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Evolutionary Economic Theories of Sustainable Development

PETER MULDER AND JEROEN C.J.M. VAN DEN BERGH

ABSTRACT Sustainable development has become the dominant concept in the study of interactions between the economy and the biophysical environment, as well as a generally accepted goal of environmental policy. So far, economists have predominantly applied standard or neo-classical theory to environmental economic problems. In this article it will be argued that to fully understand a transformation of the economic system towards sustainability, standard environmental economics needs to be complemented by an evolutionary approach, that focuses the attention on irreversible, path-dependent change and long-run mutual selection of environmental and economic processes and systems. The article provides an overview of the main existing evolutionary contributions to environmental economics. Furthermore, a number of research directions of an evolutionary approach in environmental economics are discussed. It is suggested that such an approach should go beyond evolutionary theories of technical change, which dominate evolutionary economics so far, by including co-evolution of economy and environment, sustainable consumption, endogenous preference change, and climate change modeling.

Introduction

The last decades have shown an increasing and world-wide interest in the goal of sustainable development. This can be interpreted as economic development that is consistent with long-term stable environmental quality and resource availability. The attention devoted by economists to the interaction between the economy and the biophysical environment can be traced back to the 18th century. In focusing on the availability of agricultural products and agricultural land, Thomas Malthus and David Ricardo formulated for the first time a concept of 'limits to growth'. In line with this, John Stuart Mill introduced the concept of a 'stationary state economy', referring to an economic development without (physical) growth. In post-classical economics the biophysical world moved to the background, although it did not disappear completely. The natural environment was analyzed from the perspective of

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optimal depletion of natural resource stocks (Hotelling 1931) and optimal policy in the context of externalities caused by urban pollution (Pigou 1920).

A growing awareness of the extent and potential implications of environmental pollution and degradation during the sixties stimulated the development of new areas of research, including environmental science and environmental economics. The classic article 'The Economics of the Coming Spaceship Earth' by Kenneth Boulding (1966) was one of the first manifestations of such an awareness in economics. The report 'Limits to Growth' to the Club of Rome (Meadows et al. 1972), in which the echo of Malthus could be heard, acted as a catalyst for environmental awareness in society as a whole and the scientific community in particular.

Since it was launched by the World Commission on Environment and Development (1987) *sustainable development* has over a quite short period of time become the dominant concept in the study of interactions between the economy and the biophysical environment, as well as a generally accepted goal of environmental policy. Although there has been, and still is, debate on the precise definition of the concept of sustainable development (see van den Bergh and Hofkes 1998) a broad consensus exists that it means that economic activities should be consistent with: sustainable use of renewable natural resources, protection of ecosystem features and functions, preservation of biological diversity, a level of harmful emissions remaining below critical (assimilative) thresholds, and avoidance of irreversible damage to the environment and nature (see Daly 1990). Non-renewable resources pose some difficulties in the context of sustainable development. One can choose to reduce their use as much as possible, oriented towards a long-run goal of being completely independent of them. This can be based on investments in renewable alternatives (depending on the potential uses, e.g., supplying energy or materials) and technological progress in general (materials and energy efficiency increases in production and consumption).

It has been argued that a transformation of the present economic system towards a sustainable economic system requires new policies, institutions, and mechanisms (Opschoor 1992). It can be argued that major shifts in economic structure involve uncertain and irreversible changes, selection of existing alternatives, learning, errors in decision-making, and a persistent economic disequilibrium. So far, economists have predominantly applied standard or neo-classical theory to environmental economic problems. This includes externality or welfare theory, with an emphasis on optimal choice of policy instruments (Baumol and Oates 1988), and (exogenous or endogenous) growth theory, with an emphasis on deterministic dynamic optimization models with reversible processes and continuous equilibrium (e.g. Hartwick 1977; Pezzey 1989; Gradus and Smulders 1993; Toman et al. 1995).

In this article it will be argued that to understand fully a transformation of the economic system towards sustainability, standard environmental economics needs to be complemented by an evolutionary approach, that focuses the attention on irreversible, path-dependent change, and long-run mutual selection of environmental and economic processes and systems. Understanding of the latter is essential to study sustainable (and unsustainable) development. It requires that the time horizon of the analyses is extended beyond decades and even centuries. It will be suggested that such an approach should go beyond evolutionary theories of technical change, which dominate evolutionary economics so far. The attention should be broadened to include, among others, management of environmental systems that are subject to (natural) selection and evolution, co-evolution of economic and environmental systems, changing economic structure and self-organization, and endogenous change of preferences. Only then is it possible to address real dynamic features of long-run sustainable development.

Neo-classical Environmental Economics and Sustainable Development

In mainstream environmental economic analysis the emphasis is on relative scarcity, allocation of scarce resources, and optimal welfare. The neo-classical interpretation of environmental degradation as an allocation problem has dominated environmental economics for over two decades now. It is reflected in an emphasis on optimal welfare and externalities, optimal (intertemporal) allocation of natural resources, and optimal growth as a mix of intertemporal resource allocation and investment in capital. This means that environmental problems are mainly studied in the context of externalities[1] and market equilibrium. Much attention is devoted to the question how a social optimum can be realized in a market economy with externalities. Neo-classical (environmental) economics, however, seems to be not always the most well equipped approach to address the study of development paths towards a sustainable economy. The main reason is that it focuses the attention on comparing different equilibria, usually in a comparative static framework. Neo-classical equilibrium analysis is generally weak in providing significant information about transition paths, i.e. feasible changes from one equilibrium to another. But such transition paths are essential to the study of sustainable development, given that the present economy is far from a sustainable state. It should also be noted that a focus on optimal externalities in environmental economics is not necessarily in agreement with sustainable development. This depends especially on whether externalities include also impacts of present decisions on future generations.

