Structural Change and Economic Dynamics, vol. 2, no. 2, 1991

ECOLOGICAL ECONOMICS: A RESEARCH AGENDA

ROBERT COSTANZA[1]

Ecological economics is a new *transdisciplinary* approach that looks at the full range of inter-relationships between ecological and economic systems. This breadth is essential if we are to understand and manage our planet wisely in the face of mounting interdependent global environmental, population, and economic development problems. This paper summarizes the state and goals of this emerging transdisciplinary field, particularly as regards issues of sustainability, and provides a working agenda for research. Assuring sustainability of ecological economic systems depends on our ability to make local and short-term goals and incentives (like local economic growth and private interests) consistent with global and long-term goals (like sustainability and global welfare). This requires: (1) establishing a hierarchy of goals for local, national, and global ecological economic planning and management; (2) developing better regional and global ecological economic modelling capabilities to allow us to see the range of possible outcomes of our current activities; (3) adjusting prices and other local incentives to reflect long run, global ecological costs, *including uncertainty*; and (4) developing policies that lead to no further decline in the stock of *natural capital.*

1. AN ECOLOGICAL ECONOMIC WORLD VIEW

There is increasing awareness that our global ecological life support system is endangered, and decisions made on the basis of local, narrow, short-term criteria can produce disastrous results globally and in the long run. There is also increasing awareness that traditional economic and ecological models and concepts fall short in their ability to deal with these problems.

Ecological economics is a new *transdisciplinary* field of study that addresses the relationships between ecosystems and economic systems in the broadest sense. These relationships are central to many of humanity's current problems and to building a sustainable future, but are not well covered by any existing scientific discipline.

By transdisciplinary we mean that ecological economics goes beyond the normal conceptions of scientific disciplines and tries to integrate and synthesize many different disciplinary perspectives. It is not a new discipline, but rather a new pluralistic way of looking at problems. One way it does this is by focusing more directly on the problems, rather than on the particular intellectual tools and models used to solve them, and by ignoring arbitrary intellectual turf boundaries.

[1] Director, Maryland International Institute for Ecological Economics, Center for Environmental and Estuarine Studies, University of Maryland, Solomons, MD 20688-0038, USA.

No discipline has intellectual precedence in an endeavour as important as achieving sustainability. While the intellectual tools we use in this quest are important, they are secondary to the goal of solving the critical problems of managing our use of the planet. We must transcend the focus on tools and techniques so that we avoid being 'a person with a hammer to whom everything looks like a nail'. Rather we should consider the task, evaluate existing tools' abilities to handle the job, and design new ones if the existing tools are ineffective. Ecological economics will use the tools (theory and models) of conventional economics and ecology as appropriate. The need for new intellectual tools and models may emerge where the coupling of economics and ecology is not possible with the existing tools.

1.1. *How is Ecological Economics Different from Conventional Approaches?*

Ecological economics differs from both conventional economics and conventional ecology in terms of the breadth of its perception of the problem, and the importance it attaches to environment–economy interactions. It takes this wider and longer view in terms of space, time, and the parts of the system to be studied.

Figure 1 illustrates one aspect of the relationship: the domains of the different subdisciplines. The upper left box represents the domain of 'conventional' economics, the interactions of economic sectors (like mining, manufacturing, or households) with each other. The domain of 'conventional' ecology is the lower

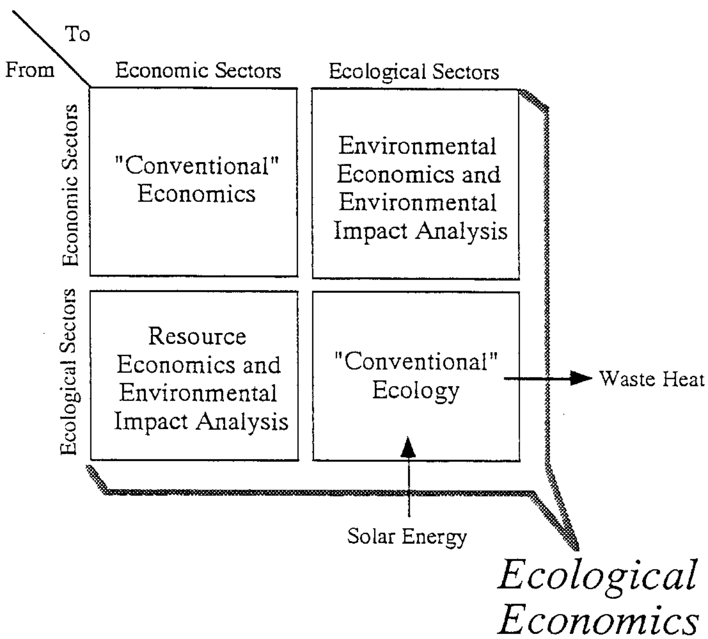

FIG. 1. The domains of conventional economics, conventional ecology, environmental and resource economics, and ecological economics.

right box, the interactions of ecosystems and their components with each other. The lower left box represents the inputs from ecological sectors to economic sectors. This is the usual domain of *resource* economics and environmental impact analysis: the use of renewable and non-renewable natural resources by the economy. The upper right box represents the 'use' by ecological sectors of economic 'products'. The products of interest in this box are generally unwanted by-products of production and the ultimate wastes from consumption. This is the usual domain of *environmental* economics and environmental impact analysis: pollution and its mitigation, prevention and mediation. Ecological economics encompasses and transcends these disciplinary boundaries. Ecological economics sees the human economy as part of a larger whole. Its domain is the entire web of interactions between economic and ecological sectors.

Table 1 presents some of the other major differences between ecological economics, conventional economics, and conventional ecology. Of course, these 'conventional' views are strawmen set up merely to sharpen the contrasts and have an unwanted side effect of masking the great diversity of views that are actually present in both ecology and economics. With this caveat in mind, they do still serve as a useful expository aid.

The basic world view of conventional economics is one in which individual human consumers are the central figures. Their tastes and preferences are taken as given and are the dominant, determining force. The resource base is viewed as essentially limitless due to technical progress and infinite substitutability. Ecological economics takes a more holistic view with humans as one component (albeit a very important one) in the overall system. Human preferences, understanding, technology, and cultural organization all co-evolve to reflect broad ecological opportunities and constraints.

