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Evolutionary Theories in Environmental and Resource Economics: Approaches and Applications

Jeroen C.J.M. van den Bergh
Department of Spatial Economics
Free University
De Boelelaan 1105
1081 HV Amsterdam, The Netherlands
fax: +31-20-4446004
jbergh@econ.vu.nl

and

John M. Gowdy
Department of Economics
School of Humanities and Social Sciences
Rensselaer Polytechnic Institute
Troy, NY, 12180-3590, USA
lgowdy@aol.com

Abstract

Recent advances in evolutionary theory have some important implications for environmental economics. A short overview is offered of evolutionary thinking in economics. Subsequently, major concepts and approaches in evolutionary biology and evolutionary economics are presented and compared. Attention is devoted, among others, to Darwinian selection, punctuated equilibrium, sorting mechanisms, Lamarckian evolution, coevolution and self-organization. Basic features of evolution, such as sustained change, irreversible change, unpredictability, qualitative change and disequilibrium are examined. It is argued that there are a number of fundamental differences as well as similarities between biological and economic evolution. Next, some general implications of evolutionary thinking for environmental economics are outlined. This is followed by a more detailed examination of potential uses of evolutionary theories in specific areas of environmental economics, including sustainability and long run development theories, technology and environment, ecosystem management and resilience, spatial evolution and environmental processes, and design of environmental policy.

1. Introduction

Evolutionary mechanisms play an important role in environmental economics at two levels of analysis. First, much work in environmental economics has since the late 1980s been motivated by the notion of sustainable development, implying a long term horizon in scientific analysis and policy-making. Although much has been written about sustainable development from a wide range of perspectives, relatively little has been said about it from an evolutionary perspective (van den Bergh 1996). A second level is that of natural resources and ecosystems which are subject to biological evolution, or at least altered by processes of selection. Biological evolution — notably mechanisms like selection and sorting (Vbra and Gould 1986) — should be considered seriously in as far as they affect the structure, morphology and functions of resources exploited by humans, as well as life-support systems upon which environmental stability and human life depend. The relevance of this is magnified by the fact that selection pressure is exerted by human activities such as mining, pollution, outdoor recreation, resource harvesting, introduction of alien species, and various agricultural practices like irrigation and use of pesticides.

On this latter level insights from evolutionary biology can be directly implemented into environmental economics' studies. Concepts and insights from evolutionary biology may also be useful in a more indirect way, namely serving as a model for general theorizing about economic evolution at the first level of sustainable development. Several general research questions commonly addressed by evolutionary economics can easily be transferred to a specific environmental economics context. Particular and unique issues and questions in environmental economics, however, can also be approached from the perspective of recent, innovative theories of evolutionary biology. For instance, coevolution between species and systems, or between systems, is a concept that seems especially suitable to address long-run relationships between economies and natural systems. Another example is the distinction between micro and macro evolution.

Evolution can be characterized as disequilibrium and qualitative (structural) change that is irreversible and unpredictable, can be gradual and radical, and is based on micro-level diversity (variation) and selection, as well as macrolevel trends and shocks ("large scale accidents"). In evolutionary biology qualitative change can be defined more precisely as a change in the frequencies of genes from generation to generation. Since in economics a unique analogue of the gene is missing, qualitative change has a broader connotation and is less specific. Furthermore, it is now common to not regard evolution as "progress" or a process of global optimization, but at best as local optimization. This is exemplified in the ideas "path-dependence" and "lock-in" in economics (Arthur 1989), and historical "bauplan" limits, "chromosome hitch-hiking" and "punctuationism" in biology (Gould and Lewontin 1979).

The organization of this article is as follows. Section 2 shortly discusses main approaches to evolutionary thinking in economics. Section 3 considers and compares major concepts and implications of contemporary evolutionary theories in biology and economics. Section 4 looks at the general implications of evolutionary thinking for environmental economics. Section 5 discusses potential applications of evolutionary thinking to problems and questions of environmental and resource economics. Section 6 presents conclusions.

2. Evolutionary Thinking in Economics

Evolutionary theory has been central to economics for well over one hundred years. Occasionally, economists have appealed directly to biological evolution as a source of insight into the workings of the economy — Veblen, Marshall, and Friedman come immediately to mind — but for the most part notions of evolution are so ingrained in the world-view of economists they go unrecognized. Evolutionary concepts such as natural selection and survival of the fittest lie at the heart of contemporary economics. It is taken for granted by most economists that economic change is driven by increases in efficiency at the margin (Gerowski 1989; Telser 1996), that evolution is synonymous with progress (Hirshleifer 1985), and that the forces of economic evolution tend to drive the economy toward a unique equilibrium (Alchian 1950; Friedman 1953, Boulding 1981). All three of these assumptions — gradualism, progress, and unique equilibria — are the subject of intense debate among contemporary evolutionary biologists. An examination of this debate and its relevance to economic theory can provide significant insights into environmental policy.