Much effort has been put in the study of instruments for environmental policy. Also here the comparative static approach has dominated. The main distinction is between command-and-control measures on the one hand and market-based instruments on the other hand (Baumol and Oates 1988; Opschoor et al. 1994; Sterner 1994). The first refers to a direct intervention by the government into the economic process, for example, through the implementation of (uniform) standards on technology, emissions, or inputs, or via quota on outputs. Market-based instruments include policy approaches in which the costs and benefits of individual agents are directly influenced, such as via charges, taxes, subsidies, or tradable permits.

The use of market-based instruments like charges and taxes requires information about the monetary value of externalities in order to provide a rough measure of environmental charge and tax levels. Ideally, the optimal levels are calculated from the hypothetical optimal equilibrium. This requires (partial or general) equilibrium analysis. Monetary valuation is one of the cornerstones of environmental economics. It includes two main approaches (Freeman 1993; Hanley and Spash 1993). The first is based on the notion of revealed preferences. Here the value of an environmental good or service (e.g. air quality) is derived from the impact it has on the prices of goods that are traded on markets (e.g. houses). The other approach is based on stated preferences, and uses questionnaires to elicit individual willingness to pay (or accept compensation) for certain environmental changes. Contingent valuation is a well-known example of the latter approach. Although it has both received extensive criticism it has given rise to many applications of economic valuation.

Since its early development, environmental economics has paid a great deal of attention to the environment-growth debate (van den Bergh and de Mooij 1999). Although this debate is still unresolved, the concept of sustainable development seems to have eased the frictions between growth optimists and pessimists. In neo-classical growth theory sustainable development has quickly been equated to ‘sustainable growth’. A central feature of the (long-run) growth models that are used to identify sustainable growth paths is the possibility of substitution between natural and human capital. Already in the seventies growth theory was applied to resource and pollution issues (Kamien and Schwarz 1982). In addition to ‘old’ growth theory, a recent wave of ‘new’ or endogenous growth theory has occurred (after Lucas 1988; Romer 1986, 1990) in which the innovation and diffusion of technological change is explicitly modeled as a driving force for economic growth. With respect to sustainable development, endogenous growth theory focuses on the contribution of technological innovation to the conditions under which economic growth can be sustained by resources and the environment (see e.g. Aghion and Howitt 1998:Ch5; Smulders 1995). A dominant insight about sustainable growth goes back to Hartwick (1977) who showed that under certain conditions investment of the net proceeds of resource extraction in economic capital can result in a constant level of consumption over time (see also Solow 1986). Such a scenario can be realized by taxing the profits of resource extraction and using the tax revenues for investment purposes. This depends on a strong belief in substitutability of natural by economic capital, which is often referred to as "weak sustainability". This is opposed to "strong sustainability," under which natural capital cannot be substituted but has to be maintained independently.

Neo-classical growth theory has recently been 'applied' in the economic analysis of climate change. This is part of a broader field that is known as 'integrated assessment,' where integration of different sciences and models is a central issue of research (Bruce et al. 1996; Parry and Carter 1998; Rotmans and Dowlatabadi 1998). The emphasis in integrated environmental assessment studies lies on scenario-building and modeling exercises. The purist's economic view within integrated assessment is based on neo-classical economics, in particular growth theory (Nordhaus 1994). The basic idea is to include both costs and benefits from climate change into an intertemporal social utility function. Much attention is devoted to analyzing optimal policy paths to reduce the emission of greenhouse gases (Nordhaus 1991; Tol 1998; Wigley et al. 1996). Among the main features of these models are constant returns to scale, the relatively minor attention devoted to irreversibility in climate change and exogenously determined development of population size and technology.

The Relevance of an Evolutionary Approach for Environmental Economics

The reason for adopting an evolutionary approach in environmental economics stems basically from some key elements of the concept "sustainable development." It is generally agreed upon that sustainable development is a process of change that includes not only quantitative but also qualitative aspects of change, a long-term horizon, and a mutual dependence of environmental quality and resource availability on the one hand and economic development on the other hand. Furthermore, it is evident that technological development and institutional aspects play a major role in the process of transforming the economic system towards sustainability (see World Commission on Economics and Development 1987). These are exactly the elements that can be considered as the building blocks of evolutionary economics (Dosi et al. 1988; Hodgson 1993; Nelson and Winter 1982; Nelson 1995).

