# THE DEVELOPMENT OF AN ECOLOGICAL ECONOMICS

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## Historical Roots and Motivations

Ecology and economics have developed as separate disciplines throughout their recent histories in the 20th century. While each has addressed the way in which living systems self-organize to enable individuals and communities to meet their goals, and while each has borrowed theoretical concepts from the other and shared patterns of thinking with other sciences, they began with different first principles, addressed separate issues, utilized different assumptions to reach answers, and supported different interests in the policy process. Bringing these domains of thought together and attempting to reintegrate the natural and social sciences has lead to what we call ecological economics. After numerous experiments with joint meetings between economists and ecologists in the 1980's (e.g. Jansson 1984), the International Society for Ecological Economics (ISEE) was formed in 1988, the journal, Ecological Economics, was initiated and published its first issue in February of 1989 (currently publishing 12 issues per year), and major international conferences have brought together ecologists, economists and a broad range of other scientists and practitioners. Several ecological economic institutes have been formed around the world, and a significant number of books have appeared with the term ecological economics in their titles (e.g. Martinez Alier 1987, Costanza 1991, Peet 1992, The Group of Green Economists 1992, Jansson et al 1994, Barbier et al. 1994, Costanza et al. 1997a, Edward-Jones et al. 2000).

As Martinez-Alier (1987) and Cleveland (1987) point out, ecological economics has historical roots as long and deep as any field in economics or the natural sciences, going back to at least the 17th century. Nevertheless, its immediate roots lie in work done in the 1960s and 1970s. Kenneth Boulding's classic "The economics of the coming spaceship Earth" (Boulding 1966) set the stage for ecological economics with its description of the transition from the "frontier economics" of the past, where growth in human welfare implied growth in material consumption, to the "spaceship economics" of the future, where growth in welfare can no longer be fueled by growth in material consumption. This fundamental difference in vision and world view was elaborated further by Daly (1968) in recasting economics as a life science - akin to biology and especially ecology, rather than a physical science like chemistry or physics. The importance of this shift in "pre-analytic vision" (Schumpeter 1950) cannot be overemphasized. It implies a fundamental change in the perception of the problems of resource allocation and how they should be addressed. More particularly, it implies that the focus of analysis should be shifted from marketed resources in the economic system to the biophysical basis of interdependent ecological and economic systems, (Clark, 1973; Martinez-Alier, 1987; Cleveland, 1987; and Christensen, 1989).

The broader focus of ecological economics is carried in a 'systems' framework. The systems approach, with its origins in non-linear mathematics, general systems theory, non-equilibrium thermodynamics, and ecosystem ecology, is a comparatively recent development that has opened up lines of inquiry that were off the agenda for earlier work in what Lotka termed biophysical economics (Clark 1976, Cleveland 1987, Martinez-Alier 1987, Christensen 1989, Clark and Munroe 1994). While bioeconomic and ecological economic models both incorporate the dynamics of the natural resources under exploitation, the former tend to take a partial rather than a general equilibrium approach (van der Ploeg et al. 1987).

The core problem addressed in ecological economics is the sustainability of interactions between economic and ecological systems. Ecological economics addresses the relationships between ecosystems and economic systems in the broadest sense (Costanza 1991). It involves issues that are fundamentally cross-scale, transcultural and transdisciplinary, and calls for innovative approaches to research, to policy and to the building of social institutions (Costanza and Daly 1987, Common and Perrings 1992, Holling 1994, Berkes and Folke 1994, d'Arge 1994, Golley 1994, Viederman 1994). In this sense, ecological economics tends to be characterized by a holistic "systems" approach that goes beyond the normal territorial boundaries of the academic disciplines.

## Basic Organizing Principles of Ecological Economics

Ecological economics is not a single new discipline based in shared assumptions and theory. It rather represents a commitment among natural and social scientists, and practitioners, to develop a new understanding of the way in which different living systems interact with one another, and to draw lessons from this for both analysis and policy. Ecological economics is conceptually pluralistic. This means that even while people writing in ecological economics were trained in a particular discipline (and may prefer that mode of thinking over others) they are open to and appreciative of other modes of thinking and actively seek a constructive dialogue among disciplines (Norgaard 1989). There is not one right approach or model because, like the blind men and the elephant, the subject is just too big and complex to touch it all with one limited set of perceptual or computational tools.

