. Of course, wastes from production and consumption processes are to some extent converted back into resources. Some of this occurs naturally through biological processes, e.g. aerobic degradation. Alternatively, certain wastes can be recycled. However, recycling is not a free process. The conversion of wastes into useable inputs consumes low-entropy energy.



From \ To	Economic sectors	Ecological sectors
Economic sectors	Phenomena studied in economics	Phenomena studied in environmental economics
Ecological sectors	Phenomena studied in resource economics	Phenomena studied in ecology

Figure 1: Input-output relations in ecological economics and the materials' balance
From: Hediger, W. (1999) *"Economic-Ecological Modelling and Sustainability: A Guideline". In: S. Mahendrarajah et al. Modelling Change in Integrated Economic and Environmental Systems, John Wiley and Sons*)

In the next section we shall review briefly some core issues in modeling in this field and provide a characterization of the available models. Section 3 focuses on macro and micro simulation models and the dynamical properties of such models. Section 4 is concerned with optimization and control of dynamical ecological-economic systems.

Because stakeholders in specific environmental issues may have diverse objectives, while their actions may have repercussions for other stakeholders, it has turned to be particularly fruitful to study such situations by means of game theory. Section 5 reviews the application of this theory to environmental modeling. Section 6 returns to the issue of optimization and control, but now in the context of game-theoretic modeling. The final section evaluations the scope and limitations of current modeling for environmental management and the likely direction of future research in this area.

2. Ecological-economic Interaction Models

An ecological-economic interaction model is a simplification of reality in which the feedback between, and within, the two systems is quantified by mathematical equations. The purpose of the model is twofold: either to obtain better insight in the underlying processes, or to act as a decision support tool for assessing the impact of certain policy changes. Figure 1 above highlighted that the formulation of ecological-economic interaction models is multi-disciplinary, with inputs from various branches of economics and ecology (with the latter being informed by the natural sciences).

The degree of simplification depends on the problem at hand: models with a limited number of variables that replicate some "stylized facts" of reality may be adequate for macro-level analysis and policy making, while a "bottom-up" approach of modeling the behavior of individual actors and their environment may be essential for the study of specific international, regional and local environmental problems. The latter type tends to have a large number of variables and equations. The massive decline in the cost of computation and the strong growth in the volume and quantity of electronically available data has greatly impacted on modeling practice, with large-scale non-linear systems becoming increasingly popular.

In the simplest and most general representation we can consider a range of variables, which represent those features of the ecosystem that are considered relevant for the problem at hand. These can be put together in a vector **v** of dimension *s*. We can similarly describe the key features of the demographic, economic and technological system by the vector **z** of dimension *r*. In later sections we shall regroup the vector $(z', v')'$ that describes the entire ecological-economic system into variables that represent the state of the system but are not amenable to direct control by policy makers as **x**, while the policy variables are grouped in the vector **u**.

While dynamical systems can be described in discrete and continuous time, there is in practical modeling a preference for the former due to the "lumpiness" of human behavior and the availability of data at discrete points in time. Computationally, however, differential equation systems can be equally well simulated. They simply require numerical integration methods for which software is readily available. In linear systems, the behavior of the model is invariant to the choice of discrete or continuous time, but in nonlinear systems the behavior of the model may differ between the two. In this chapter we shall restrict ourselves to discrete time, measured by the time index $t = 0, 1, 2, ..., T$. Most models have an explicit horizon T. In environmental issues, such a horizon may be in a rather distant future, taking into account the welfare of future generations.

A very general ecological-economic interaction model is of the form

$$\begin{aligned} \mathbf{z}_t &= f(\mathbf{z}_{t-1}, \mathbf{v}_{t-1}, \boldsymbol{\mu}_t) \\ \mathbf{v}_t &= g(\mathbf{z}_{t-1}, \mathbf{v}_{t-1}, \boldsymbol{\eta}_t) \end{aligned}, \qquad (1)$$