This basic world view is similar to that of conventional ecology in which the resource base is limited and humans are just another (albeit seldom studied) species. However, ecological economics differs from conventional ecology in the importance it gives to humans as a species and its emphasis on the mutual importance of cultural and biological evolution.

The concept of *evolution* is a guiding notion for both ecology and ecological economics (Boulding, 1991). Evolution is the process of change in complex systems through selection of transmittable traits. Whether these traits are the shapes and programmed behavioural characteristics of organisms transmitted genetically or the institutions and behaviours of cultures which are transmitted through cultural artifacts, books, and tales around the campfire, they are both evolutionary processes. Evolution implies a dynamic and adapting non-equilibrium system, rather than the static equilibrium system often assumed in conventional economics. Evolution does *not* imply change in a particular direction (i.e. progress).

Ecological economics uses an expanded definition of the term 'evolution' to encompass both biological and cultural change. Biological evolution is slow relative to cultural evolution. The price human cultures pay for their ability to adapt rapidly is the danger that they have become too dependent on short-run

TABLE 1. *Comparison of Conventional Economics and Ecology with Ecological Economics*

	Conventional economics	*Conventional ecology*	*Ecological economics*
Basic world view	Mechanistic, static, atomistic Individual tastes and preferences taken as given and the dominant force. The resource base viewed as essentially limitless due to technical progress and infinite substitutability.	Evolutionary, atomistic Evolution acting at the genetic level viewed as the dominant force. The resource base is limited. Humans are just another species but are rarely studied.	Dynamic, systems, evolutionary Human preferences, understanding technology and organization co-evolve to reflect broad ecological opportunities and constraints. Humans are responsible for understanding their role in the larger system and managing it for sustainability.
Time frame	Short 50 years maximum, 1–4 years usual.	Multi-scale Days to eons, but time scales often define non-communicating subdisciplines.	Multi-scale Days to eons, multiscale synthesis.
Space frame	Local to international Framework invariant at increasing spatial scale, basic units change from individuals to firms to countries.	Local to regional Most research has focused on relatively small research sites in single ecosystems, but larger scales becoming more important recently.	Local to global Hierarchy of scales.
Species frame	Humans only Plants and animals only rarely included for contributory value.	Non-humans only Attempts to find 'pristine' ecosystems untouched by humans.	Whole ecosystem including humans Acknowledges interconnections between humans and rest of nature.
Primary micro goal	Max profits (firms) Max utility (individuals) All agents following micro goals leads to a macro goal being fulfilled. External costs and benefits given lip service but usually ignored.	Max reproductive success All agents following micro goals leads to macro goal being fulfilled.	Must be adjusted to reflect system goals Social organization and cultural institutions at higher levels of the space–time hierarchy ameliorate conflicts produced by myopic pursuit of micro goals at lower levels, and visa versa.
Assumptions about technical progress	Very optimistic	Pessimistic or no opinion	Prudently sceptical
Academic stance	Disciplinary Monistic, focus on mathematical tools.	Disciplinary More pluralistic than economics, but still focused on tools and techniques. Few rewards for comprehensive, integrative work.	Transdisciplinary Pluralistic, focus on problems.

payoffs and, consequently, usually ignore long-term payoffs and issues of sustainability. Biological evolution imposes a built-in long-run constraint that cultural evolution does not have. To ensure sustainability we may have to reimpose long-run constraints by developing institutions (or using the ones we have more effectively) to bring the global, long-term, multi-species, multi-scale, whole systems perspective to bear on short-term cultural evolution.

The presumed goals of the systems under study are quite distinct, especially at the macro level. The macro goal of ecological economics is sustainability of the combined ecological economic system. Conventional ecology's macro goal of species survival is similar to sustainability, but is generally confined to single species and not the whole system. Conventional economics emphasizes growth rather than sustainability at the macro level. At the micro level, ecological economics is unique in acknowledging the two-way linkages between scales, rather than the one-way view of the conventional sciences in which all macro behaviour is the simple aggregation of micro behaviour. In ecological economics, social organization and cultural institutions at higher levels of the space–time hierarchy ameliorate conflicts produced by myopic pursuit of micro goals at lower levels and vice versa.

Perhaps the key distinctions between ecological economics and the conventional sciences lie in their implicit assumptions, notably about technical progress.

Conventional economics is very optimistic about the ability of technology to ultimately remove all resource constraints to continued economic growth. Conventional ecology really has very little to say directly about technology; however, to the extent that it has an opinion, it would be pessimistic about technology's ability to remove resource constraints because all other existing natural ecosystems that do not include humans are observed to be resource limited. Ecological economics is prudently sceptical in this regard. Given our high level of uncertainty about this issue, it is irrational to *bank on* technology's ability to remove resource constraints. If we guess wrong then the result is disastrous, irreversible destruction of our resource base and civilization itself. We should, at least for the time being, assume that technology will *not* be able to remove resource constraints. If it does we can be pleasantly surprised. If it does not we are still left with a sustainable system. This is why ecological economics assumes a prudently sceptical stance on technical progress.

1.2. *A Hierarchy of Goals and Incentives*

No complex system can be managed effectively without clear goals and appropriate mechanisms for achieving them. In managing the Earth, we are faced with a nested hierarchy of goals that span a wide range of time and space scales. In any rational system of management, global ecological and economic health and sustainability should be 'higher' goals than local, short-term national economic growth or private interests. Economic growth can be supported as a policy goal in this context only to the extent that it is consistent with long-term global sustainability.

Unfortunately, most of our current institutions and incentive structures deal only with relatively short-term, local, goals and incentives (Clark, 1973). This would not be a problem if the local and short-term goals and incentives simply added up to appropriate behaviour in the global long-run, as many assume they do; in other words, if they were *consistent* with global and long-term goals. Unfortunately, this often is not the case. Individuals (or firms, or countries) pursuing their own private self-interests in the absence of mechanisms to account for community and global interests frequently run afoul of these larger goals and can often drive themselves to their own demise.