Within this pluralistic paradigm, traditional disciplinary perspectives are perfectly valid as part of the mix. Ecological economics therefore includes some aspects of environmental economics, traditional ecology and ecological impact studies, and several other disciplinary perspectives as components, but it also encourages completely new, hopefully more integrated, ways to think about the linkages between ecological and economic systems.

The broad spectrum of relationships between ecosystems and economic systems are the locus of many of our most pressing current problems (i.e. sustainability, acid rain, global warming, species extinction, wealth distribution) but they are not covered adequately by any existing discipline. Environmental and resource economics, as they are usually practiced, are subdisciplines of economics focused on the efficient allocation of scarce environmental resources but generally ignoring ecosystem dynamics and scale issues, and paying only scant attention to distribution issues (Cropper and Oates 1992). Ecology, as it is currently practiced, sometimes deals with human impacts on ecosystems, but the more common tendency is to stick to "natural" systems and exclude humans. Ecological economics aims to extend these modest areas of overlap. Its basic organizing principles include the idea that ecological and economic systems are complex, adaptive, living systems that need to be studied as integrated, co-evolving systems in order to be adequately understood (Holling 1986, Proops 1989, Costanza et al. 1993).

Ecological economics also focuses on a broader set of goals than the traditional disciplines. Here, again, the differences are not so much the newness of the goals, but rather the attempt to integrate them. Daly (1992) lays out these goals in a hierarchical form as:

(1) assessing and insuring that the scale of human activities within

the biosphere are ecologically sustainable;

(2) distributing resources and property rights fairly, both within the current generation of humans and between this and future generations, and also between humans and other species; and

(3) efficiently allocating resources as constrained and defined by 1 and 2 above, including both marketed and non-marketed resources, especially natural capital and ecosystem services.

That these goals are interdependent and yet need to be addressed hierarchically is elaborated by Common and Perrings (1992), who differentiate between "Solow" or economic sustainability (Solow 1974, 1986) and "Holling" or ecological sustainability (see Holling 1986) and find them to be largely disjoint. The problem of ecological sustainability needs to be solved at the level of preferences or technology, not at the level of optimal prices. Only if the preferences and production possibility sets informing economic behavior are ecologically sustainable can the corresponding set of optimal and intertemporally efficient prices be ecologically sustainable. Thus the principle of "consumer sovereignty" on which most conventional economic solutions is based, is only acceptable to the extent that consumer interests do not threaten the overall system - and through this the welfare of future generations. This implies that if one's goals include ecological sustainability then one cannot rely on consumer sovereignty, and must allow for co-evolving preferences, technology, and ecosystems. One of the basic organizing principles of ecological economics is thus a focus on this complex interrelationship between ecological sustainability (including system carrying capacity and resilience), social sustainability (including distribution of wealth and rights and coevolving preferences) and economic sustainability (including allocative efficiency).

A major implication of this is that our ability to predict the consequences of economic behavior is limited by our ability to predict the evolution of the biosphere. The complexity of the many interacting systems that make up the biosphere means that this involves a very high level of uncertainty. Indeed, uncertainty is a fundamental characteristic of all complex systems involving irreversible processes (Costanza and Cornwell 1992, Ludwig et al. 1993, Costanza 1994, Clark and Munro 1994). It follows that ecological economics is particularly concerned with problems of uncertainty. More particularly, it is concerned with the problem of assuring sustainability under uncertainty. Instead of locking ourselves into development paths that may ultimately lead to ecological collapse, we need to maintain the resilience of ecological and socioeconomic systems (Hammer et al. 1993; Holling 1994, Jansson and Jansson 1994, Perrings 1994) by conserving and investing in natural assets (Costanza and Daly 1992).

## Material and Energy Flows in Ecological and Economic Systems: Theory and Applications

One focus of the work on joint ecological economic systems has been material and energy flows. A dominant theme in this body of work has been the grounding of conventional economic models in the biophysical realities of the economic process. This emphasis shifts the focus from exchange to the production of wealth itself (Cleveland et al. 1984). Cleveland (1987) traces the early roots of this work dating back to the Physiocrats (Quesnay 1758, Podilinsky 1883, Soddy 1922, Lotka 1922, and Cottrell 1955). The energy and environmental events of the 1960's and 1970's pushed work in this area to new levels. Energy and material flow analysis in recent times is rooted in the work of a number of economists, ecologists, and physicists. Economists such as Boulding (1966) and Geogescu-Roegen (1971, 1973) demonstrated the environmental and economic implications of the mass and energy balance principle. Ecologists such as Lotka (1922) and Odum (Odum and Pinkerton 1955, Odum 1971) pointed out the importance of energy in the structure and evolutionary dynamics of ecological and economic systems. And physicists such as Prigogine (Nicolis and Prigogine 1977, Prigogine and Stengers 1984) worked out the far-from-equilibrium thermodynamics of living systems.