in which μ_t and η_t are vectors of random variables of dimensions *m* and *n* with means that represent exogenous deterministic factors and distributions that represent non-serially correlated random fluctuations that impact on **z** and **v** respectively. The functions *f*: $R^{2r+s} \to R^r$ and *g*: $R^{2s+r} \to R^s$ map the state of the system at time *t*-1 to that at time *t*. The system (1) exhibits the Markov property in that the current state is only conditioned by the immediate past. While this may appear restrictive, in fact it is not. For any variable x_{t-k} appearing on the right hand side of a dynamical system, the system can always be augmented with the auxiliary equations $a_t^1 = x_{t-1}, a_t^2 = a_{t-1}^1, ..., a_t^k = a_{t-1}^{k-1}$ and substitution of the auxiliary variables, where required, in the original system. Models of type (1) are likely to exhibit a mixture of slow and fast changing variables, with the former being more common among **v** and the latter among **z**. However, sudden jumps are possible in both types of variables (e.g. crop failure, or a new technological innovation).

The dynamic system described by (1) is not a formal policy model, as there are no explicit policy variables and policy objectives. Policy in this model can be thought of as evolving endogenously and affecting, through equations that can be referred to as *policy reaction functions*, some elements of **z** (in the case of economic instruments of environmental policy) or **v** (in the case of the command and control approach to environmental protection). Alternatively, the impact of policies can be considered explicitly if policy can manipulate certain model *parameters*, *initial conditions* $\mathbf{z}_0$ and $\mathbf{v}_0$, or the vectors μ and η of exogenous deterministic factors and stochastic disturbances. In the latter case, simulation of (1) for unchanging values of μ and η is often referred to as a *business as usual* scenario. We return to policy objectives, instruments and the optimality of time paths in Sections 4 and 6.

The simplest dynamical model that satisfies Eq. (1) is a linear deterministic system. This system of equations is given by

$$\begin{aligned} \mathbf{z}_t &= \mathbf{A}\mathbf{z}_{t-1} + \mathbf{B}\mathbf{v}_{t-1} + \mathbf{c} \\ \mathbf{v}_t &= \mathbf{D}\mathbf{z}_{t-1} + \mathbf{E}\mathbf{v}_{t-1} + \mathbf{f} \end{aligned}. \qquad (2)$$

The first of these two matrix equations is the economic model, in which the matrix **A** represents the interrelationships in the economic, demographic and technological system, **B** is the *environmental impact* matrix and **c** is a vector of constants. In the second equation, **D** stands for the *resource impact* matrix, **E** for the matrix of coefficients that represents the interrelationships within the ecosystem, and **f** is vector of constants. If we define $\mathbf{X} = \begin{bmatrix} \mathbf{A} & \mathbf{B} \\ \mathbf{D} & \mathbf{E} \end{bmatrix}$, the system (2) can be rewritten by successive substitution as

$$\begin{bmatrix} \mathbf{z}_t \\ \mathbf{v}_t \end{bmatrix} = \mathbf{X}^t \begin{bmatrix} \mathbf{z}_0 \\ \mathbf{v}_0 \end{bmatrix} + \left[\mathbf{X}^{t-1} + \mathbf{X}^{t-2} + \ldots + \mathbf{X} + \mathbf{I}\right] \begin{bmatrix} \mathbf{c} \\ \mathbf{f} \end{bmatrix}. \tag{3}$$

Because the matrix **X** can be expressed as $\mathbf{X} = \mathbf{P}\Lambda\mathbf{Q}$, where Λ is a diagonal matrix whose diagonal elements are the characteristic roots of **X**, and **P** and **Q** are matrices such that $\mathbf{QP} = \mathbf{I}$ (identity matrix), it follows that $\mathbf{X}^i = \mathbf{P}\Lambda^i\mathbf{Q}$ for i = 1, 2,..., t and the dynamic behavior of the system is determined by the characteristic roots of Λ. These may be real or complex, but stability requires all roots to be inside the unit circle. If they are, the system converges to a *steady-state*, which is given by

$$\begin{pmatrix} \mathbf{z}_* \\ \mathbf{v}_* \end{pmatrix} = \begin{pmatrix} \mathbf{I} - \mathbf{A} & -\mathbf{B} \\ -\mathbf{D} & \mathbf{I} - \mathbf{E} \end{pmatrix}^{-1} \begin{pmatrix} \mathbf{c} \\ \mathbf{f} \end{pmatrix}. \tag{4}$$

If one or more of the elements on the diagonal of Λ is outside the unit circle, the system will explode to some boundary values such as “extreme levels” of pollution. “Zero” resources or “negligible” income may be other undesirable solutions to the system. The speed of change in the linear system is determined by the largest element of Λ. If a steady-state exists, it will be independent of the initial conditions $(\mathbf{z}_0, \mathbf{v}_0)$. The dynamical behavior of any variable in the linear deterministic system (2) is limited to only four types: monotonic explosive change; monotonic convergence, oscillatory explosive change and oscillatory convergence. A nonlinear system may exhibit a much greater variety of behavior. In such systems, the time paths and long run tendencies may also be strongly sensitive to initial conditions.

