Advances in Environmental Economics: Analysis and Modelling

Jeroen C.J.M. van den Bergh Peter Nijkamp

Dept. of Spatial Economics
Free University
Amsterdam

pn720jb

Abstract

This paper gives a concise overview of environmental-economic analysis. Important issues and modern developments in the field are surveyed in a systematic way. Next, the concept of sustainable development is discussed, as it has dominated environmental economics for almost a decade now. In addition, the issue of modelling the interface of the economy and the natural environment making use of material balance conditions is examined. The paper concludes with a consideration of issues of uncertainty in policy analysis and forecasting with particular reference to scenario analysis.

1. The Rise of Environmental Economics

Environmental economic problems are nowadays presenting a major challenge to policy analysts. In the past decades, the threatened state of the natural environment has become a key issue in policy evaluation because of the great many externalities involved. It is increasingly recognized that environmental resource conflicts will generally have far-reaching economic and ecological impacts which cannot always be encapsulated by a prevailing market system. The limits inherent in conventional economic evaluation methodologies and the necessity of analyzing unresolvable conflicts between diverse policy objectives have led to the need for more appropriate and fine-tuned analytical tools for strategic evaluation of environmental policies or plans, both locally and globally.

In analytical models for environmental and resource policy-making, the following three main types of policy objectives may be distinguished (Braat and Van Lierop 1987):

1. nature conservation objectives, e.g., 'minimum exploitation of goods and services at minimum (private and social) cost';
2. socio-economic objectives, e.g., 'production of goods and services at minimum (private and social) cost';
3. mixed objectives, e.g., 'maximum sustainable use of resource and environmental services' or 'minimum regret' choices .

Given the diverse nature of these objectives, it is widely recognized that in policy-relevant economic-environmental evaluation models, socio-economic and nature conservation objectives are to be considered simultaneously. Consequently, various multi-criteria and multi-objective methods are, in principle, an appropriate modelling tool for combined economic-environmental evaluation issues. Such methods seem to be an adequate response to policy choice situations characterized by a high degree of market failure inducing social costs to various members or groups of society.

Daly (1989) identifies three main conflicting goals in economics: optimal allocation (efficiency), acceptable distribution (equity) and optimal scale (sustainability). While an optimal allocation may result from the operation of markets, the attainment of both distributional issues and optimal scale (or at least any scale that is not above the maximum carrying capacity) requires collective action by the community on the relevant - regional, national or international -level according to the nature of the problems under consideration.

Seen from this perspective, one may refer to Tinbergen (1956), who made a useful distinction between the analytical aspect and the political aspect of public decision-making. The analytical aspect is concerned with links between all variables relevant in the decision-making process as well as with all side-conditions imposed by the economic, social and technological structure of society. This analytical aspect of a decision problem can in theory be represented by a set of formal statements or an impact model (or structural model). The political aspect concentrates on the choice of instruments and their operational implementation in order to realize the policy objectives. These policy objectives can be operationalized as a set of fixed targets to be strived for or as arguments of a community welfare function to be optimized. In particular the latter approach has received much attention in the literature on policy-making and in welfare economics, and has become an important element of the economic theory of environmental policy (see Baumol and Oates 1988). The latter approach follows standard neoclassical optimization theory and may also be referred to as externality theory.

The relevance of conventional optimization models has been questioned from many sides. The optimizing approach is based on the assumption that different objectives can be expressed in a common denominator by means of trade-offs, so that the loss in one objective can be evaluated against the gain in another. This idea of compensatory changes underlies both the classical economic utility theory, the traditional cost-benefit analysis, and the ‘externality theory’, which have been applied to a wide domain of specific environmental economic issues. The determination of a common denominator is, however, fraught with many difficulties of a practical and methodological nature. From a theoretical point of view, the optimizing principle is very elegant, since it provides an unambiguous tool to evaluate alternative strategies on the basis of their contribution to social welfare. From an operational point of view, the value of the traditional optimizing approach is however, rather limited. The associated Pareto optimality (or efficiency) is only a very weak criterion for choosing among alternative allocations or policies. And the specification of a complete and explicit social welfare function requires perfect information about all possible combinations of actions, about the relative trade-offs between all actions and about all constraints prevailing in the decision-making process. Thus, policy models have several advantages and disadvantages in their use in environmental and resource management.

This paper aims to give a concise overview of the state-of-the-art and recent advances in environmental-economic analysis. Section 2 presents a survey of important issues and modern developments in the field. In Section 3 we will pay attention to the concept of sustainable development which has dominated environmental economics for almost a decade now. Section 4 will - by way of illustration - offer a concise introduction to a model at the interface of economics and natural science, viz. the material balance model. And finally, issues of uncertainty in policy analysis and forecasting will be dealt with in Section 5 with particular reference to scenario analysis.

2. Issues in Environmental Economics

2.1 Introduction

Environmental economics is a rapidly evolving field, as is witnessed by a large number of recent textbooks (e.g., Folmer *et al.* 1995, Hanley *et al.* 1997, Perman *et al.* 1996, Siebert 1995). Its accelerated pace is also reflected in the great many monographs, edited books, journals, conferences, workshops and international projects. The variety of issues covered is increasing as well: pollution, global and climate change, biodiversity, monument conservation, international negotiations etc. To some extent this rise in scope may be ascribed to different economists from various subdisciplines of economics studying environmental issues and contributing to its progress. In addition, the multidisciplinarity nature of many issues raised in environmental economics research has caused an increase in the interaction between economists and scientists from various subdisciplines (e.g., political science, ecology, chemistry, law etc.), for purposes of either communication or integration of insights and tools.

Recent broad surveys however, are rather rare, notable exceptions being

Bromley (1995) and Van den Bergh (1998). The latter encyclopedic volume covers a wide range of issues, classified as follows:

- economics of natural resources
- economics of environmental policy
- international aspects of environmental economics and policy
- space and environmental economics
- environmental macroeconomics
- economic valuation and evaluation
- interdisciplinary issues
- methods and models in environmental and resource economics

These issues will now concisely be discussed in subsequent subsections.

2.2 Economics of natural resources

In modern approaches to natural resource economics a diversity of approaches is present, which differs according to problems studied and types of resources or sectors considered. Conventional resource economics' theory addresses optimal extraction under competitive conditions with and without capital (Hotelling rule), extraction under uncertainty, imperfect competition under monopoly and cartels, and optimal revenue and Pigouvian taxation. In the past decades also much attention is devoted to international trade aspects of resource markets under various market configurations, which has received much attention due to its relation to sustainable development and growth. These topics have been extensively treated in the classic text by Dasgupta and Heal (1979), as well as in Hartwick and Olewiler (1998), Neher (1990), and the third volume of Kneese and Sweeney (1993), which is entirely devoted to advanced resource economics. An important issue is the definition and assessment of indicators of resource scarcity, where various classes of approaches may be distinguished, based on classical, neoclassical and biophysical models of scarcity. Two other major areas of research pertain to renewable resources, namely fisheries and forestry. In these areas, important research issues are alternative management techniques, uncertainty, investments, and multiple use. The classic introduction to these resource issues is Clark (1976). For a more recent account of such renewable resources we refer to Clark (1985) and Walters (1986), and Johansson and L″fgren (1985). Clearly, environmental economic aspects of resources may also refer to other fields, such as water resources, agriculture and energy resources. In all cases, important analytical issues are the institutional setting of the problems examined, irreversibility, externalities and equity.