The principle of the conservation of mass and energy has formed the basis for a number of important contributions. The assumption was first made explicit in the context of a general equilibrium model by Ayres and Kneese (1969) and subsequently by Mäler (1974), but it also is a feature of the series of linear models developed after 1966 (Cumberland 1966, Victor 1972, Lipnowski 1976, Geogescu-Roegen 1977). All reflect the assumption that a closed physical system must satisfy the conservation of mass condition, and hence that economic growth necessarily increases both the extraction of environmental resources and the volume of waste deposited in the environment.

Perrings (1986, 1987) developed a variant of the Neumann-Leontief-Sraffa general equilibrium model in the context of a jointly determined economy-environment system subject to a conservation of mass constraint. The model demonstrates that the conservation of mass contradicts the free disposal, free gifts, and non-innovation assumptions of such models. An expanding economy causes continuous disequilibrating change in the environment. Since market prices in an interdependent economy-environment system often do not accurately reflect environmental change, such transformations of the environment often will go unanticipated.

Ayres (1978) describes some of the important implications of the laws of thermodynamics for the production process, including the limits they place on the substitution of human capital for natural capital and the ability of technical change to offset the depletion or degradation of natural capital. Although they may be substitutes in individual processes in the short run, natural capital and human-made capital ultimately are complements because both manufactured and human capital require materials and energy for their own production and maintenance (Costanza 1980). The interpretation of traditional production functions such as the Cobb-Douglas or constant elasticity of substitution (CES) must be modified to avoid the erroneous conclusion that "self-generating technological change" can maintain a constant output with ever-decreasing amounts of energy and materials as long as ever-increasing amounts of human capital are available.

Furthermore, there are irreducible thermodynamic minimum amounts of energy and materials required to produce a unit of output that technical change cannot alter. In sectors that are largely concerned with processing and/or fabricating materials, technical change is subject to diminishing returns as it approaches these thermodynamic minimums (Ayres 1978). Ruth (1995) uses equilibrium and non-equilibrium thermodynamics to describe the materials-energy-information relationship in the biosphere and in economic systems. In addition to illuminating the boundaries for material and energy conversions in economic systems, thermodynamic assessments of material and energy flows, particularly in the case of effluents, can provide information about depletion and degradation that are not reflected in market price.

There is also the effect of the time rate of thermodynamic processes on their efficiency, and more importantly, their power or rate of doing useful work. Odum and Pinkerton (1955) pointed out that to achieve the thermodynamic minimum energy requirements for a process implied running the process infinitely slowly. This means at a rate of production of useful work (power) of zero. Both ecological and economic systems must do useful work in order to compete and survive and Odum and Pinkerton showed that for maximum power production an efficiency significantly worse than the thermodynamic minimum was required.

These biophysical foundations have been incorporated into models of natural resource supply and of the relationship between energy use and economic performance. Cleveland and Kaufmann (1991) developed econometric models that explicitly represent and integrate the geologic, economic, and political forces that determine the supply of oil in the United States. Those models are superior in explaining the historical record than those from any single discipline. Larsson et al. (1994) also use energy and material flows to demonstrate the dependence of a renewable resource such as commercial shrimp farming on the services generated by marine and agricultural ecosystems.

One important advance generated by this work is the economic importance of energy quality, namely, that a kcal of primary electricity can produce more output than an kcal of oil, a kcal of oil can produce more output than an kcal of coal, and so on. Odum (1971) describes how energy use in ecological and economic hierarchies tends to increase the quality of energy, and that significant amounts of energy are dissipated to produce higher quality forms that perform critical control and feedback functions which enhance the survival of the system. Cleveland et al. (1984) and Kaufmann (1992) show that much of the decline in the energy/real GDP ratio in industrial nations is due to the shift from coal to petroleum and primary electricity. Their results show that autonomous energy-saving technical change has had little, if any, effect on the energy/real GDP ratio. Stern (1993) finds that accounting for fuel quality produces an unambiguous causal connection between energy use and economic growth in the United States, confirming the unique, critical role that energy plays in the production of wealth.