It is useful to introduce a simple notion of *sustainability*. Traditionally this was thought of in terms of *conservation*, that is, ensuring that certain elements of the vector **v** remain greater than some minimum, hence $\tilde{\mathbf{v}}_t \geq \tilde{\mathbf{v}}_0$, where $\tilde{\mathbf{v}}$ refers to some appropriate subset of the vector **v**. However, since the so-called Brundtland report, published by the World Commission on Environment and Development in 1987, the definition of sustainability also includes the notion that future generations should be able to attain at least the same level of welfare as the present. This can be formalized by imposing that, in addition, $\tilde{\mathbf{z}}_t \geq \tilde{\mathbf{z}}_0$ where $\tilde{\mathbf{z}}$ refers to some appropriate subset of the vector **z**. In the dynamical system (3) there is no guarantee that $\begin{bmatrix} \tilde{\mathbf{z}}_t \\ \tilde{\mathbf{v}}_t \end{bmatrix} \geq \begin{bmatrix} \tilde{\mathbf{z}}_0 \\ \tilde{\mathbf{v}}_0 \end{bmatrix}$ and the steady-state may therefore not be sustainable in the present meaning of the term. Sustainability is one form of optimality. The notion of optimality is also central to socio-ecological modeling. The steady state defined above may also be sub-optimal on the grounds of several other criteria.

In recent years, the nonlinear system (1) is in ecological-economic modeling preferred to the linear model (2). There are several reasons. First, as noted above, the qualitative dynamics of linear systems is rather too restrictive to mimic certain economic and ecosystem phenomena. Secondly, the model (2) is subject to the so-called *Lucas critique*: it does not take into account that a system that moves away from the steady state may trigger behavioral responses that would slow down or reverse large departures from the steady state. Hence parameter changes may result. Systems may be *self-organizing*. Thirdly, computing technology has advanced to the point that complex dynamical systems can be studied with relative ease.

When the functions *f* and *g* in (1) are nonlinear, the system can exhibit multiple steady states and a wide range of dynamical patterns, including convergence, cycles and chaotic or catastrophic changes. Nonlinear dynamical models are increasing in popularity because they can mimic the mixture of slow and fast changing phenomena that can be observed in the ecosystem. For example, a small exogenous shock may have an imperceptible effect on environmental quality for some time but trigger a catastrophic change at a later date. Some of the developments in nonlinear modeling are reviewed in the next section.

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Biographical Sketches

Jacek B Krawczyk was born in Poland, and lives in Johnsonville, Wellington, New Zealand. He got his Ph.D. in applied science awarded by the Warsaw University of Technology (WUT); and M.Sc.in control theory and computer science (ibid.).

Professor Jacques Poot, was appointed as Director of the Population Studies Center in February 2004. During the last quarter century Jacques acquired considerable research experience in population and labour economics – and related interdisciplinary fields such as regional science – in New Zealand at Victoria University of Wellington and in Japan at the University of Tsukuba. Jacques was born and educated, up to Masters level, in The Netherlands. This was followed by a PhD at Victoria University of Wellington. He is a Corresponding Member (the equivalent of an Honorary Fellow) of the Royal Netherlands Academy of Arts and Sciences. Jacques is a member of the editorial board of a number of international journals and is also Pacific editor of Papers in Regional Science.

Jacques' research interests include all aspects of the economics of population (such as migration, fertility, labour force, and ageing). He has also carried out research projects in a wide range of other areas, such as: meta-analysis of non-experimental social science research; monopsony in local labour markets; the impact of geography on economic growth; regional development; globalisation; innovation and efficiency in the New Zealand construction sector; transportation policy and the environment; housing markets; and forecasting.