For the most part, evolutionary economics has been dominated by a Darwinian selection-through-competition perspective (see the articles in Witt 1993). Several other perspectives, however, are present in modern biology, some being stimulated, for instance, by findings in paleontology. These may be at least as relevant for economic analysis as the prevailing Darwinian approach. Some of concepts and theories have made their way into economics directly from biology, for instance, hierarchical systems, coevolution, punctuated equilibrium theory, sorting versus selection, evolutionary game theory, multi-equilibria, and contingency, among others (see the articles in Gowdy 1997b). Other evolutionary perspectives in economics describe peculiar and unique features of economic systems not found in the natural world, such as hierarchical decision-making, information exchange across independent sectors (innovation and diffusion), and Lamarckian (goal-oriented or teleological) evolution based on purposeful actions.

Over the years, a number of alternative approaches to the survival-of-the-fittest core of neoclassical theory have been developed by economists, the best-known being Joseph Schumpeter's theories of qualitative change including innovative entrepreneurship and creative destruction (Schumpeter 1934), and subsequently the neoSchumpeterian type theories of technical change (e.g., Dosi *et al.* 1988). The latter focus on bounded rationality and stochastic processes of selection and mutations (Tisdell 1996).[1] Various other authentically evolutionary approaches have been tried — perhaps with less impact (so far), but not necessarily less relevant. Among these are Hayek's (e.g., 1967) grand cultural-institutional development theory, Simon's theories of human behavior, organizations and complexity (1957, 1959, 1962), Georgescu-Roegen's (1971) "bioeconomics" with its thermodynamic interpretation of long- run economic development, and of course Nelson and Winter's (1982) interpretation of evolution as gradual changes in routine-like behavior. Recently, based on the innovative work by biologists (Maynard Smith 1982), economists have tried to link equilibrium and evolutionary theories by considering strategic dynamic interactions between economic agents in a game-theoretic context (Samuelson 1997, Weibull 1995). Instead of assuming homogeneous behavior, this approach examines the impact of interaction between different behaviors via learning and selection mechanism. In other words, it recognizes diversity (variation) of behaviour. Many of the other evolutionary approaches explicitly or implicitly assume that human behaviour is consistent with some type of bounded rationality (van den Bergh *et al.* 1998). All the previous approaches view evolution as a real economic phenomenon, that is, inherent to economic dynamics over long time horizons, and not just a

[1] Opposed to this is the research program to combine endogenous growth theory, based on deterministic rational behaviour, with Schumpeterian "creative destruction", also called "vertical innovation" (Aghion and Howitt 1998).

biological metaphor. With these ideas as a base, it is easy to move toward a larger perspective on evolution which combines sequential and co-evolving physical, chemical, biological, cultural and economic phenomena (see Ayres 1994).

Evolutionary thinking is as important to economics as it is to biology for at least three reasons. First, economic systems are undergoing — and have undergone at least since the eighteenth century — extremely quick developments and patterns of qualitative, structural and irreversible change. Historically, industrial economies have not shown movement towards a steady state or steady state growth path, in spite of the dominant economic growth theory trying to make us believe so. Second, economic systems have a great capacity for sustained learning and adaptation, on various vertical decision and spatial levels, of individuals, households, groups, organizations (NGOs), firms, sectors, countries, and nowadays even on a global scale. Third, evolution can be observed in a horizontal organizational structure of the economy, involving science, technology, businesses, markets, the legal system, consumer preferences, and institutions and culture at a wider level (Nelson 1995).

3. Evolutionary Approaches: Concepts and Definitions

Here we will list a number of perspectives on evolution. Relatively much attention will be devoted to those that have received no or little attention in the economics literature so far.

Darwinian biological evolution, that is, gradual adaptation through natural selection, is a process consisting of three component principles, namely variation, heredity and individual selection (Mayr 1942). Variety and diversity, whether fully random or not, are essential because without them there can be no evolution whatsoever. The neoclassical approach with homogeneous/uniform agents is incapable of addressing such “variational evolution” in economics. The information driving evolution in actual cases is the distribution of variation in a given population. Variation comes forth via mutations and sexual recombination. Heredity means that selected units have some degree of durability and resilience, via a mechanism that passes on characteristics to other units. Individual selection is based on competition between individuals in the face of selection pressure (scarce resources, space, mating partners, etc.). This has been incorrectly interpreted as a complete model of economic evolution consequently associated with optimizing behaviour of economic agents (Alchian 1950; Friedman 1953; Hirshleifer 1985). Selection and struggle for existence provide a mechanism by which relatively well-adapted units can increase their numbers, either absolutely or relatively. This may be regarded as selective adaptation, to distinguish it from other types of adaptation (Gould and Lewontin 1979).