The analysis of energy flows has also been used to illuminate the structure of ecosystems (e.g. Odum, 1957). Hannon (1973) applied input-output analysis (originally developed to study interdependence in economies) to the analysis of energy flow in ecosystems. This approach quantifies the direct plus indirect energy that connects an ecosystem component to the remainder of the ecosystem. Hannon demonstrates this methodology using energy flow data from the classic study of the Silver Springs, Florida food web (Odum, 1957). These approaches hold the possibility of treating ecological and economic systems in the same conceptual framework - one of the primary goals of ecological economics (Hannon et al. 1986, 1991, Costanza and Hannon 1989).

## Accounting for Natural Capital, Ecological Limits, and Sustainable Scale

Most current economic policies are largely based on the underlying assumption of continuing and unlimited material economic growth. Although this assumption is slowly beginning to change as the full implications of a commitment to sustainability sink in, it is still deeply imbedded in economic thinking as evidenced by the frequent equation of "sustainable development" with "sustainable growth". The growth assumption allows problems of intergenerational, intragenerational, and interspecies equity and sustainability to be ignored (or at least postponed), since they are seen to be most easily solved by additional material growth (Arrow et al 1995). Indeed, most conventional economists define "health" in an economy as a stable and high rate of growth. Energy and resource depletion, pollution, and other limits to growth, according to this view, will be eliminated as they arise by clever development and deployment of new technology. This line of thinking often is called "technological optimism" (Costanza 1989, 2000).

An opposing line of thought (often called "technological skepticism") assumes that technology will not be able to circumvent fundamental energy, resource, or pollution constraints and that eventually material economic growth will stop. It has usually been ecologists or other life scientists (e.g. Ehrlich 1989, Daily and Ehrlich 1992 - chapter 28) that take this point of view (notable exceptions among economists are Boulding, 1966, and Daly, 1968, 1977), largely because they study natural systems that invariably do stop growing when they reach fundamental resource constraints. A healthy ecosystem is one that maintains a relatively stable level. Unlimited growth is cancerous, not healthy, under this view.

Technological optimists argue that human systems are fundamentally different from other natural systems because of human intelligence and that history has shown that resource constraints can be circumvented by new ideas (Myers and Simon 1994). Technological optimists claim that Malthus' dire predictions about population pressures have not come to pass and the "energy crisis" of the late 70's is behind us. Technological skeptics, on the other hand, argue that many natural systems also have "intelligence" in that they can evolve new behaviors and organisms (including humans themselves). Humans are therefore a part of nature not apart from it. Just because we have circumvented local and artificial resource constraints in the past does not mean we can circumvent the fundamental ones that we will eventually face. Malthus' predictions have not come to pass yet for the entire world, the skeptics would argue, but many parts of the world are in a Malthusian trap now, and other parts may well fall into it. This is particularly important because many industrial nations have increased their numbers and standard of living by importing carrying capacity and exporting ecological degradation to other regions.

The debate has gone on for several decades now. It began with Barnett and Morse's (1963) "Scarcity and growth" but really got into high gear only with the publication of "The limits to growth" by Meadows et al. (1972) and the Arab oil embargo in 1973. Several thousand studies over the last fifteen years have considered aspects of our energy and resource future, and different points of view have waxed and waned. But the bottom line is that there is still considerable uncertainty about the impacts of energy and resource constraints. In the next 20-30 years we may begin to hit real fossil fuel supply limits. Will fusion energy or solar energy or conservation or some as yet unthought of energy source step in to save the day and keep economies growing? The technological optimists say 'yes' and the technological skeptics say 'maybe' but let's not count on it. Ultimately, no one knows.

The more specific issues of concern all revolve around the question of limits: the ability of technology to circumvent them, and the long run costs of the technological "cures." Do we adapt to limits with technologies that have potentially large but uncertain future environmental costs or do we limit population and per capita consumption to levels sustainable with technologies which are known to be more environmentally benign? Must we always increase supply or can we also reduce demand? Is there an optimal mix of the two?

If the 'limits' are not binding constraints on economic activity, then conventional economics' relegation of energy and environmental concerns to the side of the stage is probably appropriate, and detailed energy analysis are nothing more than interesting curiosities. But if the limits are binding constraints, then energy and environmental issues are pushed much more forcefully to center stage and the tracking of energy and resource flows through ecological and economic systems becomes much more useful and important.