These goal and incentive inconsistencies have been characterized and generalized in many ways, beginning with Hardin's (1968) classic paper on the tragedy of the commons and continuing through more recent work on 'social traps' (Platt, 1973; Cross and Guyer, 1980; Tieger, 1980; Costanza, 1987; Costanza and Schrum, 1988; Costanza and Perrings, 1990). Social traps occur when local, individual incentives that guide behaviour are inconsistent with the overall goals of the system. Examples are cigarette and drug addition, overuse of pesticides, economic boom and bust cycles, and a host of others. Social traps are also amenable to experimental research to see how people behave in trap-like situations, and how to best avoid and escape from social traps (Edney and Harper, 1978; Tieger, 1980; Brockner and Rubin, 1985; Costanza and Schrum, 1988). The bottom line emerging from this research is that in cases where social traps exist, the system is not inherently sustainable, and special steps must be taken to harmonize goals and incentives over the hierarchy of time and space scales involved. Explicit, special steps must be taken to make the global and long-term goals incumbent on and consistent with the local and short-term goals and incentives.

This is in contrast to natural systems, which are bound by the constraints of genetic evolution. In natural systems, 'survival' generally equates to sustainability of the species as part of a larger ecosystem, and natural selection tends to produce sustainable systems in the long run. Humans have broken the bonds of genetic evolution by the expanded use of the learned behaviour our large brains allow and by extending our physical capabilities with tools. The price we pay for this rapid adaptation is a partial isolation from long-term constraints and a susceptibility to social traps.

Another general result of social trap research is that the relative effectiveness of alternative corrective steps is not easy to predict from simple 'rational' models of human behaviour prevalent in conventional economic thinking. The experimental facts indicate the need to develop more realistic models of human behaviour under uncertainty which acknowledge the complexity of most real world decisions and humans' limited information processing capabilities (Heiner, 1983).

Perhaps the most glaring and important lack of goal harmony exists today at the interface between ecological and economic systems. A primary goal of ecological economics is to harmonize these goals through a better understanding of the linkages between ecological and economic systems, especially in the long-run and globally.

1.3. *The Interface Between Ecological and Economic Systems*

Ecological systems play a fundamental role in supporting life on Earth at all hierarchical scales. They form the life-support system without which economic activity would not be possible. They are essential in global material cycles like the carbon and water cycles. They provide raw materials, food, water, recreational opportunities, and microclimate control for the entire human population. In the long run a healthy economy can exist only in symbiosis with a healthy ecology. The two are so interdependent that isolating them for academic purposes has led to distortions and poor management.

Ecological systems are also our best current models of sustainable systems. Better understanding of ecological systems and how they function and maintain themselves can yield insights into designing and managing sustainable economic systems. For example, there is no 'pollution' in climax ecosystems;[2] all waste and by-products are recycled and used somewhere in the system or harmlessly dissipated. A characteristic of sustainable economic systems should also be a similar 'closing the cycle' by finding economic uses and recycling 'pollution', rather than simply storing it, exporting it, diluting it, or changing its state, and allowing it to disrupt existing or future ecosystems that cannot use it.

In the realm of behaviour and the study of decision making, we are finding more and more that human behaviour is part of a continuum of animal behaviour and that experimental studies of human and other animal behaviour can shed much light on human behaviour. The sub-fields of experimental economics and evolutionary economics are based on this idea and have begun to bear some fruit. Understanding the linkages between ecological and economic systems and treating them as a whole, integrated system is therefore critical to sustainability.

2. A RESEARCH AGENDA FOR ECOLOGICAL ECONOMICS

To achieve sustainability, several steps are necessary, including innovative research. This research should not be divorced from the policy and management process, but rather integrated with it. The research agenda for ecological economics suggested below is a snapshot, a first guess, intended to begin the process of defining topics for future ecological economic research rather than a final word. The list of topics can be divided into five major parts: (1) sustainability: maintaining our life support system; (2) valuation of natural resources and natural capital; (3) ecological economic system accounting; (4) ecological economic modelling at local, regional, and global scales; and (5) innovative instruments for environmental management. Some background on each of these topics is given below.

[2] A 'climax' ecosystem is a mature, relatively stable system that does not have a tendency to succeed into any other ecosystem. If the natural ecosystem in an area is removed (without damaging the soil structure too much) the area will generally tend to progress through a succession of ecosystems (i.e. grass, shrubs, pine forest) until it again reaches a climax system. This climax system is not an inevitable and static equilibrium, but rather a general and probabilistic tendency based on the potential of the particular site.

2.1. *Sustainability: Maintaining Our Life Support System*

'Sustainability' does not imply a static, much less a stagnant, economy, but we must be careful to distinguish between 'growth' and 'development'. Economic growth, which is an increase in quantity, cannot be sustainable indefinitely on a finite planet. Economic development, which is an improvement in the quality of life without necessarily causing an increase in quantity of resources consumed, may be sustainable. Sustainable growth is an ability to repair itself. Indeed, there is much evidence that we have already done so. Several authors have stressed the fact that current economic systems do not *inherently* incorporate any concern about the sustainability of our natural life support system and the economics that depend on it (e.g. Costanza and Daly, 1987; Hardin, 1991; Clark, 1991). Pearce (1987) discusses the reasons for the inability of existing forms of economic organization (free market, mixed, planned) to guarantee sustainability. In an important sense, sustainability is merely justice with respect to future generations. This includes future generations of other species, even though our main interest may be in our own species.

Sustainability has been variously construed, (*cf.* Brown *et al.*, 1987; World Commission on Environment and Development, 1987; Pezzey, 1989) but a useful definition is the amount of consumption that can be continued indefinitely without degrading capital stocks—including 'natural capital' stocks (*cf.* El Serafy, 1991). In a business, capital stock includes long-term assets such as buildings and machinery that serve as the means of production. Natural capital is the soil and atmospheric structure, plant and animal biomass, etc., that taken together forms the basis of all ecosystems. This natural capital stock uses primary inputs (sunlight) to produce the range of ecosystem services and physical natural resource flows. Examples of natural capital include forests, fish populations, and petroleum deposits. The natural resource flows yielded by these natural capital stocks are, respectively, cut timber, caught fish, and pumped crude oil. We have now entered a new era in which the limiting factor in development is no longer man-made capital but remaining natural capital. Timber is limited by remaining forests, not sawmill capacity; fish catch is limited by fish populations, not by fishing boats; crude oil is limited by remaining petroleum deposits, not by pumping and drilling capacity. Most economists view natural and man-made capital as substitutes rather than complements. Consequently neither factor can be limiting. Only if factors are complementary can one be limiting. Ecological economists see man-made and natural capital as fundamentally complementary and therefore emphasize the importance of limiting factors and changes in the pattern of scarcity. This is a fundamental difference that needs to be reconciled through debate and research.