2.3 The theory of economics of environmental policy

The theory of pure environmental economics and policy is covered in the classic text by Baumol and Oates (1988), and deals with externalities, other market failures and environmental risk. As pointed out by Baumol and Oates (1988), these measures can take the form of direct regulations (e.g. maximum pollution emissions) or the form of economic disincentives (pricing systems based on social costs in the form of taxes and subsidies). Of course, mixed modes may also be possible.

In addition, there may be complementary approaches. A different economic perspective leads to a property rights approach. The 'Coase theorem' (Coase 1960) provides the theoretical basis for a non-interventionist pollution control policy. Environmental pollution is a form of market failure because of the overexploitation of resources held as common property or not owned at all; therefore, the market fails when property rights are inadequately specified. According to the property rights approach, increased government intervention should be resisted, because public ownership of many natural resources is the real root of resource control conflicts; then there is a policy failure**.** According to Coase, given certain assumptions, the most efficient solution to pollution damage situation is a bargaining process based on tradeable rights: if the polluter has the right, the sufferer can compensate him not to pollute; if the sufferer has the right, the polluter can compensate him to tolerate damage.

An important analytical issue is the choice of policy instruments in relation to efficiency, distribution and other criteria. Usually, in the literature standards and taxes are considered, focusing on an analysis of efficiency advantages of taxes over standards. But other criteria like equity, political and ethical perspectives are relevant as well. More recently, new topics like imperfect markets, technological innovation, transaction costs, tradable permits and environmental tax reform have been considered as well. In cases of environmental policy under monopoly and oligopoly entry issues are important, while the use of policy instruments and impacts of environmental degradation on market demand or supply receive increasing attention.

In the recent environmental economics literature, much emphasis is given to both advanced theory and practical lessons of experiences with tradable permits. The first stream discusses tradable permits under imperfect competition and barriers to entry, lack of trade in permit markets, and auctioning of permits. The second stream deals with the history of trading programs in permits (mainly in the US) by considering different local and global environmental problems, e.g. related to lead in gasoline, ozone depletion, acid rain, etc. The assessment of the regulation programmes is also an important topic by examining programme design goals, such as cost-effectiveness, reduction of transaction costs and better air quality.

In recent years, there is much interest in environmental tax reform, e.g., the theory of second-best environmental taxation. This literature examines whether a double dividend is feasible, i.e. having a positive impact on both environment and employment. For more discussion on these much debated issues the reader is referred to O'Riordan (1997).

Distributional issues in environmental policy have received less systematic attention so far. Economists have focused their attention on static and dynamic efficiency, information demand, ease of monitoring and enforcement, flexibility, and institutional demands of agency and regulated parties. Surveys of instruments in practice, with a particular focus on market based instruments, are presented by Sterner (1994), Opschoor and Vos (1989), Opschoor and Turner (1994), and Opschoor *et al.* (1994). This would require efficiency-equity trade-offs, both in the context of standard welfare theory, based on utilitarianism, and on the basis of other sound criteria, such as Rawlsian theories of justice, and libertarian thought. It should be recognized that efficiency and distribution in general equilibrium models are non-separable, where distribution refers to a wide category of wealth, income and rights. This can be seen as individuals' values and therefore prices depend on relative wealth positions in society. As a result, a unique determination of ‘correct’ prices is nowadays regarded impossible, as the latter will depend on distributional choices. It is not clear which alternative approach is preferable. Neo-Ricardian and Sraffian reproductive instead of allocative modelling of economic and ecological distribution have been proposed. Finally, in the context of intergenerational distributional issues the conflict between efficiency and sustainability is essential. This has focused on pleas for ethically motivated correctors of discount rates. But perhaps intergenerational transfers is a clearer and more direct way of taking care of future generations’ interests. These transfers will of course influence discount rates.

2.4 International aspects of environmental economics and policy

In contrast to models of closed economies, there are three main topics in environmental economics that have an international dimension: cross-boundary and global environmental issues; the interface between foreign trade and environmental externalities; and international policy coordination and trade agreements.

Trade issues cover in general theoretical and empirical issues, a range of equilibrium models, and the context of low developing countries. At present, there is much interest in models that can address questions related to specialization patterns, interlinkages of economic production sectors and markets, feedback effects of policies, distributional issues and leakage effects, including the use of Heckser-Ohlin models extended with environmental variables. It is widely recognized that research on trade-environment interactions needs to address spatial distances, technological innovation and particular features of developing countries. For an overview of theory in this area, see Van Beers and Van den Bergh (1996), and of empirical studies Van Beers and Van den Bergh (1997) and Jaffe *et al.* (1995).

In general, research in this area tends to address specific categories of environmental problems. In particular, transboundary environmental problems are considered with a focus on a general formalization of these problems and detailed discussions on ‘acid rain’ and global warming. Economic models have been developed to address non-cooperative and cooperative situations, design of international agreements, and relations between trade and trans-boundary pollution. The main issues covered with such models are global warming, stratospheric ozone and biodiversity. Much attention is usually given to economic costs and benefits, uncertainty aspects and policy instruments. The studies in this field relate also to policy initiatives to address global environmental problems. This includes, among others, considerations of efficient specification, dynamic issues, interactions with other taxes, international bargaining and coordination, and barriers and problems. These trade and global issues are treated in a number of books (see, among others, Anderson and Blackhurst 1992, Low 1992, Mabey *et al.* 1997, Siebert 1995, and Pearce and Warford 1993).

2.5 Space and environmental economics

Spatial dimensions of environmental problems, environmental policy and environment-economy interactions (including issues of growth and environmental sustainability) are often underrepresented in environmental economics. There is still much to do in this area, especially in a multidisciplinary setting, linked to natural sciences, notable hydrology, geography and ecology, where spatially disaggregate frameworks and models are very common (Turner *et al.* 1998).

Conventional issues that have received some attention are non-point source pollution, land use, urban environmental problems, location choice and transport. ‘Space’ is the geographical medium, which is both heterogeneous and scarce. In this context, non-point source pollution is a relevant problem in the context of diffuse sources like farmers and households and mobile sources like vehicles. This can be regarded as both a spatial and an information asymmetry problem, where the latter results from imperfect observability of the polluters by the regulator. Different incentive schemes, such as input and ambient taxes may be envisaged, both theoretically and practically. In this context, also land use and environmental quality deserve due attention (see, e.g., Xepapadeas, 1998).

An important topic is formed by regional and urban sustainability issues, by addressing three dimensions, namely land, energy and transport. Especially the relationship of transport and the environment is important, as it provokes a thorough discussion of social costs and energy efficiency of transport, including a discussion of the economic and social feasibility characteristics of transport-environment policies (Verhoef 1997).

2.6 Environmental macroeconomics

This theme is about the relationship between macroeconomics and modelling in environmental economics, while also attention is devoted to the economics of global modelling and to integrated assessment. Some of the issues are approached from the perspective of neoclassical growth theory and macroeconomics, the latter in relation to regionalized world models, environmental input-output models and qualitative scenario studies. Endogenous growth and environment receive separate attention nowadays, and has been the subject of many publications in the past few years.