Punctuated equilibrium (Eldredge and Gould 1972) refers to a pattern in natural history characterized by relatively long periods of stasis interrupted by bursts of rapid change. The punctuated equilibrium debate has raged in evolutionary biology for years now, and it is beginning to have an impact in the social sciences (see Somit and Peterson 1989). The most radical implications of punctuated equilibrium theory are: gradual change has been absent during long periods of evolutionary history; stasis is an active phenomenon (analogous to resilience over a shorter period of time); there exist "higher level" selection processes, that is, higher than natural selection acting solely on individuals; macroevolution complements aggregate impacts of adaptive/selective microevolution. (Gould and Eldredge 1993). Once it is admitted that natural selection at the margin is only one (albeit the most important one) of many possible reasons for evolutionary change, the door is open for notions like hierarchies of selection, historical lock-in, and macroevolution (Gowdy 1992). In economics, Schumpeter's “creative destruction” comes closest to puntuationism. Schumpeter interpreted Darwin’s theory as reflecting a “uniform unilinear development” (Schumpeter 1934, pp. 57-58). Instead he believed that discontinuous changes are more important, as illustrated by his much quoted statement: “Add successively as many mail coaches as you please, you will never get a railway thereby” (Schumpeter 1934, p. 65).

Sorting and *selection* is a distinction proposed by Vrba and Gould (1986) to elaborate the notions of hierarchies of selection and macroevolution. The term “selection” is reserved for the traditional Darwinian cause-effect mechanism of differential survival of adaptive traits which increase or maintain “fitness”, i.e. the expected relative frequency of descendants in the next generation. Selection is a gradual and marginal process involving the adaptation of species to a relatively stable environment. “Sorting” is a broader term referring to differential survival, no matter what the reason. Selection implies causality; a firm or an organism survives because it is more efficient or more fit. Sorting is merely a differential outcome. Agents may survive because they are “more fit” (selection) or merely because they were in “the right place at the right time”. Sorting may cover branching or multiplication of species (“speciation”), genetic drift and molecular evolution, ecological boundary conditions, and external shocks (large scale random events) such as climate change that affect extinction of species. Some of these mechanisms have been referred to as “species selection”, to distinguish them from “individual selection”, but according to Mayr (1989) “species turnover” is a more appropriate term. Note that Schumpeter’s example of coaches being replaced by railways is consistent with such a view. Economic equivalents of sorting are not so evident, partly because the distinction between selection and sorting is blurred in economics. One may think of processes like hysteresis, lock-in of technologies and increasing returns, and external shocks in open economies.[2]

Lamarckian evolution means that mutations or heredity can be steered by the unit or some external actor. This may be more appropriate as a model for economic evolution than for biological evolution, because economic actors can consciously influence the direction of economic evolution (Hodgson 1993). Consciously influencing selection processes via policies may be relevant to the implementation of evolution in the context of environmental economics. The Darwinian approach would here be different, namely focusing on the sensitivity of policy impacts given unpredictable and uncontrollable selection outcomes.

Coevolution is a useful concept for integrating evolutionary and environmental economics. It refers to the simultaneous evolution of relevant interactive species, or species and ecosystems, and analogously economic activities and their natural environments. It emphasizes that selection pressure is not merely exerted by abiotic factors, but also by other living species. Coevolution in biology can be considered the result of merging (community and population) ecology and evolutionary biology. Typically, resource scarcity limits, feedback and species interactions are central elements of both population ecology and evolutionary biology. Ehrlich and Raven (1964) used the term first, describing the evolution of butterflies and plants. It is important to understand that nearly all evolution can be considered as coevolution. Norgaard (1984) was the first to introduce the concept in economics, applying it to environmental issues. Given its conceptual richness, coevolution can be linked to Darwinian selection theory, punctuated equilibrium theory, or both. In the first case, the dominant

[2] It may be noted that some contributions in Somit and Peterson (1989) conclude that the punctuated equilibrium theory is not so relevant for social sciences at this moment for a number of reasons: the time horizon of the theory is too long (paleoanthropology); the theory is regarded untestable for many relevant social science issues (behavioural changes over 100,000 years); and the distinction between selection and sorting may be too subtle or even irrelevant for social sciences, where the individual and the gene are

mechanism is that one subsystem (or species) exerts selection pressure upon another subsystem (or species), which causes gradual change. In the second case, one subsystem creates external shocks upon the other subsystem that cause “extinction patterns” and relatively rapid changes.

Evolution is traditionally used - often in an imprecisely defined way - as referring to a qualitative, sustained and irreversible (and possibly irrevocable), unpredictable and disequilibrium change.

Qualitative change means that basic features on whatever level alter, be it that of the individual, the species, the sector, etc. Therefore, any reduction of change to an increase or decrease in a single index will miss out on core characteristics of change.