Definitions of sustainability are also obviously dependent on the time and space scale we are using. For a working definition of sustainability see Costanza *et al.* (1991).

2.2. *Valuation of Ecosystem Services and Natural Capital*

To achieve sustainability, we must incorporate ecosystem goods and services into our economic accounting. The first step is to determine values for them comparable to those of economic goods and services. In determining values we must also consider how much of our ecological life support systems we can afford to lose. To what extent can we substitute manufactured for natural capital, and how much of our natural capital is irreplaceable (El Serafy, 1991). For example, could we replace the radiation screening services of the ozone layer that are currently being destroyed?

Some argue that we cannot place economic value on such 'intangibles' as human life, environmental aesthetics, or long-term ecological benefits (Norton, 1986). In fact, we do so every day. When we set construction standards for highways, bridges and the like, we value human life—acknowledged or not—because spending more money on construction would save lives. To preserve our natural capital, we must confront these often difficult choices and valuations directly rather than denying their existence.

Because of the inherent difficulties and uncertainties in determining values, ecological economics acknowledges several different independent approaches. There is no consensus on which approach is right or wrong—they all tell us something—but there is agreement that better valuation of ecosystem services is an important goal for ecological economics.

The conventional economic view defines value as the expression of individualistic human preferences, with the preferences taken as given and with no attempt to analyse their origins or patterns of long-term change. For goods and services with few long-term impacts (like tomatoes or bread) that are traded in well-functioning markets with adequate information, market ('revealed preference') valuations work well.

However, ecological goods and services (like wetland sewage treatment or global climate control) are long-term by nature, are generally not traded in markets (no one owns the air or water), and information about their contribution to individuals' well-being is poor. To determine their value, economists try to get people to reveal what they would be willing to pay for ecological goods and services in hypothetical markets (*cf.* Conrad, 1980; Randall and Stoll, 1980; Bishop, 1982; Brookshire *et al.*, 1983; Bartlett, 1984; Randall 1986). For example, we can ask people the maximum they would pay to use national parks, even if they do not have to actually pay it. The quality of results in this method depends on how well informed people are; and it does not adequately incorporate long-term goals since it excludes future generations from bidding in the markets. Also, it is difficult to induce individuals to reveal their true willingness to pay for natural resources when the question is put directly. Contingent referenda (willingness to be taxed as a citizen along with each other citizen, as opposed to willingness to pay as an individual) is superior to ordinary willingness to pay (WTP) studies in this regard.

In practice, valuation or shadow pricing of environmental functions may require some collectively set quantitative standard. Then shadow prices can be calculated subject to the constraint represented by that standard (i.e. Hueting, 1991).

An alternative method for estimating ecological values assumes a biophysical basis for value (*cf.* Costanza, 1980; Cleveland *et al.*, 1984; Costanza *et al.*, 1989;

Cleveland, 1991). This theory suggests that in the long run humans come to value things according to how costly they are to produce, and that this cost is ultimately a function of how organized they are relative to their environment. To organize a complex structure takes energy, both directly in the form of fuel and indirectly in the form of other organized structures like factories. For example, a car is a much more organized structure than a lump of iron ore, and therefore it takes a lot of energy (directly and indirectly) to organize iron ore into a car. The amount of solar energy required to grow forests can therefore serve as a measure of their energy cost, their organization, and, hence, according to this theory, their value.

Table 2 shows the results of applying these two radically different approaches, one based on human perceptions (WTP) and one based on biophysical production (energy analysis or EA) to the valuation of wetlands in Louisiana (Costanza *et al.*, 1989). The striking feature is just how close the results are to each other. They can in fact be interpreted as setting the range within which the true value probably falls. The WTP method sets the low end of the range since it must enumerate all the individual non-marketed services of the ecosystem and develop pseudo-markets (via questionnaires or observations of behaviour) to evaluate each one. This process will almost certainly miss some important services. The EA method, on the other hand, assumes that all production of the ecosystem is valuable, directly or indirectly, and to the extent that some ecosystem services are not ultimately valuable to humans, it overestimates.

The point that must be stressed, however, is that the economic value of ecosystems is connected to their physical, chemical, and biological role in both the short-term and the long-term global system—whether the present generation of humans fully recognizes that role or not. If it is accepted that each species, no matter how seemingly uninteresting or lacking in immediate utility, has a role in natural ecosystems (which *do* provide many direct benefits to humans), it is possible to shift the focus away from our imperfect short-term perceptions and derive more accurate values for long-term ecosystem services.

TABLE 2. *Summary of Wetland Value Estimates from Costanza et al. (1989)*

Method	*Per acre present value (1983$) at specified discount rate*	
	8%	*3%*
WTP based		
commercial fishery	317	846
trapping	151	401
recreation	46	181
storm protection	1915	7549
total	$2429	8977
option and existence total values	?	?
EA based		
gross primary production conversion	6400–10600	17000–28200
'Best estimate'	2429–6400	8977–17000

Using this perspective we may be able to better estimate the values contributed by, say, maintenance of water and atmospheric quality to long-term human well-being.

2.3. *Ecological Economic System Accounting*

Gross National Product (GNP) and other related measures of national economic performance have come to be extremely important as policy objectives, political issues, and benchmarks of general welfare. Yet GNP as presently defined ignores the contribution of nature to production, often leading to peculiar results.

