Biophysical Economics: From Physiocracy to Ecological Economics and Industrial Ecology

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Abstract

Biophysical economics is characterized by a wide range of analysts from diverse fields who use basic ecological and thermodynamic principles to analyze the economic process. The history of biophysical thought is traced from the 18th-century Physiocrats to current empirical research, with emphasis on those individuals who contributed to the development of biophysical economic theory. Attention is also given to a critique of the neoclassical theory of natural resources from a biophysical perspective, and how recent empirical biophysical research highlights areas of neoclassical theory which could be improved by a more realistic and systematic treatment of natural resources.

Key Words: Biophysical economics, ecological economics, sustainable development, entropy, thermodynamics, natural resources

Key Names: Nicholas Georgescu-Roegen, Robert Ayres, Herman Daly, Robert Costanza, Bruce Hannon, Fred Cottrell, Frederick Soddy, Cutler Cleveland, Earl Cook, Juan Martinez-Alier

Introduction

Nicholas Georgescu-Roegen's work is part of a long and rich history of using thermodynamics and ecological principles to study economic systems. The most recent chapter in this history began with the energy and environmental events of the 1970s, and the economic disruptions resulting from them, which made society acutely more aware of the connection between economic well-being and the quality and availability of natural resources and ecosystem services. An intimate connection has always existed between the human economy and the natural environment because nature provides the energy, materials and ecosystem services needed to sustain life and expand economic output. Until recently, these resources and services largely were ignored in standard models of economic production. Consequently, resource events of the 1970 confronted economists with an uncomfortable dilemma: standard theories about how the economic process operated were unable to adequately explain some of the economic problems of the 1970s influenced by the peaking of domestic oil production in 1970, increased reliance on imported oil through 1978, and the energy price shocks of 1973-74 and 1980-81 (Ayres, 1978; Cleveland et al., 1984). As a result, these models have been criticized for their lack of a sophisticated and realistic treatment of the role of natural resources and ecosystem services in human economic affairs (Ayres and Kneesse., 1969; Georgescu-Roegen, 1971; Odum, 1971; Daly, 1977; Hall et al., 1986; Gever et al., 1986; Costanza, 1991; Martinez-Alier, 1987).

Many of these critiques have roots in a broad body of research known as biophysical economics[1], the basic tenets of which are the focus of this analysis. Biophysical economics begins with a conceptual model that sees the economy connected to, and sustained by, a flow of energy, materials, and ecosystem services. In this paper, I trace the evolution of the biophysical model, beginning with the Physiocratic economists of the 18th century and the formulation of the laws of thermodynamics in the early 19th century. From these origins, I will outline the development of biophysical theory to its current contribution to ecological economics and industrial ecology.

[1] Lotka (1924) coined the term in his call for the use of basic biological and physical principles to aid economic analysis.

THE PHYSIOCRATS

In the 1750s there developed in France a school of economic thought which had as its first principle that natural resources, and fertile agricultural land in particular, were the source of material wealth. Physiocracy, meaning literally 'rule of nature,' is generally acknowledged as the first organized scientific school of economic thought (Neill, 1949). Led by Francois Quesnay (1758) and his disciples (Mirabeau, 1763; Dupont, 1768), the Physiocrats maintained that the economic process could be understood by focusing on a single physical factor: the productivity of agriculture.

The Physiocrats argued that the economic process was subject to certain objective laws which operated independent of human free will. They called such forces 'Natural Law,' which had two components, physical and moral laws. Quesnay (1765) defined physical law as:

> the regular course of all physical events in the natural order which is self-evidently the most advantageous to the human race.

Moral law was:

> the rule of human action in the moral order conforming to the physical law which is self-evidently the most advantageous to the human race.

Physical laws determined important economic parameters such as rainfall and soil fertility, and embodied the Newtonian view of the physical world which dominated scientific thought at that time. The Physiocrats argued that Natural Law operated independent of human free will, and that if humans accurately deduced the 'proper' economic behavior implied by Natural Law, social welfare would be maximized.

At the heart of the Physiocrats' model was the physical productivity of the extractive sectors, and especially the surplus produced by agriculture which was called 'produit net,' net product. The Physiocrats postulated that the course of the economy rose and fell with changes in the net product. Maribeau (1763) stated:

> The whole moral and physical advantage of societies is...summed up in one point, an increase in the net product; al damage done to society is determined by this fact, a reduction in the net product. It is on the two scales of this balance that you can place and weigh laws, manners, customs, vices, and virtues.