The conceptual affinity between evolutionary and environmental economics (see also Erdmann 1993) comes forward in the most elementary definition of evolution as 'change' (Faber and Proops 1990), resulting in the elementary definition of evolutionary economics as a theory of economic change (Nelson and Winter 1982). If ecological sustainability in the long run is taken as a criterion for equilibrium (steady state) in the relationship between the environment and the economic system (Ayres 1994), environmental economics ideally should be characterized by studying the disequilibrium process of transition to such a steady state. At a more fundamental level it can be argued that, compared with neo-classical economics, the evolutionary paradigm pays more attention to long run economic developments (Faber and Proops 1990). Moreover, evolutionary economists pretend to include explicitly qualitative aspects of change in the analysis (Hodgson 1993: 23), whereas in the neo-classical tradition the emphasis is on quantitative (marginal) changes. Concerning the mutual dependence of the economic system and the environment, it can be argued that whereas in mainstream economics the economic system traditionally is depicted as a closed system ('circular flow'), in the evolutionary tradition the economic system is considered as an open system, relying upon trade of matter and energy with the rest of the (economic and natural) world (Georgescu-Roegen 1971), and changing via a process of co-evolution with the environment (Norgaard 1984). Intuitively, this provides a better starting point for studying the mutual dependence between economic and ecological processes oriented towards long-run sustainable development than the (static or dynamic) neo-classical equilibrium framework. In addition, institutional aspects of economic processes and economic aspects of technological change can be studied in the context of sustainable development using insights from the evolutionary economic tradition (see Nelson 1995).

To be more specific, integrating sustainable development into environmental economics requires that the latter has to address 'irreversibility', 'uncertainty', and (non-linear) 'dynamic feedback processes', because these are key characteristics of the interaction between economic and ecological processes. It will be argued below that this asks for integrating insights from evolutionary and self-organization theory into environmental economics.

Obviously, irreversibility is at the heart of environmental economics: economic activities have caused irreversible environmental damage like the world-wide depletion of natural resources and the loss of biodiversity. It can be argued that a mechanical ('Newtonian') methodology, designed to analyze reversible mechanisms, runs up to its limits when applied to these issues (Georgescu-Roegen 1971, Faber and Proops 1990). An evolutionary framework in which history matters is needed to deal with certain aspects of sustainable development.

There exists, in general, no such thing as perfect foresight about the future relationship between the economy and the environment. Uncertainty prevails especially with regard to the existence and size of future generations, changing preferences, technological change, and environmental processes. Uncertain or unforeseeable changes include: the impact of economic activities on (global) environmental change; the ecological impacts of environmental changes (climate change, biodiversity loss); the impact of (global) environmental change on economic activities, societies, and human health; and ways and means of people and societies to mitigate and adapt to (global) environmental change. These various uncertainties invite a broader approach than the neo-classical one to study sustainable development.

By defining environmental damage in terms of externalities, traditional welfare theory needs a marginal value of environmental 'assets'. However, uncertainty prevents us from adequately measuring the marginal value of many environmental components. For instance, the value of a species is a tricky concept, as the effect of removing a species on the ecosystem and the economic system depends, among others, on the (cyclical) state of both systems and unique conditions at the particular time of extinction (Gowdy 1997, van den Bergh and Gowdy 1998). Often there is no complete or right information available about these states or conditions. For example, a unique condition may refer to the existence of a critical or threshold level of environmental quality ('carrying capacity'). Below such a level the ecosystem 'runs down'. Marginal changes, say harvesting another species, can therefore have non-marginal effects when exceeding the critical level (Bishop 1978). This makes theoretically correct marginal valuation impossible. In general it can be argued that the neo-classical externality approach tends to underestimate the marginal value of environmental stock by not taking into account unknown threshold effects and losses (costs) due to decreasing evolutionary potential (biological diversity) and (unforeseen) changes of complex ecosystem dynamics. Some authors have for this reason stated that proper pricing of the environment is an illusion and a poor way to move society towards sustainability (Ayres 1991; Gustafsson 1998; McDaniel and Gowdy 1998).

The vast uncertainties and the consequent controversies surrounding the impact of the enhanced greenhouse effect (see e.g. Nordhaus 1994; Wigley et al. 1996) illustrate the importance of coming to grips with uncertainty. Important questions that can be raised here from an evolutionary perspective refer to the very possibility of defining optimal policy paths and whether uncertainty can be reduced to stochastic variability (as in Kolstad 1994, 1996)[2]. An evolutionary framework which attempts to deal with uncertainty, not only in terms of stochastic variability, but also in terms of non-linearity, self-organization, emerging novelty, and bounded rationality, can thus provide a valuable contribution to the economic analysis of sustainable development.

The complex character of environmental change (Holling 1987) calls attention to the importance of understanding the dynamic feedback processes between the economic system and its biophysical environment. Integrating sustainable development in economics requires that economic and ecosystems are studied neither in isolation nor solely in terms of equilibrium. Although economic development has long been studied as independent of the biophysical environment—resulting in depicting the economic system as a 'circular flow'—the mutual dependence between economic and ecological processes is broadly recognized in neo-classical economics (van den Bergh and Nijkamp 1994; Hofkes 1996). Nevertheless, the dependence is mainly interpreted and modeled in a linear, deterministic, and reversible setting. Recently it has been noted that the interaction between environmental and economic systems can also give rise to historical, irreversible patterns of change (Gowdy 1994). Furthermore, the interaction between economic and ecological processes often can be better characterized by non-linear processes (Allen 1998; Bennett and Chorley 1978).