Issues of sustainability are ultimately issues about limits. If material economic growth is sustainable indefinitely by technology then all environmental problems can (in theory at least) be fixed technologically Issues of fairness, equity, and distribution (between subgroups and generations of our species and between our species and others) are also issues of limits. We do not have to worry so much about how an expanding pie is divided, but a constant or shrinking pie presents real problems. Finally, dealing with uncertainty about limits is the fundamental issue. If we are unsure about future limits the prudent course is to assume they exist. One does not run blindly through a dark landscape that may contain crevasses. One assumes they are there and goes gingerly and with eyes wide open, at least until one can see a little better.

Vitousek et al. (1986) in an oft-cited paper estimated the percent of the earth's net primary production (NPP) which is being appropriated by humans. This was the first attempt to estimate the "scale" or relative size of human economic activity compared to the ecological life support system. They estimated that 25% of total NPP (including the oceans) and 40% of terrestrial NPP was currently being appropriated by humans. It left open the question of how much of NPP could be appropriated by humans without damaging the life support functions of the biosphere, but it is clear that 100% is not sustainable and even the 40% of terrestrial NPP currently used may not be sustainable. Daily and Ehrlich (1992) add more depth to these arguments by considering the relationships between the size and relative impact of the human population relative to the earth's carrying capacity and the implications for sustainability. Arrow et al. (1995) add a recent interdisciplinary consensus on this relationship.

A related idea is that ecosystems represent a form of capital - defined as a stock yielding a flow of services -- and that this stock of "natural capital" needs to be maintained intact independently in order to assure ecological sustainability (El Serafy 1991, Victor 1991, Costanza and Daly 1992). The question of whether natural capital needs to be maintained independently ("strong sustainability") or whether only the total of all capital stocks need to be maintained ("weak sustainability") has been the subject of some debate. It hinges on the degree to which human-made capital can substitute for natural capital, and, indeed, on how one defines capital generally (Victor 1991). In general, conventional economists have argued that there is almost perfect substitutability between natural and human-made capital (Nordhaus and Tobin 1972), while ecological economists generally argue on both theoretical (Costanza and Daly 1992) and empirical grounds (Kaufmann 1995) that the possibilities for substitution are severely limited. They therefore generally favor the strong sustainability position.

Another critical set of issues revolve around the way we define economic income, economic welfare, and total human welfare. Daly and Cobb (1989) clearly distinguish these concepts, and point out that conventional GNP is a poor measure of even economic income. Yet GNP continues to be used in most policy discussions as the measure of economic health and performance, and will continue to be until viable alternatives are available. According to Hicks (1948) economic income is defined as the quantity we can consume without damaging our future consumption possibilities. This definition of income automatically embodies the idea of sustainability. GNP is a poor measure of income on a number of grounds, including the fact that it fails to account for the depletion of natural capital (Mäler 1991) and thus is not "sustainable" income in the Hicksian sense. GNP is an even poorer measure of economic welfare, since many components of welfare are not directly related to income and consumption. The Index of Sustainable Economic Welfare (ISEW) devised by Daly and Cobb (1989) is one approach to estimating economic welfare (as distinct from income) that holds significant promise. [Editor's Note: for a brief description of this index, see footnote 7 in the chapter by Daly and Cobb in this volume.] The ISEW has been calculated for several industrialized countries and shows that in all these cases, an "economic threshold" has been passed where increasing GNP in no longer contributing to increasing welfare, and in fact in most cases is decreasing it (Max-Neef, 1995).

### Valuation of Ecological Services

All decisions concerning the allocation of environmental resources imply the valuation of those resources. Ecological economics does not eschew valuation. It is recognized that the decisions we make, as a society, about ecosystems imply a valuation of those systems. We can choose to make these valuations explicit or not; we can undertake them using the best available ecological science and understanding or not; we can do them with an explicit acknowledgment of the huge uncertainties involved or not; but as long as we are forced to make choices about the use of resources we are valuing those resources. These values will reflect differences in the underlying world view and culture of which we are a part (e.g. Costanza 1991, Berkes and Folke 1994), just as they will reflect differences in preferences, technology, assets and income. An ecological economics approach to valuation implies an assessment of the spatial and temporal dynamics of ecosystem services, and their role in satisfying both individual and social preferences. It also implies explicit treatment of the uncertainties associated with tracking these dynamics (Costanza et al. 1993).