According to the Physiocrats, agriculture was the supreme occupation because it alone yielded a disposable surplus over cost. The Physiocrats were 'unproductive' or 'sterile.' Juxtaposed between these two classes were the 'class of proprietors' consisting of the landowners, the king, and the clergy who received in the form of rent, taxes, and thithes the dollar value of the net product produced by agriculture. In the physiocratic model, economic rent was derived from unrecompensed work done by Nature since in setting food prices, cultivators take in account their labor and expenses as well as the surplus value contributed by the fertility of the soil (Beer, 1939). Quesnay (1758) measured and traced the dollar value of the flow of net product between the three classes in his Tableau Economique, a model which represented for the first time, albeit in crude from, economic concepts such as general equilibrium and the Leontief (1941) input-output system, both of which became widely used economic models.

The influence of the Physiocratic School peaked in the 1760s and declined rapidly thereafter. For most economists, the Physiocrats represent a historical curiosity and a few of their biophysical principles are evident in neoclassical or Marxist theory. However, their steadfast belief that Nature was the source of wealth became a recurring theme throughout biophysical economics.

LAWS OF THERMODYNAMICS

In the early 19th century, the physical and ecological basis economic production intuitively grasped by the Physiocrats was formalized by the discovery of the laws of thermodynamics. Soon after Carnot (1867), Clausius (1824) and others formalized the laws of thermodynamics, many physical and life scientists realized that those laws had enormous implications for their respective disciplines. Thermodynamics and the study of energy flows became a universal index by which many disparant biological and physical processes were quantified and compared. Carnot's steam engine experiments demonstrated the relevance of the Second Law of Thermodynamics of economics, namely, how much useful work could be obtained from an energy transformation. Carnot's experiments also showed that thermodynamic laws are essentially economic formulations of physical relations, for the terms 'useful' and 'unavailable' energy refer to the economy's ability to use energy to upgrade the organizational state of natural resources into useful goods and services.

Physical scientists and biologists were the first individuals to use energy flows to explain social and economic development. Joseph Henry (1873), an American physicist and first secretary of the Smithsonian Institution, remarked that:

> ...the fundamental principle of political economy is that the physical labor of man can only be ameliorated by ...the transformation of matter from a crude state to a artificial condition...by expending what is called power or energy (p. 643).

The biologist-philosopher Herbert Spencer (1880) observed that human systems have the unique ability to temporarily halt and even reverse the spontaneous increase of entropy by tapping energy flows in nature. Spencer likened the evolutionary process, both biological and social, to the entropy law because the struggle for existence was a struggle for available energy and resources. Spencer stated that:

> Evolution is a change from a less coherent form to a more coherent form, consequent on the dissipation of [energy] and the integration of matter... (p. 337).

The German chemist Wilhelm Ostwald incorporated thermodynamics into a general theory of economic development. Ostwald (1907) stated that energy was the 'sole universal generalization' because energy possesses the principle of conservation under all circumstances. For this reason, and also because for any event in the universe it is always possible to state an equation every time between the "energies that have disappeared and those newly arrived," Ostwald believed that energy laws should be the "foundation of all sciences." Based on this principle, Ostwald sketched the beginnings of civilization in energy terms. If culture is a means by which humans control their natural environment, and if all events are at root energy transformations, then civilization becomes a history of ever-increasing control of energy for human purposes. Civilization advanced as new and better ways were devised to empower human labor with inanimate energies. Ostwald (1911) stated:

> ...the progress of science is characterized by the fact that more and more energy is utilized for human purposes, and that the transformation of the raw energies...is attended by ever-increased efficiency (p. 870).

Podolinsky (1883), a Ukrainian socialist, was the first to explicitly scrutinize the economic process from a thermodynamic perspective[2]. Podolinsky was keenly aware that he was in line of succession to the Physiocrats and Carnot and Clausius, citing the former group's emphasis on nature as the source of wealth, and the economic implications of the latter pair's discoveries. Podolinsky tried to reconcile the labor theory of value with a thermodynamic analysis of the economic process. In his conclusions, which he communicated to Frederick Engels on several occasions, Podolinsky stated the socialist model was flawed because it assumed that "scientific socialism" would overcome all natural -resource scarcities and enable unlimited material expansion. Podolinsky's biophysical analysis led him to conclude that ultimate limits to economic growth law not in the shackles of the relations of production, but in physical and ecological laws.