For example, a standing forest provides real economic services for people by conserving soil, cleaning air and water, providing habitat for wildlife, and supporting recreational activities. However, as GNP is currently figured, only the value of harvested timber is calculated in the total. On the other hand, the billions of dollars that Exxon spent on the Valdez clean-up—and the billions spent by Exxon and others on the more than 100 other oil spills in the last 16 months—all actually *improved* our apparent economic performance. Why? Because cleaning up oil spills creates jobs and consumes resources, all of which add to GNP. Of course, these expenses would not have been necessary if the oil had not been spilled, so they should not be considered 'benefits'. However, GNP adds up all production without differentiating between costs and benefits, and is therefore not a very good measure of economic health.

In fact, when resource depletion and degradation are taken into account, what emerges is a radically different picture from that depicted by conventional methods. For example, Daly and Cobb (1989) have attempted to adjust GNP to account mainly for depletions of natural capital, pollution effects, and income distribution effects by producing an 'index of sustainable economic welfare' (ISEW). They conclude that while GNP in the US rose over the 1956–86 interval, ISEW remained relatively unchanged since about 1970. When factors such as loss of farms and wetlands, costs of mitigating acid rain effects, and health costs caused by increased pollution are accounted for, the US economy has not improved at all. If we continue to ignore natural ecosystems we may drive the economy down while we think we are building it up. By consuming our natural capital, we endanger our ability to sustain income. Daly and Cobb acknowledge that many arbitrary judgments go into their ISEW, but claim nevertheless that it is less arbitrary than GNP as a measure of welfare.

A number of other promising approaches to accounting for ecosystem services and natural capital are also being developed (*cf.* Ahmad *et al.*, 1989; El Serafy, 1991; Faber and Proops, 1991; Hannon, 1991; Hueting, 1991; Peskin, 1991; Ulanowicz, 1991) and this area is likely to be a major focus of research in ecological economics. The approaches are based on differing assumptions, but share the goal of attempting to quantify ecological economic interdependencies and arriving at overall system measures of health and performance. Wassily Leontief (1941) was the first to develop detailed quantitative descriptions of complex economic systems to allow a complete accounting of system interdependencies. Leontief's input–output (I–O) tables and model have become standard conceptual and applied tools in economic accounting; Isard (1972) was the first to attempt combined ecological economic system I–O analysis. Combined ecological economic system I–O models have also been proposed by several other authors (Daly, 1968; Victor, 1972; Cumberland, 1987). Ecologists have also applied several unique versions of I–O analysis to the accounting of material and energy transfers in ecosystems (Funderlic and Heath, 1971; Hannon, 1973, 1976, 1979, 1991; Finn, 1976; Barber *et al.*, 1979; Costanza and Neill, 1984; Costanza and Hannon, 1989). All variations of the analysis of interconnected ecological and/or economic systems have been referred to as *network analysis* (Wulff *et al.*, 1989).

Network analysis holds the promise of allowing an integrated quantitative treatment of combined ecological economic systems. One promising route is the use of 'ascendancy' (Ulanowicz, 1980, 1986) and related measures (Wulff *et al.*, 1989) to quantify the degree of organization in ecological, economic, or any other networks. Measures like ascendancy go several steps beyond the traditional diversity indices used in ecology. They estimate not only how many different species (or sectors) there are in a system but, more importantly, how those species are organized. This kind of measure may provide the basis for a quantitative and general index of system health applicable to both ecological and economic systems.

Another promising avenue for research in network analysis has to do with its use for 'pricing' commodities in ecological or economic systems (Costanza, 1980; Costanza and Herendeen, 1984; Costanza and Hannon, 1989). The 'mixed units' problem arises in any field that tries to analyse interdependence and limiting factors in complex systems that have many different types and quantities of interacting processes and commodities. Ecology and economics are two such fields. Network analysis in ecology has avoided this problem in the past by *arbitrarily* choosing the commodity flowing through the system as an index of interdependence (i.e. carbon, enthalpy, nitrogen, etc.). This ignores the complex interdependencies among commodities and assumes that the chosen commodity is a valid 'tracer' for relative value or importance in the system. This assumption is unrealistic and severely limits the comprehensiveness of an analysis whose major objective is to deal comprehensively with whole systems.

There are evolving methods for dealing with the mixed units problem based on analogies to the calculation of prices in economic I–O models. Starting with a more realistic *commodity by process* description of ecosystem networks that allows for joint products, one can ultimately convert the multiple commodity description into a pair of matrices that can serve as the input for standard (single commodity) network analysis. The new single commodity description incorporates commodity and process interdependencies and limiting factor relationships in a manner analogous to the way economic value incorporates production interdependencies in economic systems (Costanza and Hannon, 1989). This analysis allows an estimation of the biophysical cost of components of combined ecological and economic systems as a complement to subjective evaluations.

An example of this approach applied to the global ecological economic system is given below. It is a classic static 'accounting' I–O approach that allows joint products and input data in physical, non-commensurable units. Economic and ecological commodities and processes can both be included in the model.

According to Fig. 2, the system is divided into a number of interacting processes (j) and commodities (i). A *commodity* is defined as some identifiable unit moving through the system. It can be a simple element (like carbon) or a complex structure (like plant biomass or cars) or a service (like transportation). Commodities are transformed (produced, consumed, or combined into more complex commodities) in *processes*. Biomass, for example, is produced by the photosynthetic process, which combines (consumes) water, carbon dioxide, sunlight, and nutrients into plant material. $\mathbf{U}$ is a matrix whose elements are the amount of commodity i used in process j during the specified time interval. $\mathbf{V}$ is a matrix whose elements are amount of commodity i produced in process j during the specified time interval. $\mathbf{e}$ is a vector of net inputs to each process in the system. $\mathbf{r}$ is a vector of net exports and $\Delta \mathbf{s}$ is a vector of net changes in stock of each commodity in the system. $\mathbf{w}$ is a vector of the depreciation (entropic dissipation) of each commodity stock, and $\mathbf{p}^N$ is a vector of the total inputs of each commodity from all processes $(\mathbf{V} + \mathbf{w})$.

A row from the accounting diagram in Fig. 2 can be stated in continuous time as:

$$\sum_j V_{ij} + w_j = \sum_j U_{ij} + r_i + \Delta s_i. \tag{1}$$

Each commodity in the system is conserved. However, each commodity is measured in its own units, and the matrix can include apples, oranges, or any number of other commodities.