Sustained and irreversible change implies that it is not merely temporary, reversible adaptation, but that some unique, historical and path-dependent process is taking place. This stresses that historical events may in combination with increasing returns to scale lead to a lock-in of — possibly nonoptimal — technologies (Arthur 1989). It may be noted that this is different from the neoclassical approach — at best concerned with dynamic but a-historical allocation problems — which regards changes under ideal economic regulation as optimal at the margin and the pattern over time as intertemporally optimal.

Unpredictable change means that there is a high degree of uncertainty and indeterminism involved. It should be noted that many processes in reality are predictable, of course with some degree of imprecision due to measurement errors and minor disturbances. Examples are gravity dominated processes, operation of machines, and thermodynamic (energetic) processes. Economic development is unpredictable as it is influenced by unpredictable processes: technological and organizational innovations, environmental cycles

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undefined. Gould and Lewontin (1993) survey the evidence for punctuated equilibria in natural history.

and disturbances, complex interactions between so many subsystems, and so many decisions made by so many individuals that are influenced by so many factors. From a Darwinian perspective one may regard the enormous diversity of elements at every level of the economic system (individuals, groups, activities, cities and regions) as a reason for accepting a diversity of potential development directions.

Disequilibrium change is implicit in most evolutionary theories. It reflects the idea that the world's social, physical and biological systems are characterized by disequilibrium states, so that "change" is not a process of moving from one equilibrium to another. This has important implications for economics. In the static neoclassical model, conditions are supposed under which there is only one unique competitive equilibrium (Hahn 1973). Similarly, in growth theory neoclassical conditions assure an identical long-run growth rate for all relevant variables. If disturbed, the economy will always return to its "natural" growth rate, much like the outdated notion of an ecosystem always being capable of reaching the "climax" state (Holling 1986). However, evolution — either as gradual or sudden change — makes it impossible for an economy to maintain any equilibrium position. As a result, disequilibrium is persistent. Ayres (1998a) argues that disequilibrium is even present at a very fundamental level, as it stimulates various types of behavior: individuals buy because their possessions and their needs are not in equilibrium, investment takes place because there is a disequilibrium between demand and supply, and so on.

Finally, modern ideas found in *self-organization theory* (Prigogine and Stengers 1984; Silverberg 1988; Silverberg *et al.* 1988; and Witt 1992) support the idea that living and economic systems should be regarded as open systems that are *far from thermodynamic equilibrium.* Such systems require a continuous inflow of low-entropy energy, so as to allow for metabolic processes to maintain their structure and functions, as well as to fuel growth and change on various system levels (e.g., Foster 1993).

Table 1. Types of Evolution and Economic Interpretations

Biological Evolution	Nature of Change	Economic Equivalent	Sorting Mechanism
Darwinian evolution	Marginal, gradual, micro	Neo-classical, Nelson/ Winter routines and innovation, neoSchumpeterian diffusion models, evolutionary game theory	Competition among individuals (individual selection), stochastic mechanisms of innovation/selection, genetic algorithms
Punctuated equilibrium	Non-marginal, rapid, macro	Creative destruction, qualitative/structural change, long waves (inventions followed by innovations)	Hysteresis, lock-in, adaptation, resilience, increasing returns, external shocks, vertical innovation
Lamarckian evolution	Gradual or rapid, micro and macro	Development theories, social-cultural evolution, cooperative behavior	Conscious, purposeful, forward-looking decisions, group selection, learning
Self-organization	Marginal or non-marginal, slow or rapid, micro and macro	"Invisible hand", spontaneous order, stochastic neoSchumpeterian models, deterministic chaos	Reaction to external shocks, thermo-dynamic processes, hysteresis, deterministic chaos, sensitivity
Coevolution	Simultaneous change of sub-systems	Complementarity, ecological economics, Wilkinson's ecological theory of economic development	Mix of Darwinian selection and punctuated equilibrium, dynamic interaction between subsystems, evolution in each subsystem

Table 1 summarizes some of the evolutionary approaches mentioned above. Although we realize that more categories are possible, given that economists know little about biological evolution, a simplification of the wide range of insights is necessary. Changes can be either marginal or non-marginal, gradual or rapid, and micro or macro. All combinations are found in biological as well as economic “realities”.[3]

At this point it is also useful to indicate the obvious differences between biological and economic evolution (see also Eldredge 1997; and Hodgson 1993):