Another important research direction concerns empirical research with a macroeconomic orientation on growth and environment, dominated by a search for so-called environmental or Green Kuznets curves. Here attention is devoted to the choice of indicators, data, statistical methods, interpretation of empirical results, and policy implications (e.g., Ekins 1997).

An important issue is the choice of sustainability indicators. This theme covers a conceptual framework for indicator development, as well as a scheme of aggregation and spatial and analytical demarcation. A number of approaches can be recognized: a single aggregate indicator like ‘green GDP’, genuine savings measures, etc.; a set of multiple economic and environmental indicators, and indicators which can address all elements of economic-environmental cause-effect chains such as activities, pressures, environmental quality and policy (e.g., Van den Bergh and Van Veen 1998). Recently, aggregate physical indicators like the ecological footprint and the material intensity per service (MIPS) have received much attention (Wackernagel and Rees 1996, Weizs„cker *et al.* 1997). However, the aggregation procedure underlying these is subject to much arbitrariness.

Good surveys of theoretical economic views on growth, environment and sustainability is offered by Toman *et al.* (1995) and Pezzey (1989) (including a long list of definitions of sustainable development). A wide range of indicators of sustainable development is presented in Atkinson *et al.* (1997). An interesting systems perspective on sustainability is Clayton and Radcliffe (1996).

2.7 Economic valuation and evaluation

Valuation has received ample attention in environmental economics, on a theoretical and methodological level (Freeman 1993, Johansson 1987 and Bromley 1995). Main methods cover recreation demand models, hedonic pricing models, and contingent valuation (CV) models. Recreation models refer to valuation methods that include indirect methods, recreation demand models and traditional travel cost models that all use travel costs as core information. The differences between these relate to continuity versus discreteness of demand, i.e. they focus on the number of visits to a particular site versus the choice between alternative sites, respectively. Clearly, there is also much interest in the development and application of hedonic pricing methods for economic valuation of environmental change, where detailed attention is devoted to various sophisticated theoretical and statistical refinements, such as the timing of adverse impacts of environmental pollution on property values, functional forms and two-stage models. Some of this refers to the results of meta-analysis of hedonic studies. Two early books on CV are Mitchell and Carson (1989) and Cummings *et al.* (1990), while recently two important publications have appeared (e.g., Bjornstad and Kahn 1996; Kopp *et al.* 1997). In the context of environmental economics, meta-analysis has received a great deal of attention recently, also in relation to benefit or value transfer. This is often approached from a broad perspective, covering conceptual issues, statistical issues, alternative methods, the relation with benefits transfer, and the fundamental and practical limits to meta-analysis (see van den Bergh *et al.* 1997).

2.8 Interdisciplinary issues

Interdisciplinary issues may refer to the interface of environmental economics with physics and biology, dealing with material flows, energy transformation and ecological processes which may be considered to be essential knowledge for environmental economists. Examples of ‘physical principles’ are the material balance principle and the ‘entropy law’ in environmental economic studies, in relation to production processes, economy-environment interactions, and long-run growth. Other important issues are product cycles, ‘dematerialization’ and recycling. These topics of materials, energy and thermodynamics in relation to economics and the environment have been extensively discussed in Ayres (1978 and 1998), Ayres and Ayres (1996), Daly and Umaña (1981), Faber *et al.* (1987), Georgescu-Roegen (1971, 1976), Kneese *et al.* (1970), Martinez-Alier (1991), Peet (1992), Perrings (1987) and Ruth (1993). A complementary topic, namely ‘ecological principles’, devotes attention to the structure, classification, succession, development and management of ecosystems. For example, the importance of biological diversity for ecosystem functioning is an important issue. Multidisciplinary focal points are in particular addressed in ecological economics. Introductions to ecological economics are provided by Costanza *et al.* (1997a,b), Daly and Cobb (1989), Daly and Townsend (1993), Martinez-Alier (1987), Peet (1992), and van den Bergh (1996).

In this context, we witness also a great popularity of evolutionary perspectives in economics as applied to environmental problems. Attention is here devoted to traditional and modern insights of evolutionary biology and how these have influenced evolutionary economics. Other approaches are also recently discussed, notably based on Schumpeterian theories and thermodynamics, followed by an account of modelling of evolutionary systems. As a result, in recent years special attention is given to a number of topics, including mechanisms for the selection of economic agents, hierarchical organization, structural economics and industrial ecology, and management of evolutionary natural systems. The most important contributions in this respect are Boulding (1978), Clark *et al.* (1995), Faber and Proops (1990), Gowdy (1994), Munro (1997) and Norgaard (1994).

In view of the complexity of the interdisciplinary problems, involving description, estimation, analysis and evaluation, there is a need for an appropriate analytical framework allowing for a comprehensible and operational representation of a real-world environmental economic system. The strong quantitative tradition in economics has in the recent past enabled researchers to include environmental elements fairly easily in conditional models. Nevertheless, in integrating economic and environmental or ecological models various difficult methodological problems have to be faced, such as: differences in time scales (general economics focuses on short to medium term effects, whereas most of ecology is based on medium to long turn processes); differences in aggregation levels (in economic models high compared to most ecological models), differences in spatial scales (the spatial scale of many ecological variables is sometimes very low, whereas that of many economic variables is rather high) and differences in measurement levels of the variables (the level of precision may vary, and thus there is a clear need for methods taking also into account information of a mixed type).

2.9 Methods and models in environmental and resource economics

It is evident that there is a range of methods that are often used in environmental economics. Models aiming at depicting, predicting or analyzing problems of an integrated economic-environmental nature are commonly referred to as economic-environmental or economic-ecological models (see Hafkamp 1984, James 1985, Braat and Van Lierop 1987, Van den Bergh 1996). They are characterized by a variety in technical structure (nonlinear/linear, static/dynamic, descriptive/forecasting/optimizing), and may be considered as the result of a trade-off between generality, precision and realism (see Costanza *et al.* 1993). The main method used in environmental economics is (partial or general) equilibrium analysis, which is well covered in standard economic and environmental economics textbooks. In particular, input-output analysis (IOA) in environmental economics has become very popular. It includes various extensions in environmental economic applications, materials balance and physical models, dynamic models, and Social Accounting Matrices extended with economic-environmental flows. Furthermore, there is much interest in applied or computable general equilibrium (CGE) models. It covers methodological principles, and the standard elements related to producer and consumer behaviour, foreign trade, multi-regional models, dynamics, and closure rules. Such models may also incorporate abatement technologies, environmental policy instruments and measures of welfare change. Subsequently, game theory in environmental policy analysis has also become an important topic, especially in three areas of application in environmental economics, namely international environmental problems, interaction between a regulator and regulated agents, and strategic competition between governments or between economic agents. From a dynamic perspective optimal control techniques are often used to solve environmental economic problems formulated as continuous dynamic optimization models.

3. The Notion of Environmentally Sustainable Development

The concept of sustainability has already a long history (see Nijkamp and Van den Bergh 1997). The most well known definition of sustainable development is probably the one given by the World Commission on Environment and Development (WCED 1987): "… *paths of human progress which meet the needs and aspiration of the present generation without compromising the ability of future generations to meet their needs*". From a more strictly economic perspective, Goodland and Ledec (1987) define sustainable development as: "… *a pattern of social and structural economic transformations which optimizes the benefits available in the present without jeopardizing the likely potential for similar benefits in the future*". This definition implicitly assumes a need to maintain yields from renewable natural systems over long periods of time. Other approaches to the concept of sustainable development focus on the physical or natural resource base of any economy. Pearce and Turner (1990) claim that sustainable development implies maintenance over time of aggregate resource stocks, such that the potential to generate welfare is not allowed to fall below the current level. Clearly, this viewpoint raises also important questions concerning the measurability of environmental quality and environmental capital (see, e.g., Pezzey 1993, Van den Bergh and Van der Straaten 1994, Jansson et al. 1994). Thus, the debate on sustainability has not led to an unambiguous view on its precise meaning.