Within the evolutionary tradition the concept of co-evolution can serve as a framework to study the interaction between economic and ecological processes, because of its emphasis on the dynamic feature of the mutual dependence between economic and ecological processes. Co-evolution has been introduced into biology as an evolutionary process based on reciprocal responses between two closely interacting species (Ehrlich and Raven 1964; Baker and Hurd 1968). As a result, co-evolutionary theories paved the way for a closer connection between two separate research fields of biology, namely evolutionary biology and ecology (the study of the relationship between living organisms and their biotic and abiotic environment). Evolutionary biology in turn became one source of inspiration for evolutionary economics. Within economics, co-evolution has been introduced in the sustainability debate by Norgaard (1984, 1985, 1989, 1994).

It should be noted that co-evolution has mainly received attention so far by economists working within the emerging field of Ecological Economics. Ecological Economics can be described as the research field that aims to address the relationship between ecosystems and economic systems, based on a mix of economic and ecological theories and models (Costanza 1989; Costanza et al. 1997a,b; van den Bergh 1996). "In ecological economics, development is viewed as an evolutionary process with continuous feedbacks between a changing economy and the environment" (Klaassen and Opschoor 1991). Furthermore, Ecological Economics can be characterized by the attention paid to (non-linear) ecological-economic systems and its emphasis on the irreversible nature of environmental transformation and degradation, in particular through the existence of threshold effects and the relevance of the entropy-law to environment-economy interaction. Moreover, Ecological Economics seems open to bounded rationality models of individual behavior (van den Bergh et al. 2000). All these features suggest that a stronger link between evolutionary economics and environmental economics can successfully be established within the context of Ecological Economics, although, of course, evolutionary economics bears relevance for the whole field of environmental economics.

By way of summary a schematic illustration of the main interactions between biology, economics, physics, and their respectively sub-fields is given in Figure 1. It should be noted that the interactions involve not just use of analogies but also transferring of methodologies.

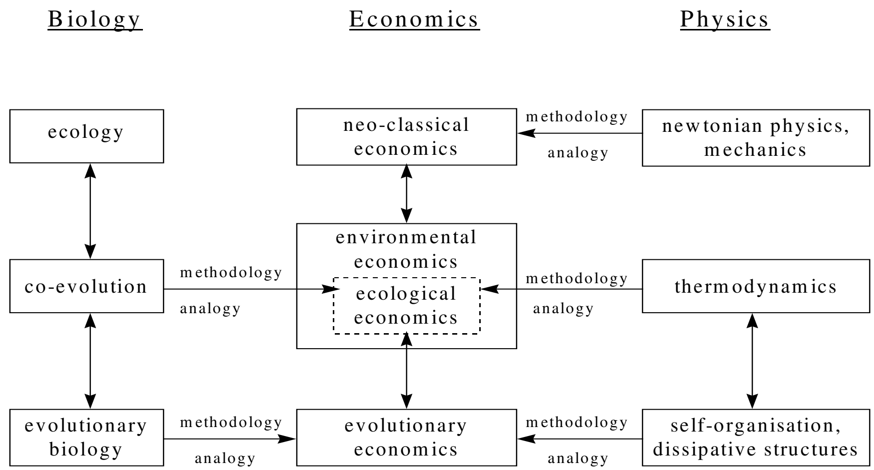

FIGURE 1. LINKING EVOLUTIONARY ECONOMICS TO ENVIRONMENTAL ECONOMICS: THE MAIN INTERACTIONS BETWEEN THE RELEVANT (SUB-) DISCIPLINES

From this figure it is clear that the use of analogies is of cognitive value: applying a concept in a different scientific discipline than it originally comes from can be inspiring, it can generate new insights and it can help to structure scientific results or ideas in a fruitful way (see Hodgson 1993). Of course, a justified use of analogy-driven concepts is not a matter of just copying but requires that they meet the particular character of the discipline to which they are applied. This can be referred to as qualified recapturing.

Of course, the idea of linking evolutionary concepts to environmental problems is not entirely new. In the next section an overview is given of existing evolutionary approaches within environmental economics, and their significance for the study of sustainable development.

Evolutionary Approaches in Environmental Economics: A Survey

Introduction. The basic idea of an evolutionary approach in environmental economics is to study economy-environment interactions based on the view that both economic development and environmental change should be seen as evolutionary processes (Ayres 1991, 1994; Clark et al. 1995; Faber and Proops 1990; Gowdy 1994; Norgaard 1994). As has been mentioned, this implies that irreversibility, uncertainty, learning, selection, bounded rationality, errors in decision-making, and complex system dynamics will be taken into account.

Below some light is cast on the way this has been done so far by providing an overview of the main existing evolutionary contributions to environmental economics. These contributions will be discussed along the lines of a classification reflecting the main fields to which evolutionary approaches have been applied so far. The distinguished fields overlap somewhat. For this reason some contributions will be mentioned under different fields.

Integrating the physical environment. The economic system is not isolated from the physical environment, but is subject to a physical flow or 'throughput' (Daly 1992) of materials and energy: from extraction (natural resources) to restitution (waste). It is here that thermodynamics obviously has some relevance to environmental economics: the first law of thermodynamics, approximated by the mass balance concept, can be seen as the theoretical foundation for studying the physical components involved with economic processes. Originally, mass balance was studied in the context of a general equilibrium framework (Ayres and Kneese 1969). Recently the concepts 'Industrial Metabolism' (Ayres and Simonis 1994) and 'Industrial Ecology' (Graedel and Allenby 1995; Socolow et al. 1994) have gained attention as useful frameworks to operationalize mass balance in applied studies of economic processes.