Ecological economics is different from environmental economics in this regard in terms of the latitude of approaches to the ecosystem valuation problem it allows. It includes more conventional willingness to pay (WTP) based approaches, but it also explores other more novel methods based on explicitly modeling the linkages between ecosystems and economic systems in the long run (Costanza and Folke 1997). Costanza et al. (1989) explore this comparison by estimating both WTP based and energy analysis based values for wetlands in coastal Louisiana, and find an interesting degree of agreement. This emphasis on the direct assessment of ecosystem functions and values, independently and prior to attempting to tie it to people's perceptions of those functions and values, is extended in de Groot (1994) and Larsson et al. (1994), who enumerate these functions and estimate them for an example in Columbia, respectively. A more recent study (Costanza et al. 1997) synthesized a range of previous studies using a variety of techniques and estimated the total global value of ecosystem services at 16-54 trillion $US/yr -- in the same order of magnitude as global GNP.

Spash and Hanley (1995) look at the issues of preference formation and limited information in estimating WTP based values for biodiversity preservation. They conclude on empirical grounds that a significant portion of individuals exhibit "lexicographic" preferences - that is they refuse to make trade-offs which require the substitution of biodiversity for other goods. This places significant constraints on the use of stated preferences, as used in contingent valuation studies, for valuation of ecosystem services and decision making. It places more emphasis on the need to develop more direct methods to assess the value of these resources as a supplement to conventional WTP based methods.

Bingham et al. (1995) provide a broad interdisciplinary consensus and summary of these issues, which resulted from a US EPA funded policy forum on ecosystem valuation. The forum emphasized the need to develop "decisive information" relevant to management problems and choices.

The issue of ecosystem valuation is far from solved. In fact it is probably only in the early stages of development. Conventional WTP based approaches have severe limitations. Key directions for the future pointed to in Bingham et al. (1995) and Costanza et al. (1997) include integrated ecological economic modeling, as elaborated in the next section.

## Integrated Ecological Economic Modeling and Assessment

The emphasis on (a) issues of scale and limits to the carrying and assimilative capacity of ecological systems, and (b) underlying dynamics of those systems both imply the need for a new approach to the modeling of joint systems. It is not surprising, therefore, that this is an active area of research in ecological economics. Indeed, it is where we most expect new advances to be made as a result of the ongoing dialogue between economists and ecologists.

The range of issues that need to be addressed in attempting to integrate economic and ecological models was first explored by Braat and van Lierop (1987). While the next steps are likely to be even harder, as we shall see later, they indicate just how difficult it is to take even the first steps in bridging the modeling gap between disciplines that have long diverged both methodologically and conceptually. Costanza, Sklar and White (1990), Hall and Hall (1993), Bockstael et al (1995) and Voinov et al. (1999) illustrate some of the reasons why this is so, while developing new types of ecological economic models to overcome these difficulties. One reason for the difficulty in bridging the modeling gap is that economics, as a discipline, has developed almost no tools or concepts to handle spatial differentiation beyond the notions of transport cost and international trade. The spatial analysis of human activity has been seen as the domain of geographers, and has had remarkably little impact on the way that economists have analyzed the allocation of resources. This makes collaboration between economists and disciplines based more directly on spatial analysis very difficult. Yet, recent work in this area shows just how important an understanding of economic and ecological landscapes is to the development of integrated models. The program of research, is having to develop new concepts as well as new models to deal with this problem. Liu, Cubbage and Pulliam (1994) offer another example of the importance of landscape in identifying the economic implications of such familiar concepts as forest rotation times. Since the development of spatially explicit integrated models is one of the areas in which ecological economics is expected to develop most rapidly in the next few years, it would seem that geographers are likely to become an increasingly important part of the research agenda in ecological-economics.

A second characteristic of ecological-economic models concerns the way in which the valuation of ecological functions and processes is reflected in the model structure. The point was made in the previous section that valuation by stated preference methods (estimation of willingness to pay or accept using contingent valuation or contingent ranking) may capture the strength of people's perceptions and their level of income and endowments (their ability to pay), but it generally fails to capture the impact of a change in ecosystem functions and processes on the output of economically valued goods and services. Unless the role of non-marketed ecological functions and processes in the production of economically valued goods and services is explicitly modeled, it is hard to see how they can be properly accounted for in economic decision-making. Barbier (1994) and Ruitenbeek (1994) illustrate ways in which ecological functions and processes are embedded in decision-models, and the implications this has for valuation.