There has also been much discussion on the question whether a growing economy is compatible with sustainability. According to Costanza (1987), "*sustainability does not necessarily mean a stagnant economy, but we must be careful to distinguish between growth and development*". Economic growth which is an increase in quantity cannot be sustained indefinitely on a finite planet. Economic development which is an improvement in the quality of life without necessarily causing an increase in quantity of resources consumed, may be sustainable. Sustainable growth is in the long term essentially an impossibility. Sustainable development should therefore become our primary long-term policy goal. Hence, the goal of the sustainability of natural resources and of the environment is to direct explicitly economic development. Following Costanza *et al.* (1991, p8), a practical definition of global sustainability is the following: Sustainability characterizes a relationship between quickly-changing human economic systems and larger dynamic, but normally slower-changing ecological systems, in which: i) human life can continue for a very long period of time (say more than 1000 years), ii) human individuals can flourish (are free and happy); and iii) human cultures can develop; and iv) effects of human activities remain within bounds, so as not to destroy the diversity, complexity, and functioning of the ecological life support system. Although it is not difficult to be critical on any definition of sustainable development, this one, while leaving sufficient freedom to fill in the details, at the same time enlightens the four major components in the debate as well as the modelling of the concept. There is a multiplicity of complementary and sometimes alternative definitions, albeit that the meaning is largely clear.

The discussion on sustainable development has also led to a renewed interest in the ecology-economy perspective (Costanza 1991). The economic system is an open dynamic system of the overall finite global ecosystem, similar in many ways to ecological subsystems. The two systems are physically connected by the throughput of energy and matter from ecosystem sources and by other environmental goods and services sustaining economic activity. This means that economic production of any commodity needs natural resources, and gives rise to the transformation of natural resources - from discovery, extraction, refinement and so on - into useful raw materials and eventually into humanely produced goods and services; it also requires the use of industrial energy as well as the support by ecosystems that are being driven by solar energy input. The economic subsystem rests on these bio-physical foundations, which may be formalized through ecosystems' theory and the laws of thermodynamics. One important implication is that the economy must behave, to be sus-tained, in a way that is consistent with these bio-physical laws, which cannot be circumnavigated. This insight requires that market processes are in some way integrated with them.

The previous observations provoke also questions on the role of markets. Since market prices do not reflect exactly the relative scarcity of environmental resources, it is necessary from a political economic point of view, in order to avoid an overexploitation of these resources, to impose appropriate regulatory measures by public authorities. In fact, since the rational decisions of individual agents lead necessarily to an outcome that is inconsistent with the best interests of society, a ’social trap’ (Costanza 1987) exists. The users of a common resource stock have little incentive for the conservation of that resource; Hardin (1968) has called this the ‘tragedy of the commons’. The situation may even be worse in the case of open access resources. For instance, as long as fish in the sea can be caught profitably, fishermen will wish to do so, and this may lead to severe over-fishing not taking into account long-term effects (Clark 1990). In order to cope with such externalities, policy measures may have to be introduced.

From an ecological-economic perspective, the expansion of the economic subsystem is limited by the size of the overall finite global ecosystem of and by its dependence on the life support sustained by intricate ecological connections which are more easily disrupted as the scale of the economic subsystem grows relative to the overall system. Since the human expansion, with the associated exploitation and disposal of waste and pollutants, not only affects the natural environment as such, but also the level and composition of environmentally produced goods and services required to sustain society, the economic subsystem will be limited by the impacts of its own actions on the environment (Folke and Käberger 1991).

In the context of sustainable development especially the spatial dimension has received little attention. The importance of the spatial element arises from a reciprocal relationship: (1) local processes have global impacts; and (2) global trends give rise to local effects. For example, the loss of ecosystems in some regions may have a large impact on global climatological conditions and geochemical cycles. Over-grazing and deforestation may lead to large-scale soil erosion, downstream sedimentation, floodig and salinisation (see, e.g., Clark and Munn 1986). Furthermore, environmental processes do not uniformly and smoothly impact all regions, but may have important different consequences at a regional scale (see, e.g., Alcamo et al. 1990). The specific regional environmental and economic structure determines the sensitivity of a region to external environmental and economic forces (Siebert 1985, 1987).

Studying sustainability in a multi-regional system may be useful to deal with the spatial implications of global sustainability, in terms of regional activities and inter-regional tradeflows. Verhoef and Van den Bergh (1995a, 1995b) present analytical and numerical results of such a type of investigation, in the context of sustainable transport. Based on an extended spatial price equilibrium model, an optimal trade-off can be made between mobile and immobile sources of pollution, between regional production (with autarky as an extreme case) and trade dependence, and between volume reductions and technological solutions. The model also allows to consider to what extent partial - such as isolated, single sector - policies can lead to sustainability goals. Although transport is pre-eminently linked to issues of spatial sustainability, one can also translate the results to other types of open systems, such as countries, sectors and ecosystems. A similar issue is studied in Van den Bergh and Nijkamp (1995), now in an explicit dynamic simulation modelling context where economic and environmental processes of two regions, and their trade and environmental interactions, are dynamically specified. The resulting model is used to trace, among others, sustainable growth in an open economy, the effect of dissimilarity between regional environmental processes, and the role of technological progress and diffusion. Essential for the outcomes is the endogenous pattern of interregional trade in the model.

4. The Material Balance Approach in Environmental Economic Modelling

In the past decades a wide variety of economic-environmental models have been developed with more or less success (see for overviews inter alia Hafkamp 1984; and Van den Bergh 1996). The present section is based on the viewpoint that a long run economic-environmental analysis, which is needed for issues of sustainable development, should be based on two main elements: (i) the long run relationship between the economy and the natural environment is characterized by two-way interactions between on the one hand population growth, investment, technology and productivity, and on the other hand declining environmental quality and resource exhaustion; and (ii) a more realistic representation of the interdependence between various environmental effects, from extraction to emission, can be realized by adopting a materials balance perspective on economic processes. This means that direct mutual impacts between the economy and the environment, as well as indirect economic-environmental influences are taken into account, by separating between individual effects from and on production, consumption and welfare. Wilkinson (1973) had already introduced the idea of ecological disequilibrium to link economic change to environment-economy relationships. Inclusion of such environmentally influenced economic change in impact models has been undertaken inter alia by Faber and Proops (1990) and Van den Bergh (1993). Complementary and related models stem from applied systems theory, notably in the fields of biophysical "macroscopic mini-models" derived from energy language diagrams (Odum 1987) and of global modelling (Meadows *et al.* 1982). The main shortcomings of these models in comparison with a materials balance approach are the lack of consistent description of the relation between substitution and productive inputs (or components of welfare), virgin resource extraction and waste generation and residuals emission.