Although the latter concepts, derived in analogy with ecology, may be regarded as weakly related to an evolutionary approach (Allen 1994), thermodynamics did invoke a fundamental evolutionary view on economic processes through the second law of thermodynamics. The second or entropy law, which roughly states that physical processes are characterized by an irreversible loss of useful or concentrated energy, has been introduced in economic science by Georgescu-Roegen (1966, 1971) and is put to use by economists in two ways. In the first, primarily identified with the work of Georgescu-Roegen and Daly, the entropy law exemplifies environmental degradation. From this point of view environmental degradation is basically an increase of the stock of high entropy energy and materials resulting from economically motivated transformations of low entropy materials energy into high entropy materials and energy. In the second way, the entropy law is taken to understand the behavior of thermodynamic structures or systems, which are open to their environment in terms of matter and energy. One can argue that the economic system is such an open ('dissipative') thermodynamic system. Fundamental insights that have been raised from studying these open structures or systems is that they are to be found in a situation far from thermodynamic equilibrium and that they are capable of generating and maintaining a certain degree of internal order. Therefore, this can be referred to as the theory of self-organization (Nicolis and Prigogine 1977; Prigogine and Stengers 1984).

The relevance of the second law for environmental economics has been discussed in, among others, Ayres (1991, 1994, 1998b); Binswanger (1993); Faber and Proops (1990); Ruth (1995, 1996); and O'Connor (1991). From this body of literature it can be concluded that the relevance of the entropy law for economics in general and environmental economics in particular is methodologically intertwined with evolutionary and self-organization theory because the entropy law is a fundamental evolutionary law (Georgescu-Roegen 1966: 67).

Furthermore, the entropy law has, mainly through the work of Georgescu-Roegen and Daly, been applied to the environment-growth debate. The debate focused on the question whether or not the entropy law defines absolute limits to economic growth (for an overview of the central issues in the debate see *Ecological Economics* 1997).

Another application of thermodynamics in the field of environmental economics is given by O'Connor (1993). He provides a production function model based on the irreversibility implication of the entropy law. Based on an input-output approach, rather similar to that of Perrings (1987), he models economy-environment interdependencies focusing on the link between the material basis of production processes and technological change.

The most concrete contribution to environmental economics based on the above mentioned issues derived from evolutionary and self-organization theory is presented in Ayres and Martinas (1995) and Ayres (1998b). They have developed an exergy-indicator to measure and compare resource inputs and outputs, including wastes and losses. Exergy is, in fact, the 'useful' part of energy or, to be more precise, the amount of available low-entropy energy. In other words it is what most people mean when they use the word energy somewhat carelessly . An exergy indicator calculates the amount of 'useful' energy involved with economic processes and may thus be seen as a physical indicator for the degree of sustainability of economic activities and even as a factor of production like labor and capital.

Co-evolution of economy and environment. Economic evolution has been mostly considered as independent of the natural environment, as an autonomous process. However, recently it has been noted that the interaction between evolving environmental and economic systems can also give rise to historical, irreversible patterns of change. This has been coined "co-evolution" (Norgaard 1994; Gowdy 1994). Co-evolution may take the form of economies responding to resource scarcity, environmental degradation, and environmental regulation. It emphasizes that technological innovations within the economic system can be stimulated by environmental and resource characteristics, in time and space. Even the industrial revolution has been explained from a co-evolutionary perspective (Wilkinson 1973). The concept of sustainable development can be immediately linked to this concept of co-evolution, as it describes long-run development of economies that are restricted in terms of land use, resource use, pollution, and other types of environmental disturbance.

Co-evolution has become widely accepted in biology, and can be considered the result of merging (community and population) ecology and evolution. Interestingly from the perspective of environmental economics, resource scarcity limits and feedbacks are central elements of both population ecology and evolutionary biology. Ehrlich and Raven (1964) used the term first, referring to the evolution of butterflies and plants. In a way, all evolution can be considered as co-evolution whereby selection pressure does not only result from the abiotic environment but is also exerted by other living species.

Several authors have argued in favor of applying co-evolution to study economic systems and their relation to the environment, notably resource based activities like agriculture (Gowdy 1994; Norgaard 1994:Ch.4), rainforest use (Norgaard 1994:Ch10) and fisheries (Allen and McGlade 1987). Co-evolution has also been proposed as a framework for understanding interaction between management of, and evolution in biological systems (Norgaard 1994:Ch3). Munro (1997) has developed an economic model on pest control in view of the spread of resistance as an unintended impact of human activity upon biological evolution that has economic implications as well. Finally, co-evolution can also involve the policy or regulatory reactions to environmental change (Hinterberger 1994; Norgaard, 1994). This calls into attention the relevance of different levels and types of co-evolution, in terms of management of semi-natural systems, sector developments in relation to natural environments, and structural and technological innovation in the face of resource scarcity and environmental degradation. For example, Clark et al. (1995) have developed a spatial model based on interregional input-output analysis which takes into account a co-evolutionary relationship between regions, economic sectors, and the environment. This is done by modeling feedback mechanisms as a function of the relative attractiveness of different regions in terms of economic activities and environmental quality.