A third characteristic concerns the role of integrated modeling in strategic decision-making. One of the challenges to ecological economics has been to devise methods to address strategic 'what if' questions in a way that reflects the dynamics of the jointly determined system. This is clearly an extremely difficult task, and we indicate some of the reasons why this is so momentarily. Baker, Fennesy and Mitsch (1991) and Duchin and Lange (1994) illustrate different approaches to the task at the microeconomic and macroeconomic levels respectively. The general problem confronting anyone attempting to model long-run dynamics explicitly is that ecological economic systems are complex non-linear systems. The dynamics of economic systems are not independent of the dynamics of the ecological systems which constitute their environment, and that as economies grow relative to their environment, the dynamics of the jointly determined system can become increasingly discontinuous (Perrings 1986, Costanza et al 1993, Arrow et al. 1995). Indeed, the development of ecological economics can be thought of as part of a widespread reappraisal of such systems.

In ecology, this reappraisal has influenced recent research on scale, complexity, stability and resilience; and is beginning to influence the theoretical treatment of the coevolution of species and systems. The results that are most important to the development of ecological economics concern the link between the spatial and temporal structure of coevolutionary hierarchical systems. Landscapes are conceptualized as hierarchies, each level of which involves a specific temporal and spatial scale (Holling 1987, 1992, Costanza et al. 1993). The dynamics of each level of the structure are predictable so long as the biotic potential of the level is consistent with bounds imposed by the remaining levels in the hierarchy. Change in either the structure of environmental constraints or the biotic potential of the level may induce threshold effects that lead to complete alteration in the state of the system (O'Neill, Johnson and King, 1989).

In economics there is now considerable interest in the dynamics of complex non-linear systems (Anderson et al. 1988, Brock and Malliaris 1989, Goodwin 1990, Puu 1989, Hommes 1991, Benhabib 1992). Economists have paid less attention to spatial scale and its significance at or near system thresholds (though see Puu 1981, Rosser 1990), but there is now a growing body of literature with roots in geography which seeks to inject a spatial dimension into nonlinear economic models (see for example White, 1990). There is also an economic analog to the biologist's interest in evolution and the significance of codependence between gene landscapes. The steady accumulation of evidence that economic development is not a stationary process, that human understanding, preferences and technology all change with development and that such change is generally non-linear and discontinuous, has prompted economists to seek to endogenize technological change (Romer 1990). Although the adaptation of this work by environmental economists has been rather disappointing, the treatment of technology and consumption preferences as endogenous to the economic process is a fundamental change that brings economics much closer to ecology.

The challenge to ecological economics in the future is to develop models that capture these features well enough to incorporate at least the major risks in economic decisions that increase the level of stress on ecological systems.

## Summary and Conclusions

This paper is a sample of the range of transdisciplinary thinking that can be put under the heading of ecological economics and the theories and models that have informed that work. While it is difficult to categorize ecological economics in the same way one would a normal academic discipline, some general characteristics can be enumerated.

- the core problem is the sustainability of interactions between economic and ecological systems.
- an explicit attempt is made at pluralistic dialogue and integration across disciplines, rather than territorial disciplinary differentiation.
- an emphasis is placed on integration of the three hierarchical goals of sustainable scale, fair distribution, and efficient allocation.
- there is a deep concern with the biophysical underpinnings of the functioning of jointly determined ecological and economic systems.
- there is a deep concern with the relationship between the scale of economic activity and the nature of change in ecological systems.
- since valuation based on stated willingness to pay reflects limitations in the valuer's knowledge of ecosystems functions, there is an emphasis on the development of valuation techniques that build on an understanding of the role of ecosystem functions in economic production.
- there is a broad focus on systems and systems dynamics, scale, and hierarchy and on integrated modeling of ecological economic systems.

These characteristics make ecological economics applicable to some of the major problems facing humanity today, which occur at the interfaces of human and natural systems, and especially to the problem of assuring humanity's health and survival within the biosphere into the indefinite future. It is not so much the individual core scientific questions that set ecological economics apart - since these questions are covered independently in other disciplines as well - but rather the treatment of these questions in an integrated, transdisciplinary way, which we feel is essential to their understanding and the development of effective policies. The solutions being considered in ecological economics are deserving of increasing attention.

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