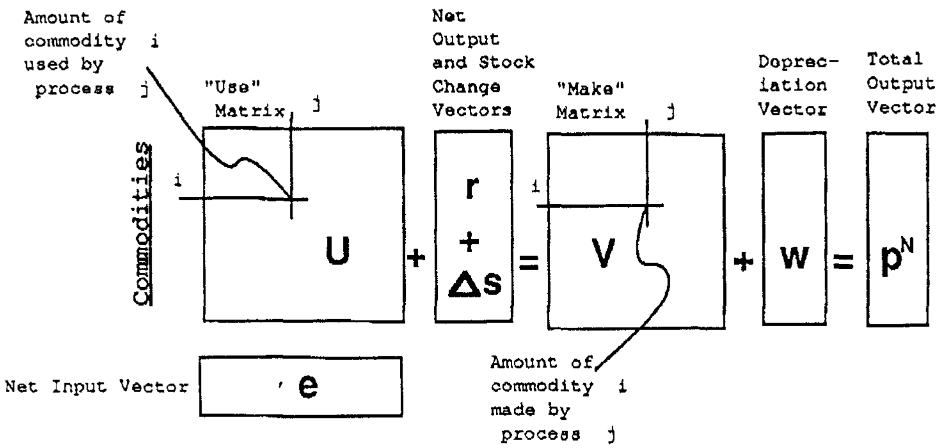

FIG. 2. Multicommodity ecological economic system flow accounting diagram. Joint products appear as multiple entries (more than one commodity) in columns of the 'make' matrix for a single process. Refer to equation (1).

One of the possible uses of such a table is to derive weights that can put all the different commodities in comparable units based on their interdependence relationships. To do this one can assume that the total value of all inputs to each process equals the total value of all outputs from that process, or:

$$\sum_i \varepsilon_i U_{ij} + e_j = \sum_i \varepsilon_i V_{ij}, \tag{2}$$

where ε_i is the weighting factor for each commodity necessary to convert the commodities into commensurable units. Call these ε_i ecological interdependence factors (EIFs). We can solve for the EIFs using the entire system of functional interdependence embodied in the I–O tables.

Rewriting equation (2) in vector–matrix form:

$$\boldsymbol{\varepsilon}\mathbf{U} + \mathbf{e} = \boldsymbol{\varepsilon}\mathbf{V} \tag{3}$$

rearranging yields:

$$\mathbf{e} = \boldsymbol{\varepsilon}(\mathbf{V} - \mathbf{U}) \tag{4}$$

and solving for the weighting factors yields:

$$\boldsymbol{\varepsilon} = \mathbf{e}(\mathbf{V} - \mathbf{U})^{-1} \tag{5}$$

Tables 3 and 4 are examples of a global multicommodity flow table set up in the multiple output, commodity–process format discussed above. Numbers in the tables are estimates of global flows in mixed physical and economic units for the year 1980 (Costanza and Neill, 1981). Rows 3–9 in the tables represent global material cycles for major natural commodities that are currently the subject of intense scientific study and measurement. For example, rows 7 and 8 represent the global water cycle, while row 5 represents the global carbon cycle. Thus, while Tables 3 and 4 are rough estimates at a very crude level of aggregation, an enormous research effort is already underway to improve and disaggregate the data necessary for the construction of improved tables in the near future. The I–O framework allows the interconnections between these global cycles and the global economy to be explicitly laid out and several kinds of analysis to be performed.

Table 3 shows the inputs of the commodities listed along the left, to the processes listed along the top. This is the **U** matrix. Note that the units for the commodities are different (they are not commensurable) so one cannot add down the columns of **U**. The outputs of each commodity from each process are listed in Table 4. This is the **V** matrix.

Note that conservation holds for each commodity but not for the processes whose inputs and outputs are generally measured in different units. The total output of each commodity from all the processes that produce it (the row sum of **V**) is equal to the total input of that commodity to all the processes that use it (the row sum of **U**), including the amount of commodity that is 'depreciated' or exported (**r**). Processes (columns in **V**) that contain more than one entry

TABLE 3. *Global multicommodity input ('use') matrix* (**U**), *along with the vectors for net export + stock replacement* (**r**), *total output excluding waste heat* (**p**), *and the net input vector* (*sunlight,* **e**)[1]

Commodities	*Processes*									*Net output*	*Total output*
	urban economy (1)	*agriculture (2)*	*natural plants (3)*	*animals (4)*	*soil (5)*	*deep ocean (6)*	*surface ocean (7)*	*atmosphere (8)*	*deep geology (9)*	**r**	**p**
Manufacturing goods (1)	2.71	0.08	0	0	0	0	0	0	0	1.19	3.98
Agricultural products (2)	1.28	4.55	0	3.27	0	0	0	0	0	0	9.1
Natural products (3)	1.18	0	0	27.9	103.4	34.6	0	0	0.16	0.06	167.3
Nitrogen (4)	55	62.4	208	0	493.6	0	168	389.5	0	0	1376.5
Carbon (5)	0	8.2	147	0	0	15.6	37.2	110.3	0	0	318.3
Phosphorous (6)	12.6	28.5	1345.7	0	8.4	0	21	9.5	13	0	1438.7
Water vapour (7)	0	0	0	0	0	0	0	496100	0	0	496100
Fresh water (8)	1008	15490	51226	0	111419	0	424700	0	0	2000	605843
Fossil fuels	5	0	0	0	0	0	0	0	0	−4.93	0.07
Net input (sunlight) (**e**)	0	23	227	0	0	0	606	0	0		

[1] Units are (1) manufactured goods 10^{12} \$/yr; (2) agricultural products, 10^{15} g dry wt/yr; (3) natural products, 10^{15} g dry wt/yr; (4) nitrogen, 10^{12} gN/yr; (5) carbon, 10^{15} gC/yr; (6) phosphorous, 10^{12} gP/yr; (7) water vapour, km^3/yr; (8) fresh water, km^3/yr; (9) fossil fuel, 10^{15} gC/yr; (**e**) sunlight, 10^{18} kcal/yr. Complete references are given in Costanza and Neill (1981).