For an investigation of economic-ecological integration at both a theoretical and operational level of modelling one may - as indicated above - also include materials balance conditions to account in a consistent way for material flows that lead to various interlinked effects. Although the use of material balance models was already propagated more than two decades ago (see Ayres and Kneese 1969 and Kneese *et al.* 1970), it has unfortunately seen little application. Furthermore, the combination of non-linear models and materials balance conditions is rare, in both theory and applications. The main reason is that materials balance analysis or materials accounting can be done much more easily with linear production functions. Exceptions are Faber *et al.* (1987), Gross and Veendorp (1990), Van den Bergh (1991), Ruth (1993), Kandelaars and Van den Bergh (1996).

The concept of materials balance applies to all natural and economic processes. It means that materials in a physical system are not lost, and that material inputs in processes end up in either stock accumulation or material output flows. It should be mentioned here, that the material input is larger than the useful goods output, in view of spillage and auxiliary materials (like water and fertilizer in agriculture) (see Ayres and Kneese 1989).

In formalizing the materials balance principle in environmental economic models, the following steps are required: (i) relevant variables should be in material units; (ii) where necessary, transformations must be modelled between (variables in) material units and other units; and (iii) materials balance conditions should be specified for economic variables in the economic system, for ecological/physical variables in the environmental system, for economic-environmental interactions (which include both economic and environmental variables). Production functions can be formulated in various ways to satisfy the materials balance principle. Application of the materials balance principle to the production process expresses that all material input must end up somewhere: in final or capital goods or in waste. The link between production theory and materials balance is rarely touched upon in the literature. Some theoretical and conceptual steps taken in this direction were set by Anderson (1981) and Smith and Weber (1989). Some properties for a Cobb-Douglas production function that satisfies the materials balance condition are derived by Gross and Veendorp (1990). They show with a standard economic growth analysis that such a function sets a limit to growth for the case of an economy that obtains its material inputs from a non-renewable resource. A discussion of mass balance production functions in relation to the distinction between direct and indirect substitution mechanisms is contained in Van den Bergh (1997).

The use of materials balance conditions can provide insight in many areas of environmental and environmental-economic research. Examples are: studies on the physical and ecological limits to economic growth, based on the notion that resource and assimilative capacities may restrain materials flows entering and leaving economic systems; resource scarcity over longer periods of time given various production and consumption scenarios; integrated materials-product chain policies such as materials and product recycling, e.g. via deposit-refund systems, waste taxation or subsidies on technology, materials flows analysis between economic and environmental systems, such as nutrient flows in wetland areas, on the boundary of hydrological, ecological and agricultural production processes.

It is clear that a materials balance representation may also be helpful in depicting the spatial aspects of a complex economic-environmental system, including the distribution of pollution. The physical dimensions incorporated in a materials balance model allow for a proper and consistent mathematical representation of both physical and economic linkages, including their geographical distributions. It is clear that - despite the progress made in environmental modelling - uncertainty is still a dominant feature. This will be discussed in the next section.

5. Scenarios in Environmental Modelling

The strong quantitative tradition in economics has enabled researchers to include environmental elements - measured in a cardinal metric - fairly easily in conventional models focusing on the interface of economics and the environments. However, qualitative aspects are harder to deal with in traditional models and, therefore, there is a clear need for methods that are able to take into account information of a 'mixed' type (both qualitative and quantitative measurements). Another problem related to the available information concerns the uncertainty contained in this information. Ideally, the information should be precise, certain, exhaustive and unequivocal. But in reality, it is often necessary to resort to information that does not have those characteristics so that one has to face uncertainty of a stochastic and/or fuzzy nature present in the data (Munda 1993). If it is impossible to exactly identify or establish the future state of the problem faced, a stochastic uncertainty is created. This type of uncertainty is well known; it has been thoroughly studied in probability theory and statistics. Another type of uncertainty derives from the ambiguity of this information, since in the majority of the particularly complex problems addressing the interface of environment and men, much of the information is expressed in linguistic terms so that it is essential to come to grips with the fuzziness that is either intrinsic or informational typical of all natural languages.

Fuzzy uncertainty does not concern the occurrence of an event, but the event itself in the sense that it cannot be described unambiguously. This situation is very common in human systems. Spatial-environmental systems in particular are complex systems characterized by subjectivity, incompleteness and imprecision (e.g., ecological processes are quite uncertain and little is known about their sensitivity to stress factors such as various types of pollution). Zadeh (1965) writes: “as the complexity of a system increases, our ability to make a precise and yet significant statement about its behaviour diminishes until a threshold is reached beyond which precision and significance (or relevance) become almost mutually exclusive characteristics” (incompatibility principle). Therefore, in these situations statements such as “the quality of the environment is good”, or “the unemployment rate is low” are quite common. Fuzzy set theory is a mathematical theory for modelling situations in which traditional modelling languages that are dichotomous in character and unambiguous in their description cannot be used. Human judgements, especially in linguistic form, appear to be plausible and natural representations of cognitive observations. We can explain this phenomenon by cognitive distance. A linguistic representation of an observation may require a less complicated transformation than a numerical representation, and therefore, less distortion may be introduced in the former that in the latter. In traditional mathematics variables are assumed to be precise, but when we are dealing with our daily language, imprecision usually prevails. Intrinsically, daily languages cannot be precisely characterized on either the syntactic or semantic level. Therefore, a word in our daily language can formally be regarded as a fuzzy set.

In a decision problem it is possible to distinguish two main elements, available information and manipulation rules for this information. A fuzzy decision model is essentially characterized by the presence of a set of membership functions. These membership functions can be defined on one or more of the other components of the model; therefore, the degree of fuzziness of the model may very accordingly. Both continuous and discrete fuzzy multicriteria methods exist in the literature. Recently a new discrete multicriteria model whose impact (or evaluation) matrix may include either crisp, stochastic or fuzzy measurements of the performance of an alternative with respect to a criterion has been developed (Munda *et al.* 1994). Applications can be found in forestry management, or landscape planning where linguistic information or value statements are preponderant. It may be concluded that fuzzy approaches are a crucial component of modern decision analysis. There are also other approaches to the treatment of uncertainty, and these will now be discussed.

Evaluation methods and techniques can also be extended with complementary analytical tools, such as scenario analysis. Scenario analysis is one of the methods and techniques of prospective policy research that have become very popular since the late sixties. Especially in the case of unstructured decision problems with uncertain and fuzzy outcomes, scenario analysis may be an appropriate instrument. The main difference between scenario analysis and conventional methods of policy analysis is that scenarios do not only contain a description of one or more future situations, but also a description of a consistent series of events that may connect the present situation with the described future situation(s) (see Rienstra 1998).

Scenarios can be identified by four characteristics (cf. Van Doorn and Van Vught 1981):

- A scenario is either descriptive or normative. The prospective paths and pictures of a descriptive scenario are based on the know-how developed in the past and present. The question whether these paths and pictures are desirable or not, is not raised. The first scenarios designed by Kahn and Wiener (1967), are in agreement with this description. The construction of normative scenarios is based upon the ideas of the scenario-writers or scenario-users. The future paths and pictures are selected by these writers and users. The so-called Ozbekhan-scenarios (see Ozbekhan 1969), as a response to Kahn and Wiener, may be regarded as member of this category (cf. Van Doorn and Van Vught 1981).
- Another distinction that can be made is the difference in direction of the scenario analysis. If future pictures are based upon the present situation and future paths leading to it, then the scenario is said to be projective. On the other hand, if at first the future situations are determined and next the paths leading to this situation, then in fact these paths lead from the future backwards to the present. As they are composed afterwards, the scenario belongs to the class of prospective scenarios. Prospective scenarios are always normative, while projective scenarios are either descriptive or normative.
- A scenario can be characterized as a trend scenario or as an extreme (or contrast) scenario. Trend scenarios are in fact an extrapolation of the present situation. Extreme scenarios on the other hand, try to construct future paths and future situations that are considered to be in principle feasible, though very unlikely. They are both always projective scenarios.
- The last distinction to be made is whether a normative scenario is based upon the preferences of the majority of people, or whether it is based on the preferences of a small minority. The first group may be characterized as “common opinion” scenarios, and the second as “happy few” scenarios.