1. Evolution generally occurs at a faster pace in economic than in biological systems. Ideas may be preserved, and as a result extinction is never absolute in economics. A sad example is the everlasting knowledge about nuclear weapons.
2. There may seem no clear and certainly no singular equivalent in economics to the unit of selection, i.e. the gene (but see Faber and Proops 1990). However, people, products, books, artifacts and structures can all contain information in a durable way. Moreover, social, cultural and economic foundations like knowledge, science, religion, art, habits, rituals, institutions and politics are not essentially different from biological genes, as they have significant durability under a wide range of external conditions. Or, in the words of Norgaard (1994, p. 87), “One type of gene is no more real than the other”. Moreover, if macroevolution and higher level sorting exist in biological systems, the gene is not the exclusive unit of selection, and selection not the only mechanism of durable change, in biological evolution anyway. Therefore, the lack of an equivalent to the gene in economic evolution would not be such a serious criticism after all (see Winter 1964; Hodgson 1995).
3. Macroevolution occurs in both biological and economic systems. Moreover, there is no obvious economic analogue for the biological sexual recombination mechanism to generate new genetic structure. In economic systems inheritance can occur in different ways and on different aggregation levels. Finally, economic mutations can come forth in many different

[3] In the last decades various tools have been developed that have simplified evolutionary modelling and stimulated formalization and application of evolutionary theories. These tools include genetic algorithms, neural networks, cellular automats, fuzzy sets, and nonlinear models (including deterministic chaos models). See Janssen (1998) for more discussion in the context of environmental-economic modelling.

ways. The neoDarwinian model as proposed by some authors thus offers an incomplete description of economic evolution.

4. Lamarckian evolution, including learning, occurs on various levels in economic systems, such as that of individuals, groups and sectors. In biological systems such learning is largely absent. This is related to the fact that the distinction between genetic change and learning is clear-cut, whereas in economics such a distinction is blurred. Another way to state this point is that adaptations in biology along specific branches ("lineages") of evolution (species, families, etc.) cannot be transferred to other branches. In economies, however, technologies developed and lessons learned in one sector can be easily transferred to other sectors.

4. Evolutionary Thinking in Environmental Economics: Some General Implications

There are a number of general implications of evolutionary theory directly relevant to environmental economics. In the first place there is not a single "best" state of the economy. Irreversibility and historical lock-in of technologies create severe limits to optimal (re)allocation of natural resources over time. Most traditional dynamic models, notably those in resource economics and growth theory, do not recognize this point.

Another insight is that the attempt to measure "marginal value" is inappropriate for many environmental features. For example, the calculation of the marginal value of a species is a futile exercise. Species are interconnected to ecosystems, climate and other species in a continually changing environment. The calculation of the effect of removing one species on the ecosystem or the economy will be different at different times of the year, and will vary according to the state of the ecosystem in various cycles, and the unique conditions at the particular time the species is removed. (see Vatn and Bromley 1994; Gowdy 1997a; Bromley 1998). Accurate prediction is impossible, and the main policy implication is that we should focus on saving ecosystems, not species, that is, to err on the side of caution.

Related to the previous point is that non-marginal or non-gradual change is important. This includes threshold effects, the most dramatic example being the potentially huge environmental and economic impacts of global climate change. The "extinction debt" from biodiversity loss is another case in point (Tilman *et al.* 1994). Passenger pigeons, for example, needed very large flocks to survive and at some point in the late 1800s harvesting a "marginal" number of them drove the species to extinction (McDaniel and Gowdy 1998).

Next, many policies or resource management practices may be evaluated too optimistically in terms of effectiveness due to evolutionary impacts not being taken into account. Externalities, in the traditional welfare-economic sense, should really include the relevant array of selection and evolutionary processes. If this is not done, then externalities will be underestimated and policies based on the notion of optimal externalities are doomed to failure.

Taking this argument one step further, a final implication of the existence of evolutionary forces is that the equilibrium-based welfare theorems of neoclassical economics do not hold. In other words, the association of a competitive market equilibrium with a social welfare or Pareto optimum falls apart. Insights in the economic theory of environmental policy loose much credibility. What comes in place is a policy theory that shifts the weight from economic efficiency to risk-avoidance strategies and effectiveness criteria.

5. Potential Application Areas

5.1 Sustainable long-run development

Evolutionary thinking can help clarify the debate between advocates of "weak" and "strong" sustainability. The standard economic approach to sustainability, weak sustainability, focuses on maintaining the total capital stock necessary to insure that net national product is non-declining (Pearce and Atkinson 1995). Near-perfect and reversible substitution between "natural capital" and human created capital ("machines and knowledge") is assumed. This view reduces "sustainability" to sustaining economic growth (Solow 1992). Such "weak sustainability" may be a poor policy guide — even to maintaining economic output — when uncertainty, irreversibility, and coevolution are taken into consideration (Ayres *et al.* 1998).