On the basis of the literature on co-evolutionary theory and history several policy lessons can be drawn: experimentation should be undertaken cautiously on a small scale with as much monitoring as possible; experiments with very long time commitments should be very carefully evaluated; diversity is good, without it co-evolution may stagnate; additional components to existing economic systems, such as technologies, institutions, or regulation, may when favorably selected, exert a large influence in the long run; time delays of effects of processes may be significant, illustrated by the impact of the industrial revolution on current CO_2 concentration in the atmosphere; and finally, highly complex networks of locked in interactive subsystems may gradually evolve over long periods of time, but when additional pressures or selection forces "unlock" such systems, evolution may be rapid (see Norgaard 1994).

Technological change, resource use, and pollution. Technological development plays an important role in the context of sustainable development:

the way in which energy and material are transformed in the economic process ('throughput') depends mainly on the state of technological knowledge. This implies that technological innovation can change the composition of the material basis of economic processes

Benhaïm and Schembri (1996), Faber and Proops (1990), Faucheux (1997), Freeman (1996), Kemp and Soete (1992) and Kemp (1997) have argued that evolutionary and self-organization theories of technological change are beneficial to processes of environmental technological change. Their main argument is that in evolutionary and self-organization models technological and behavioral diversity, uncertainty, path-dependency, and irreversibility are elaborated in a more sophisticated and explicit way as is the case in neo-classical growth models. On the basis of neo-Austrian capital theory Faber and Proops (1990) have developed an economy-environment model which allows for endogenous innovation and technical progress. Driven by resource scarcity, technical change occurs by way of a so-called rolling myopic plan approach, that is a series of overlapping finite time-horizon plans. This approach is supposed to reflect limited knowledge about the future and bounded rationality.

Kemp (1997) and Faucheux (1997) have, among others, argued the policy relevance of developing an evolutionary framework for understanding change in complex environmental technology systems. Such a framework is thought to be in line with the literature on technological paradigms, technological regime (-shifts), technological trajectories or innovation avenues, lock-in and complex technological systems dynamics (see Arthur 1989; Dosi 1982; Dosi et al. 1988; Sahal 1985; Saviotti and Metcalfe 1993). It should be noted that these theoretical notions within the evolutionary tradition may need an additional interpretation, when applied to theorizing on environmental technological change. For example, it can be argued that the well-known notion of 'lock-in' needs an additional interpretation to the traditional one, when applied in the context of environmental economics. When talking about environmental technological change, often the challenge is faced of escaping technological lock-in to environmentally unsustainable practices and triggering a 'lock-out' away from unsustainable systems (see, e.g., Islas 1997; Cowan and Hulten 1996). In other words, the relevant competition processes refer not so much to (two) similar introduced technologies (as in the Arthur 1989 model) but more to the relation between an existing (dominant) polluting technology and an introduced clean technology.

In addition, in Kemp (1996, 1997) and Rip and Kemp (1998) it has been argued that an evolutionary theoretical framework for understanding environmental technological change should build upon the idea that ecological modernization, defined as the replacement of existing trajectories of consumption and production by more sustainable ones, goes beyond the control of particular pollutants and eco-efficiency. It requires the development of new technology systems (for example in transport, chemical industry, agriculture) offering substantial environmental improvements. This implies that fruitful theorizing includes, among others, the notion of technological niche development and management, sustainable technological regime-shifts, and the evolution of large technological systems and innovative networks (see Kemp et al. 1997).

A non-linear model of technological change, based on some elements from the theory of self-organization, has been formulated in Edenhofer and Jaeger (1998). Their model is a modified version of the Goodwin-Silverberg model on growth cycles and 'creative destruction' (Silverberg 1984) and employs so-called replicator equations to derive a selection process in which techniques expand or contract due to their superior profitability. The basic idea of replicator equations[3] stems from biology where they have been introduced by Fisher (1930). They can be seen as a formalization of the evolutionary idea of fitness because they describe the evolution of a population (here: technique) in such a way that species (here: techniques) with above-average fitness (here: profitability) will expand in relative importance, those with below-average fitness will decrease, while the average fitness changes with the relative population weights. As a result of this evolutionary process long-run fluctuations in prices, wages, and patterns of output are produced within the model, basically driven by sustainable technological innovations. These innovations are triggered by rising energy prices, due to environmental policies (taxes, energy cap). The model shows that these environmental policies are able to establish the conditions under which the new (energy efficient) technology is evolutionary superior.

Economics of climate change. In the economics of climate change evolutionary contributions are remarkably rare. An example of an approach to model climate change that is close to the evolutionary tradition is presented in Janssen (1998) and Janssen and de Vries (1998). These authors use a multi-agent modeling approach to address the issue of adaptive responses of agents to climate change in view of different perspectives among the agents on technological progress, climate sensitivity, the expected damage costs and the expected mitigation costs. Three such perspectives or worldviews are considered, namely an individualist, hierarchist, and egalitarian one. The first of these can be regarded as very optimistic about sustainable growth and the latter as the most pessimistic. A dynamic economy-energy-climate model is used to calculate the impacts of decisions by agents who are uniquely linked to their worldview. It is then possible to see what will happen under the condition that there is no learning when the worldview is in accordance with reality ("utopia") or not ("dystopia"). One step further, the impacts are assessed when there is (stochastic) adaptive behavior. This is modeled via a genetic algorithm that changes the distribution of perspectives among the population. Finally, the impact of surprises is also examined. It is argued that the results are useful to understand the role of ignorance, imperfect information, and social dynamics that determine perspectives on particular environmental policies.