TABLE 4. *Global multicommodity output ('make') matrix* (**V**), *along with the vector for total input*[1]

Commodities	*Processes*									*Total input*
	urban economy (1)	*agriculture (2)*	*natural plants (3)*	*animals (4)*	*soil (5)*	*deep ocean (6)*	*surface ocean (7)*	*atmosphere (8)*	*deep geology (9)*	
Manufacturing goods (1)	3.98	0	0	0	0	0	0	0	0	3.98
Agricultural products (2)	0	9.1	0	0	0	0	0	0	0	9.1
Natural products (3)	0	0	163.4	3.9	0	0	0	0	0	167.3
Nitrogen (4)	80	31	0	295	340.5	0	182	448	0	1376.5
Carbon (5)	5	6.1	73.6	14	46.5	15.6	49.5	108	0	318.3
Phosphorous (6)	14.2	0	0	0	241.3	1161.1	0	9.5	12.6	1438.7
Water vapour (7)	79	5931	50740	0	14650	0	424700	0	0	496100
Fresh water (8)	929	9829	0	0	98985	0	0	496100	0	605843
Fossil fuels (9)	0	0	0	0	0	0	0	0	0.07	0.07

[1] Units same as in Table 3.

represent 'joint products'. At the global level joint products are significant and unavoidable.

Tables such as Tables 3 and 4 are potentially useful for a wide range of purposes. Possible uses include: (1) to study interdependence in the linked ecological economic system in a number of ways; (2) to estimate the direct and indirect impacts of aspects of global climate change; and (3) to serve as the starting point for dynamic models (e.g. Duchin and Szyld, 1985) of the global environment and economy aimed at evaluating alternative scenarios. One of the many possible uses is to calculate the direct and indirect use matrix, $(\mathbf{V}-\mathbf{U})^{-1}$, and the EIFs using the methods described above. This matrix and vector are shown in Table 5. Note that Table 5 contains many negatives. This reflects the fact that each entry in the inverse matrix represents the *net* direct and indirect input (or output if negative) of the row commodities to (or from if negative) the column processes.

The EIFs (the $\boldsymbol{\varepsilon}$ column vector) can be interpreted as the direct and indirect solar energy cost (since sunlight, the $\mathbf{e}$ row vector, is the only net input to the global system) per unit of each row commodity. For example, manufactured goods require about 190×10^{18} kcal of solar energy (directly and indirectly) per 10^{12} \$ of output or 190×10^{6} kcal solar/\$. Fresh water requires 0.55×10^{18} kcal of solar energy/km^3 of water or 55×10^{16} kcal solar/km^3 or 550×10^{6} kcal solar/m^3 or 2.2×10^{6} kcal solar/gal, making 86 gallons of fresh water about as costly for the global ecological economic system to produce, according to the model, as a dollar's worth of manufactured goods. Fossil fuels, according to the model, require about 96×10^{18} kcal of solar energy/10^{15} gC of fossil fuel or (at 10 kcal/gC) about 10×10^{3} kcal solar/kcal fossil, indicating the much more concentrated form of fossil fuel versus solar energy. Comparing the cost of manufactured goods with fossil fuel indicates that 19 000 kcal of fossil fuel is about as costly as \$1 of manufactured goods.

There is no guarantee that using this method will produce an all-positive $\boldsymbol{\varepsilon}$ vector. A negative $\boldsymbol{\varepsilon}_i$ would be interpreted as a commodity, the production of more of which would require (directly and indirectly) less solar energy input, or conversely, a commodity whose production would decrease if more solar energy were applied to the system. All of the commodities in the system as we have aggregated it should probably have positive ε_i, so a negative ε_i might more reasonably be interpreted as resulting from problems with the data.

This simplified example shows the possibility of implementing global ecological economic I–O accounting as first suggested by Daly (1968). The approach allows a comprehensive treatment of the interdependencies between ecological and economic systems and (among a host of other possible uses) the derivation of EIFs to weight the products of ecological systems. These EIFs can be thought of as ecological system 'costs' based on the production and consumption interdependencies in linked ecological and economic systems. This is a more elaborate version of the simple energy analysis method discussed earlier for wetlands.

However, this approach, like all others, is limited by its underlying assumptions and the precision of the data that go into it. There is no one modelling approach

TABLE 5. *Matrix* $(\mathbf{V}-\mathbf{U})^{-1}$ *for the* **U** *and* **V** *matrices shown in Tables* 3 *and* 4, *respectively*[1]

Commodities	*Processes*									*EIF* (ε)
	urban eco-nomy (1)	*agri-culture (2)*	*natural plants (3)*	*ani-mals (4)*	*soil (5)*	*deep ocean (6)*	*surface ocean (7)*	*atmos-phere (8)*	*deep geology (9)*	
Manufacturing goods (1)	0.79869	0.01329	−0.00029	0.00018	−0.00112	−0.00001	0.00002	0.00002	−0.00070	190.365
Agricultural products (2)	0.17925	0.21105	−0.00453	0.00281	−0.00013	−0.00013	0.00037	0.00037	−0.01112	13.997
Natural products (3)	0.07260	−0.02471	0.00916	0.00063	−0.00336	0.00027	0.00051	0.00051	0.02249	39.158
Nitrogen (4)	−0.06323	−0.01735	−0.00619	0.00384	−0.02421	−0.00018	0.00050	0.00050	−0.1520	0.630
Carbon dioxide (5)	−0.00592	−0.03113	0.00256	−0.00020	0.00142	0.00008	0.00052	0.00052	0.00629	57.123
Phosphorous (6)	0.11335	−0.01646	0.01109	0.00086	−0.00289	0.00119	0.00051	0.00051	0.03216	1.167
Water vapour (7)	0.28014	0.02434	0.06136	0.00070	0.09619	0.00183	0.00070	0.00070	0.15070	0.550
Fresh water (8)	0.24934	0.01992	0.05349	0.00069	0.08183	0.00159	0.00067	0.00067	0.13136	0.550
Fossil fuels (9)	57.04948	0.94962	−0.02038	0.01265	−0.07970	−0.00061	0.00165	0.00165	14.23566	96.171

[1] Entries in this matrix indicate the *direct and indirect* inputs (or outputs if negative) of the row commodities to (or from) the column processes. EIFs for the commodities based on this matrix and the direct sunlight input vector listed in Table 3 (using equation 6) are shown as the last column on the right.

that can give us all the information we need about something as large and complex as the whole biosphere. Even with the best conceivable modelling capabilities, we will always be confronted with large amounts of uncertainty about the response of the environment to human actions.