Surprisingly, most of the debate on sustainable development has omitted any reference to evolutionary considerations. The dominant literature in economics on sustainable development focuses on deterministic equilibrium growth theory in which development is reduced to an a-historical growth process characterized by accumulation of a one-dimensional capital stock which allows for perfectly reversible development (Toman *et al.* 1995). A long-run perspective on the impact of environmental regulation on economic structure requires embedding the concept of sustainable development in (co)evolutionary theory. The following perspectives may be useful in this respect.

An initial model of long-run historical change and environmental degradation may focus on important changes. The transitions between societies in history, such as from hunting and gathering to agriculture to industrial societies, are one example (Gowdy 1994; van den Bergh and van der Straaten 1994). These have been argued to be consistent with the theory of punctuated equilibrium (Somit and Peterson 1989). Nicholas Georgescu-Roegen (1971) has emphasized irreversibility of long run economic development as a consequence of the laws of thermodynamics, notably the entropy law. In addition, he has suggested “exosomatic development” of humans as a step in our evolution to overcome our biological shortcomings as humans. In this context, he has identified three technical “Promethean” innovations as crucial for important changes of economic production over history: fire, agriculture and the steam engine (Mesner and Gowdy 1999). Each of these introduced a completely new relationship between humans and their natural environment. This may be seen in the light of punctuated equilibrium theory. It should be noted that the relevance of thermodynamics for economic analysis, and especially of the entropy law for growth theories, is still debated (Foster 1997; special issue of *Ecological Economics* 1997; Ayres 1998b).

Over a shorter period, Wilkinson’s ecological model of economic development focuses on the industrial revolution (Wilkinson 1973; Common 1988). It recognizes a number of human strategies to respond to resource scarcity such as: new techniques, new resources, new goods, and migration. Few formal models exist to address such changes: some authors have developed complex systems models (Clark *et al.* 1995; Allen 1997); others have used compact nonlinear models some of which generate deterministic chaos (Day and Walter,1989).

A topical problem for which evolutionary models of long-run development may be useful is climate research. In fact, this is one of the few areas where (optimal) growth models have been actually “applied” (Nordhaus 1994), leading to considerable criticism from, and competition with, more descriptive and multidisciplinary approaches (see Rotmans and de Vries 1997). The issues of uncertainty and irreversibility have been addressed in the traditional economic growth theory context by Kohlstadt (1994), through adding stochastic elements to Nordhaus’ (1994) “DICE” model. Surprisingly, this approach regards economic irreversibility due to overinvestment in greenhouse gases abatement techniques as more worrisome than irreversibility of natural processes like GHG accumulation in the atmosphere, climate change and derived ecological effects. This seems precisely the result of a focus on economic efficiency, and a neglect of uncertainty associated with environmental and economic evolution.

An evolutionary economic perspective could clarify the role of path-depency and the impact and costs of continuing energy intensive production and consumption activities based on fossil fuel inputs, that cause technologies to get further and further locked-in. A wider coevolutionary perspective could take irreversible changes in economy and environment over longer periods simultaneously into account, such as changing land use patterns and large scale migration due to gradual changes in temperature. Few studies have pursued evolutionary modelling in this area (Janssen 1998). Janssen and de Vries (1998) have studied the interaction of nonlinear complexity, stochastic processes and genetic algorithms that describe the selection over time of different perspectives on climate policy, based on a combination of risk-aversive/loving decision-makers and (in)correctly predicting. This type of work may be extended to generate lessons for climate policy in the face of uncertainty and evolution. This would require a new policy theory, based on linking social objectives (a combination of efficiency and effectiveness) to system dynamics (stochastic processes and sorting at various levels including individual selection).

Another wide-ranging application is in the area of economic structure and substance/materials flows. Presently, there is much interest for concepts like “dematerialization” and “industrial ecology”. An evolutionary perspective links changes in materials use to longer term trends and uncertain processes involving growth (level changes), substitution between primary (and secondary) inputs, changes in the sectoral structure, technological innovation, and changes in life-styles and preferences. This involves the emergence of new activities, "green industrial design", "miniturization", recycling, and the impact of these on the whole economy (Ayres 1998). The evolution of preferences, or better, the coevolution of preferences and technology —related to demand-supply interactions — is the ultimate source of change on a fundamental level, and one that affects life-styles and associated material and energy use patterns. Some initial work has been done with a focus on major, durable consumer goods (see Noorman and Schoot-Uiterkamp 1998).

5.2 Environment and Technology

Much of the general research on evolution and technology, based on neo-Schumpeterian analysis (Dosi *et al.* 1988) and Nelson and Winter (1982), is directly applicable to technological change as discussed in environmental economics. Some work has already been done in this direction (Ayres and Miller 1980; Faber and Proops 1990; Kemp 1997). Important focal points of this research is as follows. The lock-in of non-optimal technologies creates environmental and other social costs. Examples are car-based transport and fossil-fuel based energy generation. Stringent environmental regulation may have positive innovative effects on environmental performance of firms through technological inventions and innovations. In this context, an evolutionary perspective could shed light on the much debated Porter hypothesis (Porter and van der Linde 1995; Palmer *et al.* 1995), which states that a strict environmental policy may stimulate technological innovations which create a first-mover advantage, and the benefits related to these may outweigh the costs associated with an initially deteriorating international competitive position.[4] This depends of course on the type of issue and the speed

[4] This is one example of the more general "double dividend" hypothesis focusing on "win-win" changes, discussed in Section 5.5.

with which technology diffusion operates.