Preferences, consumption, life-styles, and the environment. Changes in consumption that reduce environmental pressure have so far received relatively little attention within environmental economics in general and evolutionary environmental economics in particular. Only a few authors have taken up the issue of sustainable consumption from an evolutionary perspective. Whereas within the neo-classical tradition, preferences are in general treated as exogenous or given[4]—and as a result, shifts at the demand side are assumed to be solely determined by shifts in prices—Norton et al. (1998) criticize the implicit assumption of consumer sovereignty in the context of sustainable development. Since the latter needs a long-term perspective it makes no sense to talk about fixed and given tastes and preferences. Their contribution is a conceptual one, proposing to develop an evolutionary framework for explaining preference formation, including cultural, social, and psychological factors[5]. Stern (1997) puts forward the issue of changing preferences for sustainability in the context of substitution. He argues that complementary to the (limits of) substitution of production factors sustainable development requires the very possibility of substitutability in consumption. An important notion here is 'lexicographic preferences', which embody a degree of irreversibility as they reflect that a minimum endowment of environmental goods is necessary to realize a positive level of utility (Spash and Hanley 1995). It has to be noted that Stern draws a parallel with the production function literature, suggesting to endogenize preferences analogous to the endogenization of technology. Nevertheless, he does not extend this argument in favor of an evolutionary approach to changing preferences. A broader discussion on behavior and preferences in the context of environmental policy analysis is provided by van den Bergh et al. (2000).

Evolutionary Economics, Environmental Economics, and Sustainable Development: Research Directions

There are a number of issues in the realm of environmental economics that can be elaborated with the help of theories and models in evolutionary economics. A few of these will be discussed here with a focus on sustainable development.

The growth debate. Since the 1960s the relationship between economic growth and preservation of environmental quality is subject to much controversy. According to one view, economic growth is a requirement for preserving environmental quality. The opposite view argues that economic growth will increase the pressure on the environment and therefore, preserving environmental quality requires zero or even negative growth rates. The debate is concentrated on the following questions (van den Bergh and de Mooij 1999): Is economic growth desirable? Is economic growth possible? Can economic growth be controlled or stimulated? Evolutionary economics can contribute to further understanding of the positions in the growth debate.

It needs no argument that a growing economy has to undergo structural changes if it wants to meet the conditions for sustainability. An evolutionary perspective may shed new light on the relationship between sectoral dynamics and environmental pressure. In line with evolutionary population models in which evolution is considered simultaneously in the short term (seasonal fluctuations) and in the long term (structural change) economic models may be developed that take into account a simultaneous consideration of short and long-term development (evolution) in the production structure. In such an approach the question of which sectors or activities will 'survive' in view of the need for sustainability is a matter of long-term evolution.

An important argument supporting the view that economic growth does, in the long term, not conflict with preserving environmental quality, is the hypothesis that the relationship between economic growth and environmental pressure can be characterized in terms of 'decoupling' (or 'delinking'). The argument stems from empirical research suggesting that environmental quality declines during early stages of economic development but improves in later stages (Selden and Song 1994; Shafik and Bandyopadhyay 1992; Panayatou 1993). In other words, the relationship between economic growth and environmental pressure follows an inverted-U pattern and is therefore called the Environmental Kuznets-curve (EKC) after the relationship Kuznets (1955) suggested to exist between income inequality and income per capita. Among the explanations offered for the existence of the EKC are the hypotheses that increasing welfare leads to increasing valuation of environmental quality as well as to increasing availability of environmental beneficial technologies. After the initial evidence supporting the EKC, recent studies have called the EKC into serious question (Arrow et al. 1995; de Bruyn and Opschoor 1997; de Bruyn 1999). The latter two studies even argue that the relationship between economic growth and environmental pressure is not so much characterized by a U-curve but follows a N-shape pattern, suggesting a 're-linking' of economic growth and environmental pressure.

The EKC hypothesis motivates further research from an evolutionary perspective for at least two issues. The first one refers to the argument that technological development will facilitate a decoupling of economic growth from environmental pressure. This is the production side of the referred growth debate. The theoretical concepts from the evolutionary literature on (environmental) technological change, as discussed in the section on technological change, resource use, and pollution (p.121) could be developed by conducting case studies and developing analytical or simulation models. The second issue refers to the hypothesis that increasing welfare will shift preferences in a more ecological sustainable direction, i.e. giving higher value to the preservation (or restoration) of environmental quality.

Sustainable consumption. Changing current consumption patterns into a more ecological sustainable direction is not only a matter of developing the right concepts, but also of asking the right questions. Important questions in view of the debate on growth versus environment, refer to future consumption patterns of commodities, food, water, energy, and so on. Will material consumption continue to grow with increasing levels of income? To answer this question we need to know more about the development of a 'consumption culture' in developing countries, the way in which additional income will be distributed among a variety of products and sectors and the existence of 'rebound' effects that might compensate for the gains obtained from increasing eco-efficiency.[6] Furthermore, changing current consumption patterns asks for understanding the determinants of consumption. This requires going beyond economic instruments and technological solutions by taking into account social-cultural and psychological factors as well (Wilhite and Shove 1998). Attention should be given to the evolution of needs, preferences, and lifestyles when trying to understand the determinants of consumption behavior (Duchin and Lange 1994; National Resource Council 1997).