It is evident that the use of scenarios is of great importance - as a complementary tool - for multidimensional environmental planning problems. In recent global environmental change models and climatological models scenarios have become an intrinsic component to map out uncertain futures. A series of examples can be found in Zwerver et al. (1995).

In view of the uncertainty incorporated in many planning analyses also information systems should be given due attention in environmental planning. This does not only hold true for monitoring systems, but also for decision support systems and expert systems. Clearly, such systems form also an extremely useful contribution to a rationalization of complex planning problems. Examples can be found in land use planning (using geographic information systems - GIS), regional and environmental management and infrastructure planning (see for details Giaoutzi and Nijkamp 1993).

Thus, both scenario experiments and information systems may provide useful decision support methods for environmental management under uncertainty. In many practical situations, researchers have to create visions on the future as a frame of reference for judging unexpected developments. Scenarios are different from forecasts, as realism is not necessarily a main feature. It may thus be concluded that scenarios are essentially communication instruments. They aim to explore uncertain futures by depicting the consequences of imaginary (though possible) futures.

6. Prospect

The pathway of environmental economic analysis and modeling has exhibited various interesting patterns. To some extent, the interest in this new approach was depending on new insights and progress generated in the natural sciences. But also the public awareness and policy initiatives have prompted a wide array of research questions. The analytical apparatus existed already in some embryonic form, as major parts of the questions raised could in principle be tackled by means of standard concepts in conventional economic thinking. However, the focus on externalities, the importance of equity issues, the need for proper valuation methods for intangible goods and the demand for proper policy instruments in non-market (or semi-market) systems created a big research challenge. The avalanche of current publications on almost all aspects of the environment witness a rapid drive to maturity. This accelerated growth path has led to a clear profile and a receptive policy attitude in regards to the fruits of environmental economic thinking.

References

Alcamo, J., R. Shaw, and L. Hordijk (eds.), 1990. *The Rains Model of Acidification: Science and Strategies in Europe.* Kluwer Academic Publishers, Dordrecht.

Anderson, J.M., 1981. *Ecology for Environmental Sciences: Biosphere, Ecosystems and Man.* Edward Arnold, London.

Anderson, K., and R. Blackhurst (eds.), 1992. *The Greening of World Trade Issues*. Harvester Wheatsheaf, New York.

Atkinson, G., R. Dubourg, K. Hamilton, M. Munashinghe, D. Pearce, and C. Young, 1997. *Measuring Sustainable Development: Macroeconomics and the Environment*. Edward Elgar, Cheltenham.

Ayres, R.U., 1978. *Resources, Environment and Economics: Applications of the Materials/ Energy Balance Principle.* Wiley-Interscience, New York.

Ayres, R.U., and L.W. Ayres, 1996. *Industrial Ecology: Towards Closing the Materials Cycle.* Edward Elgar, Cheltenham.

Ayres, R.U., and A.V. Kneese, 1969. Production, consumption and externalities. *American Economic Review*, vol. 59, pp. 282-297.

Ayres, R.U., and A.V. Kneese, 1989. Externalities: Economics and thermodynamics. In: F. Archibugi and P. Nijkamp (eds.), *Economy and Ecology: Towards Sustainable Development*. Kluwer Academic Publishers, Dordrecht, pp. 89-119.

Baumol, W.J., and W.E. Oates, 1988. *The Theory of Environmental Policy*. 2nd ed. Cambridge University Press, Cambridge, UK.

Beers, C. van, and J.C.J.M. van den Bergh, 1996. An overview of methodological approaches in the analysis of trade and environment. *Journal of World Trade*, vol. 30, pp. 143-167.

Beers, C. van, and J.C.J.M. van den Bergh, 1997. An empirical multi-country analysis of the impact of environmental regulations on foreign trade. *Kyklos*, vol. 50, pp. 29-46.

Bergh, J.C.J.M. van den, 1991. *Dynamic Models for Sustainable Development*. Ph.D. Dissertation. Thesis Publishers, Amsterdam.

Bergh, J.C.J.M. van den, 1993. A framework for modelling economy-environment-development relationships based on dynamic carrying capacity and sustainable development feedback. *Environmental and Resource Economics*, vol. 3, pp. 395-412.

Bergh, J.C.J.M. van den, 1996. *Ecological Economics and Sustainable Development: Theory, Methods and Applications.* Edward Elgar, Cheltenham, UK.

Bergh, J.C.J.M., 1997. Economic processes, thermodynamics and values: Interpretations of “capital” and “substitution” in materials balance production functions. Discussion Paper TI 97-153/3. Tinbergen Instituut, Amsterdam/Rotterdam.

Bergh, J.C.J.M. van den, 1998. *Handbook of Environmental and Resource Economics*, Edward Elgar, Cheltenham, UK.

Bergh, J.C.J.M. van den, K.J. Button, P. Nijkamp and G.J. Pepping, 1997. *Meta-analysis in Environmental Economics.* Kluwer Academic Publishers, Dordrecht.

Bergh, J.C.J.M. van den, and P. Nijkamp, 1995. *Growth, Trade and Sustainability in the Spatial Economy*, TRACE Discussion Paper TI 95-170. Tinbergen Institute, Amsterdam-Rotterdam.

Bergh, J.C.J.M. van den, and J. van der Straaten (eds.), 1994. *Toward Sustainable Development: Concepts, Methods and Policy.* Island Press, Washington D.C.

J.C.J.M. van den Bergh, and D.B. van Veen-Groot, 1998. Geaggregeerde indicatoren in de milieu-economie: Een vergelijking van 12 OESO-landen. *Milieu*, (to be publisched).

Bjornstad, D.J., and J.R. Kahn (ed.), 1996. *The Contingent Valuation of Environmental Resources: Methodological Issues and Research Needs*. Edward Elgar, Cheltenham.

Boulding, K.E., 1978. *Ecodynamics: A New Theory of Societal Evolution*. Sage Publications, Beverly Hills.

Braat, L.C., and W.F.J. van Lierop (eds.), 1987. *Economic-Ecological Modelling*. North-Holland, Amsterdam.

Bromley, D.W. (ed.), 1995. *Handbook of Environmental Economics*. Blackwell, Oxford.

Clark, C.W., 1976. *Mathematical Bioeconomics: The Optimal Management of Renewable Resources*. Wiley-Interscience, New York.

Clark, C.W., 1985. *Bioeconomic Modelling and Fisheries Management.* Wiley-Interscience, New York.

Clark, C.W., 1990. *Mathematical Bioeconomics: The Optimal Management of Renewable Resources.* 2nd ed. Wiley, New York.