This type of research can start from the question of whether firms sufficiently realize potential benefits of technological innovation, and which policies are needed to provide accurate incentives to unlock non-optimal technologies. So the issue is one of technology policy, which may involve various instruments besides the neoclassical prices and standards: information sharing, networking, infrastructure, protection, subsidizing, creating less uncertainty, timely information about intended policies, continuity and reliability of policy-making etc. The selective pressures should be examined, which may be product markets, labour markets, capital markets, oligopolistic competition, social rules, political pressure, etc. Moroever, technology policy should focus on breaking down various barriers, to be preceded by a careful assessment of these.

5.3 Biological Evolution, Ecosystems, Resilience and Biodiversity

The newer concepts of “resilience” and “biodiversity” from contemporary ecology can be used to examine the long-run evolution of socio-economic systems (Levin *et al.* 1998). Resilience is a specific type of stability, and has been suggested to be the ecological equivalent or interpretation of the “sustainability” concept (Common and Perrings 1992). It has been defined in two ways, namely as the ability of systems to either maintain structure and functions in the presence of external stress, or return to a steady state following a perturbation (see Perrings 1998). The relationship between biodiversity and resilience has received some attention recently, since biodiversity has become a point of concern in itself (Holling *et al.* 1994). Two different views exist on the relationship between biodiversity and resilience. The first stresses that species have overlapping roles and therefore adding or losing species causes little or no change until a threshold is reached. The second divides species in an ecosystem into functional groups of species that act in an ecologically similar way. The relevant groups in the present context are “drivers or keystone species” and “passenger species”. The first group dominates the development of the respective ecosystem. In this perspective, resilience depends on the diversity of drivers as well as of passengers that are potential drivers. In other words, such passengers, seemingly redundant species playing only a minor role in a particular ecosystem, may take the role of keystone species as environmental conditions change. The presence of these species insures the resilience of ecosystems, that is, their ability to adapt to new conditions. Evolving economic systems may also be described as being more or less resilient, in terms of being adaptable to economic changes as well as environmental changes due to some redundancy of capacity and information present in them. Perrings (1998) argues that resilience is as important to economic systems as it is to environmental systems, and that changes of economic, environmental and combined system equilibria could usefully be described by way of a Markov process. This casts a new light on integrated modelling (see van den Bergh 1996).

Standard environmental economics does not address resilience, “redundancy” or even ecological stability, even if it seems of equal importance to economies and ecosystems (Tisdell 1998). The existing deterministic-equilibrium type of economic analysis of macrolevel sustainability (Toman *et al.* 1995) and of sustainable use of renewable resources like fisheries and forests (Clark 1990), should be made consistent with the notion of resilience. Maximum sustainable yield and economic efficiency are no longer straightforward criteria in modelling renewable resources. This has a direct implication for the debate about the economic value of biodiversity.

Research on resource management in relation to evolving quasi-ecosystems like agriculture, forestry and fisheries should acknowledge that in addition to reversible mechanistic processes, irreversible evolution can occur via the use of various controls (Norgaard 1994). In fisheries, fishing net maze size may generate selective pressure on fish size, and relatively small fish may increase its proportion in the fished population (McGlade and Allen 1987). In agriculture, use of pesticides, herbicides, and fungicides may create selective pressure on pests, non-useful herbs and fungi, so that the resistant ones may increase their proportion in the respective populations. As a result, management practices in the future are affected negatively, i.e. these become less effective and more expensive (Munro 1997). Furthermore, if such practices are performed on a large scale then spatial externalities may occur from farmers intensively using various control measures to others being more careful in application of these measures. An evolutionary analytical perspective may also give attention to evolution of resource-based systems via degradation of land, development of monocultures and associated degradation of (indigenous) farming knowledge (Clark *et al.* 1995; Martinez-Alier 1987). Finally, the prevention of natural fires in forests may lead to a buildup of biomass, which in turn will increase the probability of large and extremely hot fires. If these occur, the system may flip — possibly irreversibly — to a completely different structure with loss of biodiversity and (attractive) functions (Holling 1986).