Podolinsky's work foreshadowed by nearly a century three concepts now widely used by some biophysical analysts: the use of energy flow analysis to characterize the efficiency of food production systems (Steinhart and Steinhart, 1974; Pimentel and Pimentel, 1979; Cleveland, 1995); modeling labor productivity as a function of the quantity of energy used to subsidize the efforts of labor (Cleveland et al., 1984); and the importance of the energy surplus or net energy yielded by an energy supply process (Cottrell, 1955; Odum, 1971; Gilliland, 1975; Hall et al., 1986).

Podolinsky calculated the energy surplus delivered by the food production system of his day by comparing the caloric value of food produced to the energy used to produce it, including the energy content of the seeds and the caloric expenditure of human and draft animals used in the process.

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[2] Martinez-Alier and Naredo (1982) and Martinez-Alier (1987) translated and discussed Podolinsky's (1883) two-part article *Human labour and the unity of energy*. Much of this discussion is based on their work.

Podolinsky calculated that yields per area and energy surpluses were greater in ecosystems that were subsidized by human-controlled energy inputs relative to unsubsidized natural ecosystems.

EARLY TWENTIETH CENTURY

The early 20th century was characterized by a growing body of literature devoted to the analysis of the role of natural resources in human affairs, and particularly in economic production. The most notable author was Frederick Soddy (1922, 1926), a Nobel laureate in chemistry, who applied the laws of thermodynamics to economic systems and devoted a significant part of his professional career to a critique of standard economic theory. Like the Physiocrats, Soddy (1922) maintained that a comprehensive theory of economic wealth has biophysical laws as first principles because:

> life derives the whole of its physical energy or power not from anything self-contained in living matter, and still less from an external deity, but solely from the inanimate world. It is dependent for all the necessities of its physical continuance upon the principles of the steam engine. The principles and ethics of all human conventions must not run counter to those of thermodynamics (p. 9).

Soddy emphasized that solar energy empowers all life processes. Human life is sustained by replenishing itself with solar energy captured and transformed by plants, which Soddy called the “original capitalists.” Like Ostwald, Soddy believed economic progress was made possible by the transition from direct solar energy to successive masteries of nonrenewable stores of fossil fuels. When humans first tapped energy capital (fossil fuel stocks) rather than energy revenue (solar energy), unprecedented accounts of economic work became possible. The ‘flamboyant era’ society now enjoys stems not only from human ingenuity but also from our inheritance of solar energy from the Carboniferous era embodied in fossil fuels.

Soddy (1926) argued that the fatal flaw of economics was a confusion of wealth, which has a distinct physical dimension, with debt, a purely imaginary mathematical quantity with no physical dimension. Unlike wealth, debts can be created by a ‘wave of the hand’ or ‘a will of the mind’ because:

> Debts are subject to the laws of mathematics rather than physics. Unlike wealth, which is subject to the laws of thermodynamics, debts do not rot with old age. On the contrary, they grow at so much per annum, by the well known mathematical laws of simple and compound interest (p. 70).

Soddy believed this confusion led to the development of financial institutions that were divorced from the physical principles underlying the production of wealth. Banks create money arbitrarily through the fractional reserve requirement system, and then loan the 'fictitious' money at interest. Wealth, the physical quantity represented by money, cannot grow forever at a compound interest rate as the laws of thermodynamics clearly imply. Soddy postulated that at some point debts would outstrip wealth, causing the banking system to collapse. Citing the economic malaise of the Depression as evidence, Soddy proposed as remedies a 100 percent reserve requirement and a statue requiring a constant price level.[3]

Writing at about the same time as Soddy was Alfred Lotka (1914, 1922, 1924), a mathematical biologist who argued that the mechanisms of natural selection could be explained in energy terms. Lotka did not specifically apply his biophysical principles to economics, but his theories were subsequently used by other analysts (Odum, 1971) to emphasize the relation between energy quality and living systems. Lotka proposed that the evolutionary process, combined with the laws of thermodynamics, formed a natural 'law' that underlay all human behavior. Lotka proposed that the battle of organic evolution was a "general scrimmage for available energy" in which all players were energy transformers - plants as energy accumulators animals as engines which burned the solar energy in plants. For Lotka (1922), survival was game governed by the laws of thermodynamics:

> ...in the struggle for existence, the advantage must go to those organisms whose energy-capturing devices are most efficient in directing available energies into channels favorable to the preservation of the species (p. 147).

[3] For more on Soddy's economic theories, see Trenn (1979) and Daly (1980).