Clark, C.W., and R.E. Munn (eds.), 1986. *Sustainable Development of the Biosphere*. Cambridge University Press, Cambridge.

Clark, N., F. Perez-Trejo, and P. Allen, 1995. *Evolutionary Dynamics and Sustainable Development: A Systems Approach.* Edward Elgar, Aldershot and Vermont.

Clayton, A.M.H., and N.J. Radcliffe, 1996. *Sustainability: A Systems Approach*. Earthscan, London.

Coase, R., 1960. The Problem of Social Costs. *Journal of Law and Economics*, vol. 3, pp. 1-44.

Costanza, R., 1987. Social Traps and Environmental Policy. *BioScience*, vol. 37, pp. 407-412.

Costanza, R. (ed.), 1991. *Ecological Economics: The science and Management of Sustainability*. Columbia University Press, New York.

Costanza, R., J. Cumberland, H. Daly, R. Goodland, and R. Norgaard, 1997b. *An Introduction to Ecological Economics.* Island Press, Washington D.C.

Costanza, R., H.E. Daly, and J.M. Bartholomew, 1991. Goals, Agenda and Policy Recommendations for Ecological Economics. In: R. Costanza (ed.), *Ecological Economics: The Science and Management of Sustainability.* Columbia University Press, New York, pp.1-20.

Costanza, R., C. Perrings, and C.J. Cleveland (eds.), 1997a. *The Development of Ecological Economics*, Edward Elgar, Cheltenham, UK.

Costanza, R., L. Wainger, C. Folke, and K.-G. M„hler, 1993. Modeling complex ecological economic systems. *Bioscience*, vol. 43, pp. 545-555.

Cummings, R.G., D. Brookshire, and W. Schulze (ed.), 1990. *Valuing Environmental Goods: An Assessment of the Contingent Valuation Method.* Rowman & Littlefield.

Daly, H.E., 1989. Steady-state and growth concepts for the next century. In: F. Archibuchi and P. Nijkamp (eds.), *Economy and Ecology: Towards Sustainable Development*. Kluwer, Dordrecht.

Daly, H.E., and W. Cobb, 1989. *For the Common Good: Redirecting the Economy Toward Community, the Environment and a Sustainable Future.* Beacon Press, Boston.

Daly, H.E., and K.N. Townsend (eds.), 1993. *Valuing the Earth: Economic, Ecology and Ethics*. MIT Press, Boston.

Daly, H.E., and A.F. Umaña (eds.), 1981. *Energy, Economics and the Environment.* AAAS Selected Symposia Series, Westview Press, Boulder, Col.

Dasgupta, P.S., and G.M. Heal, 1979. *Economic Theory and Exhaustible Resources*. Cambridge

University Press, Cambridge.

Doorn, J. van, and F. van Vught, 1981. *Nederland op Zoek naar zijn Toekomst*. Spectrum, Utrecht.

Ekins, P., 1997. The Kuznets curve for the environment and economic growth: examining the evidence. *Environment and Planning A*, vol. 29, pp. 805-830.

Faber, M., H. Niemes, and G. Stephan, 1987. *Entropy, Environment and Resources: An Essay in Physico-Economics*. Springer-Verlag, Heidelberg.

Faber, M., and J.L.R. Proops, 1990. *Evolution, Time, Production and the Environment*. Springer-Verlag, Heidelberg.

Folke, C., and T. K„berger (eds.), 1991. Socio-economic Dependence on the Life-Supporting Environment. *Linking the Natural Environment and the Economy: Essays From the Eco-Eco Group*. Kluwer, Dordrecht, pp. 77-94.

Folmer, H., H. Landis Gabel, and J.B. Opschoor (eds.), 1995. *Principles of Environmental and Resource Economics: a guide for students and decision makers.* Edward Elgar, Aldershot UK, Brookfield, US.

Freeman III, A.M., 1993. *The Measurement of Environmental and Resource Values: Theory and Methods.* Resources for the Future, Baltimore.

Georgescu-Roegen, N., 1971. *The Entropy Law and the Economic Process*. Harvard University Press, Cambridge, MA.

Georgescu-Roegen, N., 1976. *Energy and Economic Myths.* Pergamon, New York.

Giaoutzi, M., and P. Nijkamp, 1993. *Decision Support Models for Regional Sustainable Development.* Avebury, Aldershot, UK.

Goodland, R., and G. Ledec, 1987. Neoclastic Economics and Principles of Sustainable Development. *Ecological Modelling*, vol. 38, pp. 19-46.

Gowdy, J., 1994. *Coevolutionary Economics: The Economy, Society and the Environment.* Kluwer Academic Publishers, Dordrecht.

Gross, L.S., and E.C.H. Veendorp, 1990. Growth with exhaustive resources and a materials-balance production function. *Natural Resource Modeling*, vol. 4, pp. 77-94.

Hafkamp, W., 1984. *Economic-Environmental Modeling in a National-Regional System*. North-Holland, Amsterdam.

Hanley, N., J.F. Shogren, and B. White, 1997. *Environmental Economics - In Theory and Practice*. MacMillan, London.

Hardin, G., 1968. Tragedy of the Commons. *Science*, vol. 162, pp. 1243-1248.

Hartwick, J.M., and N.D. Olewiler, 1998. *The Economics of Natural Resource Use.* 2nd ed. Addison-Wesley, NY.

Jaffe, A.B., S.R. Petersen, P.R. Portney, and R.N. Stawine, 1995. Environmental regulation and the competitiveness of US manufacturing: What does the evidence tell us. *Journal of Economic Literature*, vol. 33, pp. 132-163.

James, D.E., 1985. Environmental economic, industrial process models, and regional-residuals management models. In: A.V. Kneese and J.L. Sweeney (eds.), *Handbook of Natural Resource and Energy Economics*, vol. 1. North-Holland, Amsterdam.

Jansson, AM., M. Hammer, C. Folke, and R. Costanza (eds.), 1994. *Investing in Natural Capital: The Ecological Economics Approach Sustainability.* Island Press, Washington D.C.

Johansson, P.-O., 1987. *The Economic Theory and Measurement of Environmental Benefits*. Cambridge University Press, Cambridge.

Johansson, P.O., and K.G. Löfgren, 1985. *The Economics of Forestry and Natural Resources.* Basil Blackwell, Oxford.

Kahn H., and A.J. Wiener, 1967. *The year 2000*. MacMillan, New York.

Kandelaars P., and J.C.J.M. van den Bergh, 1996. Analysis of materials-product chains: Theory and application. *Environmental and Resource Economics*, vol. 8, pp. 97-118.

Kneese, A.V., R.U. Ayres, and R.C. D'Arge, 1970. *Economics and the Environment: A Materials Balance Approach.* Johns Hopkins Press, Baltimore.

Kneese, A.V., and J.L. Sweeney (eds.), 1985/1993. *Handbook of Natural Resource and Energy Economics*, Vol. 1-3. North-Holland, Amsterdam.

Kopp, R.J. W.W. Pommerehne, and N. Schwarz (ed.), 1997. *Determining the Value of Non-Marketed Goods : Economics, Psychological, and Policy Relevant Aspects of Contingent Valuation Methods.* Kluwer Academic Publishers, Dordrecht.

Low, P., 1992. *International Trade and Environment.* World Bank Discussion Papers no. 159. World Bank, Washington D.C.