Of course, this is an agenda for multidisciplinary research. However, it also motivates a potentially fruitful broadening of the existing economic theoretical framework. Pioneering steps in this direction have been taken by Georgescu-Roegen (1966), with his work on lexicographic preferences, and Scitovsky (1976). They have each made an attempt to integrate sociological and (cognitive and social) psychological concepts into economic theory. It is suggested that evolutionary economics should build on this work.

Climate change modeling. From an evolutionary point of view, the interaction between economic processes and climate change seems a perfectly suitable topic to be studied in terms of two (co-)evolving systems. Such an approach should be able to integrate uncertainty, irreversibility, and thus path-dependency into the analysis. These elements are overlooked by many traditional economic analyses of climate change policy although it has to be noted that recently attempts have been made to include uncertainty, irreversibility, and learning in integrated assessment models (Kolstad 1994, 1996; Lempert et al. 1996; Zapert et al. 1998).

In short, it is expected that an evolutionary contribution to this field can be fruitful through modeling long-run non-linear feedback mechanisms between economic processes and climate change, uncertainty and lock-in phenomena. The latter implies the recognition of a possible divergence between rational optimizing behavior at the micro-level and sub-optimal outcomes at the macro-level.

Policies for sustainable development. One of the most important insights of evolutionary thinking for policy is that current systems are not necessarily optimal from an efficiency perspective, even if prices are 'correct' from a neo-classical point of view (i.e. reflect externalities, are based on perfect competition, etc.). The reason is that systems can be locked-in, that is to say that they are the (unsustainable) result of unique, historical, path-dependent processes. From this perspective the problems faced by environmental policy-making are enormous. Historical developments have created a system that depends on fossil fuel use, transport over long distances, use of toxic materials, passenger transport dominated by private car use, etc. Policy suggestions based on economic equilibrium analysis tend to focus on efficiency, and do not worry about how to move away ('lock-out') from a locked-in system. Evolutionary thinking may add to the understanding of this transition process. This is essential for environmental economics as the desired changes, in the face of potential climate change risks, are quite extreme.

A second insight of evolutionary thinking that is directly relevant for environmental policy-making follows from the non-marginal structure of desired changes, which makes equilibrium analysis miss out on certain effects of these changes. For instance, the potential double dividend of environmental tax revisions—shifting the tax burden from labor to material and energy resource inputs in production—can be systematically underestimated with equilibrium analysis. Present inefficient technologies may be locked-in as a result of network externalities and sunk costs. Well-known examples are systems which require a significant amount of private and public investment and network support such as transport and infrastructure, energy generation and provision, and traditional materials-product connections like metals-cars. Evolutionary thinking may shed more light on the potential size of the various benefits in terms of extra employment, less environmental pressure, and more tax revenues of environmentally motivated tax revisions (Ayres 1998a). This may lead to more support for such policies.

A third issue that evolutionary economics may address is the long-run effectiveness and stability of environmental policies. The question here is which policies, including property rights, standards, taxes, tradable permits, and voluntary agreements, are least sensitive to various kinds of social, economic, and environmental change? Changes may cause instruments to become less effective, less efficient, to have unanticipated effects, etc. In this context a number of effects need to be considered, such as changing economic sector structure, changing technology, product innovation, and changing life-styles (see Ring 1997).

Conclusions

Although the traditional neo-classical economics approach in environmental economics has generated many useful insights about environmental policy it does not offer a complete perspective on needed policy and strategies to realize a sustainable development. The most simple explanation is that the traditional insights are essentially static, in the sense that they focus on hypothetical optimal equilibria without noting transition problems relating to barriers created by historical lock-in of present systems and technologies. Furthermore, the long-term impact of proposed "optimal policies" is incomplete as well, since selection of products, behavior, and production techniques is not addressed. Essentially, long-term projections are based on models that are usually deterministic, a-historical, and that lack variation of actors, products, technologies, etc. Consequently, these models can address neither uncertainty at various aggregation levels, nor path-dependence and lock-in of systems and technologies. It has been argued here that a serious interest in studying sustainable development from an economic perspective requires more than a neo-classical approach. Evolutionary and co-evolutionary processes at various levels need to be taken into account.

There are only a few applications of evolutionary thinking and models in environmental economics. Moreover, there does not seem to be consistency among different applications. This paper has tried to create some framework for addressing crucial issues in environmental economics from an evolutionary perspective. Subsequently, both theoretical modeling and applied modeling are required.

NOTES

1. Negative externalities or external costs are usually defined as negative - undeliberated and uncompensated - physical impacts of one economic agent's actions upon another agent's utility or production (costs or benefits). Uncompensated means that they are outside the realm of the market (see e.g. Baumol and Oates 1988).
2. For a (classical) methodological treatment of this issue see Knight (1921).
3. Sometimes referred to as mathematical predator-prey relations.
4. A notable exception is given in the work of Earl (1983) on endogenizing preferences in a social context.
5. Although they pretend to give an explanation in their article, in fact they only argue in favor of such an explanation.
6. Rebound-effects are counter productive effects on the macro, meso, and micro level due to adaptive behavior on the demand side when new resource-saving technologies and/or behavioral options are introduced (Hinterberger et al. 1997).

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