Two general lessons from evolutionary biology are as follows. The first is that some seemingly redundant features of ecosystems, economies, and even human cultures, should be preserved even though static analysis shows them to be inefficient. The second is that maximum attainable diversity should be strived for to sustain “evolutionary potential” and maximize adaptive flexibility of future economic and environmental change. This is consistent with the “precautionary principle” (Ciriacy-Wantrup 1968). The empirical support for the punctuated equilibrium theory (surveyed in Gould and Lewontin 1993) has indicated that environmental systems have been able to realize much stability (“stasis”) over time, where processes of adaptation must have played an important role. Such notions of stasis in spite of changing conditions may provide links between biodiversity, resilience, selection and evolution.

5.4 Spatial Evolution

Consideration of the spatial and international dimensions of environmental economics problems has increased over the last decade. Attention has been given to the relationship between environmental factors, environmental regulation and international trade, and location of firms. Most of this is based on neoclassical theory that regards international issues in terms of allocation and externalities. However, it should be noted that international trade and location are the result of a long and slow process of coevolution of production and consumption in multiple countries or regions. Historical accidents, cultural factors and locked-in processes have certainly played an enormous role. Economists would tend to approach this by considering sunk costs as an indication of the barrier to international reallocation of activities.

Examining the evolutionary character of trade requires an integration of the separate literatures on sustainable development (with a dynamic orientation), trade and environment (with a static orientation), and firms’ location choice (static) (van Beers and van den Bergh 1997). The economics literature on the influence of environmental regulation on location choice has omitted historical and environmental factors that would perhaps be better explained in a (co)evolutionary framework (Markusen 1999). Other elements play a role in spatial evolution: migration and environment (Gowdy 1999); spatial structure and transport (Nijkamp and Reggiani 1993); and patchworks of land cover and use (Clark *et al.* 1995).

5.5 Policy and Project Issues

Equilibrium analysis (general or partial) of environmental policy instruments cannot take adaptive, learning and path-dependent processes into account. As a result, some effects of such instruments are not considered, due to the non-marginal structure of changes. An interesting example is the discussion about the potential double dividend of ecological tax revisions — improving the environment and employment (Goulder 1995) — which may 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 models may thus shed more light on the potential size of the various “dividends” (extra employment, less environmental pressure, technical progress, changed income distribution) of large scale tax revisions (Ayres 1998a).

A second issue that evolutionary economics may address is the long run effectiveness and stability of environmental policies. The question is here which policies (property rights, standards, taxes, tradeable permits, convenants/voluntary agreements) are least sensitive to, or most stable against, various kinds of evolutionary change? Changes may cause instruments to become less effective, less efficient, to have unanticipated effects, etc. In particular two elements are important. First, to what extent does the instrument contribute to sustainability? Second, what selective pressure is exerted by particular instruments on economic activities, technology, product innovation, etc.? (see Ring 1997).

Finally, how should project evaluation and decisions be brought into agreement with evolutionary insights? Notably in the context of planning for nature — parks, maintenance, protection — irreversibility, resilience and biodiversity should be taken into account. Economists have used cost-benefit analysis (namely, the Krutilla-Fisher algorithm) in such a setting. Some issues remain unaddressed, notably the relation between the size of natural areas and the resilience and evolutionary potential of its ecosystems. Moreover, experimentation should be small scale and carefully monitored; decisions and investments with extremely long time commitments should be extremely carefully evaluated. Developing policy models with evolutionary features may lead to elaboration of these general insights.

6. Conclusions

The goal of sustainable development has often been regarded as a break with traditional thinking and practice. This seems to invite replacing or at least complementing static, equilibrium oriented approaches of research by dynamic, evolutionary ones. It was shown that there are many choices open then, as evolutionary theory is not well-bounded, and quite diverse of content, which may be regarded as consistent with one of its core concepts. Evolutionary theory as applied to economics and environmental economics is broader than evolutionary biology, which in turn is broader than Darwinian selection. Punctuated equilibria, sorting mechanisms and co-evolution are some important additions to the original theory. Although economics can learn much from modern evolutionary biology, distinctive features of economic evolution should be recognized. For instance, ideas may be preserved so that extinction is never so absolute as in natural history, while technologies developed and lessons learned in one sector can be quite easily transferred to other sectors.

Several general implications of contemporary evolutionary theory are important to environmental economics. Evolution implies a focus on complementarity rather than substitution. Evolution implies that there cannot exist any economic equilibrium so that the link between market outcomes and social welfare becomes less clear. As a result, economic valuation becomes less useful for social decision-making, and the economic theory of environmental policy loses its basis. Irreversibility and historical lock-in of technologies severely constrain (re)allocation of natural resources over time, or, in other words, an optimum based on equilibrium theory would face severe implementation barriers. System diversity may be maximized to sustain “evolutionary potential” and realize much adaptive flexibility necessary for “resilience”, which is consistent with the “precautionary principle”. It will be exciting to see some of these ideas elaborated in theoretical models or empirical studies.

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