2.4. *Ecological Economic Modelling at Local, Regional, and Global Scales*

Since ecosystems are being threatened by a host of human activities, protecting and preserving them requires the ability to understand the direct and indirect effects of human activities over long periods of time and over large areas. Computer simulations are becoming important tools for investigating these interactions, and interactions in other areas of science as well. Without the sophisticated global atmospheric simulations now being done, our understanding of the potential impacts of increasing carbon dioxide concentrations in the atmosphere due to fossil fuel burning would be much more primitive. Dynamic computer simulations can now be used to understand not only economic performance (Duchin and Szyld, 1985) but also human impacts on ecosystems (Costanza *et al.*, 1990), our economic dependence on natural ecosystem services and capital, and the interdependence between ecological and economic components of the system (Braat and van Lierop, 1985; Braat and Steetskamp, 1991).

Several recent developments make such computer simulation modelling feasible, including the accessibility of extensive spatial and temporal data bases, and advances in computer power and convenience. Computer simulation models are potentially one of our best tools to help understand the complex, non-linear, and often chaotic dynamics of integrated ecological economic systems.

Even with the elaborate modelling capabilities, however, we will always be confronted with large amounts of uncertainty about the response of the environment to human actions (*cf.* Funtowicz and Ravitz, 1991). Learning how to effectively manage the environment in the face of this uncertainty is critical and is a major item on the research agenda of ecological economics (Costanza, 1987; Perrings, 1987, 1989, 1991; Costanza and Perrings, 1990).

The research program and theoretical basis of ecological economics can thus be described as an integrated, multi-scale, transdisciplinary, and pluralistic approach to quantitative ecological economic modelling. While acknowledging the large remaining uncertainty inherent in modelling, these systems are developing new ways to effectively deal with this uncertainty (Norgaard, 1989). In particular, our systems of government regulation to account for environmental externalities do a poor job of incorporating scientific understanding of the behaviour of these systems and especially the uncertainty in our understanding. Some innovative ways of managing these systems may therefore be in order.

2.5. *Innovative Instruments for Environmental Management*

Current systems of regulation are not very efficient at managing environmental resources for sustainability, particularly in the face of uncertainty about long-term values and impacts (Arrow and Fisher, 1974; Perrings, 1987; Costanza, 1989; Cumberland, 1990). They are inherently reactive rather than proactive. They induce legal confrontation, obfuscation, and government intrusion into business. Rather than encouraging long-range technical and social innovation, they tend to suppress it. They do not mesh well with the market signals that firms and individuals use to make decisions, and do not effectively translate long-term global goals into short-term local incentives.

We need to explore promising alternatives to our current command and control environmental management systems, and to modify existing government agencies and other institutions accordingly. The enormous uncertainty about local and transnational environmental impacts needs to be incorporated into decision making. We also need to better understand the sociological, cultural, and political criteria for acceptance or rejection of policy instruments.

One example of an innovative policy instrument currently being studied is a flexible environmental assurance bonding system designed to incorporate environmental criteria and uncertainty into the market system, and to induce positive environmental technological innovation (Perrings, 1989, 1991; Costanza and Perrings, 1990).

In addition to direct charges for known environmental damages, a company would be required to post an assurance bond equal to the current best estimate of the largest potential future environmental damages; the money would be kept in interest-bearing escrow accounts. The bond (plus a portion of the interest) would be returned if the firm could show that the suspected damages had not occurred or would not occur. If they did, the bond would be used to rehabilitate or repair the environment and to compensate injured parties. Thus, the burden of proof would be shifted from the public to the resource-user, and a strong economic incentive would be provided to research the true costs of environmentally damaging activities and to develop cost-effective pollution control technologies. This is an extension of the 'polluter pays' principle to 'the polluter pays for uncertainty as well'. Other innovative policy instruments include tradeable pollution and depletion quotas at both national and international levels. Also worthy of mention is the newly emerging Global Environmental Facility of the World Bank which will provide concessionary funds for investments that reduce global externalities.

2.6. *Maintaining Natural Capital to Assure Sustainability*

A minimum necessary condition for sustainability is the maintenance of the total natural capital stock at or above the current level (Pearce and Turner, 1989; Costanza and Daly, 1991). While a lower stock of natural capital may be sustainable, given our uncertainty and the dire consequences of guessing wrong, it is best to at least provisionally assume that we are at or below the range of sustainable stock levels and allow no further decline in natural capital. This 'constancy of total natural capital' rule can thus be seen as a prudent minimum condition for assuring sustainability, to be abandoned only when solid evidence to the contrary can be offered (Costanza and Daly, 1991). There is disagreement between technological optimists (who see technical progress eliminating all resource constraints to growth and development) and technological sceptics (who do not see as much scope for this approach and fear irreversible use of resources and damage to natural capital). By limiting total system natural capital at current levels (preferably by using higher severance and consumption taxes) we can satisfy both the sceptics (since resources will be conserved for future generations) and the optimists (since this will raise the price of natural capital resources and more rapidly induce the technical change they anticipate). By limiting physical growth, only development is allowed and this may proceed without endangering sustainability.

ACKNOWLEDGEMENTS

This paper develops from several earlier pieces and influences. In particular, the first meeting of the International Society for Ecological Economics held on May 21–23, 1990 at the World Bank in Washington DC, and the workshop at the Aspen Institute on Maryland's eastern shore that immediately followed it on May 24–26 stimulated the development of many of these ideas. The Aspen workshop resulted in a book (Costanza, 1991), the summary chapter of which (Costanza *et al.*, 1991) provided the basis for this paper. The paper was also presented at the 1991 AAAS Annual Meeting, 14–19 February, in Washington, DC. I would like to thank F. Duchin and three anonymous reviewers for detailed and helpful suggestions on earlier drafts.

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