Mabey, N., S. Hall, C. Smith, and S. Gupta (eds.), 1997. *Argument in the Greenhouse : The International Economics of Controlling Global Warming* (Global Environment Change Series). Routledge, London.

Martinez-Alier, J., and K. Schluepmann, 1987. *Ecological economics*. Basil Blackwell, Oxford.

Martinez-Alier, J., and K. Schluepmann, 1991. *Ecological economics: Environment, Energy and Society*. Basil Blackwell, Oxford.

Meadows, D.H., J. Richardson, and G. Bruckmann, 1982. *Groping in the Dark: The First Decade of Global Modeling*. Wiley, New York.

Mitchell, R., and R. Carson, 1989. *Using Surveys to Value Public Goods: The Contingent Valuation Method.* Resources for the Future, Washington D.C.

Munda, G., 1993. Multiple criteria decision aid: Some epistemological considerations. *Journal Multicriteria Analysis in Physical Planning.* Elsevier Science Publ., Amsterdam.

Munda, G., P. Nijkamp, and P. Rietveld, 1994. Qualitative multicriteria evaluation for environmental management. *Ecological Economics,* vol. 10, pp. 97-112.

Munro, A., 1997. Economics and biological evolution. *Environmental and Resource Economics*, vol. 9: 429-449.

Neher, P.A., 1990. *Natural Resource Economics: Conservation and Exploitation*. Cambridge University Press, New York.

Nijkamp, P., and J.C.J.M. van den Bergh, 1997. New advances in economic modelling and evluation of enviornmetnion issues. *Euroepan Journal of Operational Research*, vol. 99, pp. 180-196

Norgaard, R.B., 1994. *Development Betrayed: The End of Progress and a Coevolutionary Revisioning of the Future.* Routledge, London and New York.

O'Riordan, T. (ed.), 1997. *Ecotaxation*. Earthscan, London.

Odum, H.T., 1987. Models for national, international, and global systems policy. In: L.C. Braat and W.F.J. van Lierop (eds.), *Economic-Ecological Modelling*. North-Holland, Amsterdam.

Opschoor, J.B., and R.K. Turner, 1994. *Economic Incentives and Environmental Policies.* Kluwer Academic Publishers, Dordrecht.

Opschoor, J.B., A.F. de Savornin Lohman and J.B. Vos, 1994. *Managing the Environment: The Role of Economic Instruments.* OECD, Paris.

Opschoor, J.B., and J.B. Vos, 1989. *Economic Instruments for Environmental Protection*. OECD, Paris.

Ozbekhan, H., 1969. Towards a general theory of planning. In: E. Jantsch (ed.), *Perspectives of Planning*. OECD, Paris, pp. 31-50.

Pearce, D.W., and J.J. Warford, 1993. *World Without End: Economics, Environment and Sustainable Development*. Oxford University Press, Oxford.

Pearce, D.W., and R.K. Turner, 1990. *Economics of Natural Resources and the Environment*. Harvester Wheatsheaf, New York.

Peet, J., 1992. *Energy and the Ecological Economics of Sustainability.* Island Press, Washington D.C.

Perman, Y. Ma, and J. McGilvray, 1996. *Natural Resource & Environmental Economics.* Addison-Wesley, Longman Ltd., London.

Perrings, C., 1987. *Economy and environment.* Cambridge University Press, New York.

Pezzey, J., 1989. *Economic Analysis of Sustainable Growth and Sustainable Development*. Environmental Department Working paper no. 15, Environmental Department, The World Bank.

Pezzey, J., 1993. Sustainability: An interdisciplinary guide. *Environmental Values*, vol. 1, pp. 321-362.

Rienstra, S., 1998. *Options and Barriers for Sustainable Transport Policies.* Ph.D. Thesis. Faculty of Economics, Free University, Amsterdam.

Ruth, M., 1993. *Integrating Economics, Ecology and Thermodynamics*. Kluwer Academic Publishers, Dordrecht, Netherlands.

Siebert, H., 1985. Spatial aspects of environmental economics. In: A.V. Kneese and J.L. Sweeney (eds.), *Handbook of Natural Resource and Energy Economics*, vol. 1. North-Holland, Amsterdam.

Siebert, H., 1987. *Economics of the Environment: Theory and Policy*, 2rd ed. Springer-Verlag, Berlin.

Siebert, H., 1995. *Economics of the Environment: Theory and Policy*, 4rd ed., Springer-Verlag, Berlin.

Smith, J.B., and S. Weber, 1989. Contemporaneous externalities: Rational expectations, and equilibrium production functions in natural resource models. *Journal of Environmental Economics and Management*, no. 17, pp. 155-170.

Sterner, T. (ed.), 1994. *Economic Policies for Sustainable Development*. Kluwer Academic Publishers, Dordrecht.

Tinbergen, J., 1956. *Economic Policy: Principles and Design*. North-Holland, Amsterdam.

Toman, M.A., J. Pezzey, and J. Krautkraemer, 1995. Neoclassical economic growth theory and "sustainability". In: D.W. Bromley (ed.), *Handbook of Environmental Economics*. Blackwell, Oxford.

Turner, R.K., J.C.J.M. van den Bergh, A. Barendregt, and E. Maltby, 1997. Ecological-economic analysis of wetlands: Science and social science integration. TI Discussion Paper 98-050/3. Tinbergen Institute, Amsterdam/Rotterdam.

Verhoef, E., 1996. *The Economics of Regulating Road Transport*. Edward Elgar, Cheltenham, UK.

Verhoef, E.T., and J.C.J.M. van den Bergh, 1995a. A spatial price equilibrium model for environmental policy analysis of mobile and immobile sources of pollution. In: J.C.J.M. van den Bergh, P. Nijkamp and P. Rietveld (eds.) *Recent Advances in Spatial Equilibrium Modelling: Methodology and Applications*. Springer-Verlag, Berlin.

Verhoef, E.T., and J.C.J.M. van den Bergh, 1995b. *Transport, Spatial-Economic Equilibrium and Global Sustainability: Markets, Technology and Policy*. TRACE Discussion Paper TI 95-80. Tinbergen Institute, Amsterdam-Rotterdam.

Wackernagel, M., and W. Rees, 1996. *Our Ecological Footprint: Reducing Human Impact on the Earth*.

Gabriola Island, BC and Philadelphia, PA, New Society Publishers.

Walters, C., 1986. Adaptive Management of Renewable Resources. MacMillan, New York.

WCED, 1987. *Our Common Future*. Oxford University Press, Oxford.

Weizsäcker, E. von, A.B. Lovins, and L.H. Lovins (1997). *Factor Four: Doubling Wealth - Halving Resource Use, A Report to the Club of Rome.* Earthscan, London.

Wilkinson, R., 1973. *Poverty and Progress: An Ecological Model of Economic Development*. Methuen and Co., London.

Zadeh, L.A., 1965. Fuzzy Sets. *Information Control*, vol. 8, pp. 338-353.

Zwerver, S., R.S.A.R. van Rompaey, M.T.J. Kok, and M.M. Berk (eds), 1995. *Climate Change Research*. Elsevier, Amsterdam.

Xepapadeas, A., 1998. Non-point source pollution control. In: J.C.J.M. van den Bergh (ed.), *Handbook of Environmental and Resource Economics*. Edward Elgar, Cheltenham.