The use of energy as a unifying concept for social, political and economic analysis reached a zenith with the technocratic movement in the USA and Canada during the 1930s. Led by the flamboyant and energetic Howard Scott, the Technocrats began in 1918 as a group called the Technical Alliance. The Alliance conducted an industrial survey of North America in which economic parameters were measured in energy units rather than dollars. Although the Alliance lasted only a few years, the Depression provided fertile ground for the re-emergence of the technocratic movement which used depressed economic conditions as a rallying point for their call for a complete overhaul of existing economic and political institutions. In 1921, Howard Scott and others formed Technocracy, Inc., and in conjunction with the Industrial Engineering Department at Columbia University, began an empirical analysis of production and employment in North America in energy units. The association with a prestigious university like Columbia combined with Scott's flamboyant relationship with the press made Technocracy internationally famous.

Technocrats believed that politicians and businessmen could not manage a complex, rapidly advancing industrial society. The technocrats proposed replacing politicians with scientists and engineers who had the technical expertise to manage the economy. This would allow social and economic institutions to reap the full benefits technological progress had made possible. With technical trained people making decisions, the Technocrats saw no physical limitations on expanding industrial output. They favored the continual replacement of labor with capital and energy, realizing as did Podolinsky and Soddy that empowering labor with greater quantities of fuel increased the productivity of labor.

The technocratic philosophy assumed that energy was the critical factor determining economic and social development. The Technocrats measured social change in physical terms: the average number of kilocalories used per capita per day. Money would be replaced by energy certificates, the total supply of which would be determined by the total amount of energy used in the production of goods and services. Every adult above the age of 25 would receive an equal portion of the total net energy used. People under 25 would receive a special 'maintenance allowance.' Like Soddy (1926), the Technocrats viewed with contempt the interest-bearing ability of regular money, so the energy certificate was to be non-transferable, non-negotiable, non-interest bearing, and had to be used within a specified period of time. Public interest in Technocracy waned in the 1940s as New Deal politics gained popularity, their forecasts of economic collapse proved false, and World War II began (Berndt, 1983).

THE 1950s

This was an exceptional period for research on the role of energy and natural resources in social and economic development. The work of White (1949, 1959), Ayres and Scarlott (1952), Putnam (1953), Cottrell (1955), Hubbert (1956) and Thirring (1958) stands today as some of the most insightful work ever done in this area.

The most comprehensive assessment of the role of energy in human societies was by W. Fred Cottrell (1955, 1972), a sociologist at Miami (Ohio) University for many years after an earlier career as a railroad man. Cottrell's (1955) *Energy and Society* is an extremely perceptive and readable analysis of the role of energy in human affairs. Cottrell emphasized two aspects of the relation between energy quality and economic and social development. The first was a quantity he termed "surplus energy," the difference between the energy delivered by a process and the energy invested in the delivery process. The second point Cottrell emphasized was the connection between the amount of energy used to subsidize the efforts of labor and the productivity of labor. Cottrell was impressed by the way much of what was called 'technological change' operated: using increasing amounts of higher quality energy (especially fossil fuels) per laborer to perform a specific economic task. According to Cottrell, the Industrial Revolution was revolutionary is economic terms because human labor was supplemented by enormous quantities of inanimate energy in the form of fossil fuels. Such subsidies powered an unprecedented increase in the amount of work done per worker-hour.

Cottrell also examined the influence of energy quality and energy surpluses on the development of social and cultural patterns. For example, the unidirectional character of energy in flowing water dictated certain economic and social arrangements between those who lived at river mouths and those upstream from them. Bulky raw materials much as grains, ores and timber were often produced in the hinterland and sent downstream to river mouth cities where those raw materials were combined to produce more valuable goods. Great accumulations of wealth and populations occurred in downstream cities, but very often such wealth did not find its way back upstream.

Despite his emphasis on energy, Cottrell did not argue that physical laws determined all social arrangements. Rather, he argued that resource availability set the general direction of social change. According to Cottrell, nature says to humans, "if you want this, here are the conditions under which you may have it." The two most important conditions are: (1) the investment of a minimum amount of already extracted energy to find and develop additional amounts of energy from the environment, and (2) the use of some available energy to protect one's energy flow from others seeking to use it for their own preservation. In regards to the first condition, Cottrell believed that the most important quality of an energy source was the surplus energy it delivered. Cottrell observed that, in general, societies adopted a new energy technology only if it delivered a greater energy surplus, and hence a greater potential to produce goods and services. The Industrial Revolution produced unprecedented economic and social expansion in large part because the energy surplus delivered by fossil fuels dwarfed that produced by the renewable energy sources used prior to the Revolution. Cottrell also observed that economies are sensitive to change over time in the magnitude of the surplus delivered by an energy source. Such changes were a function of the physical properties of the resource and the technologies used to extract it, with the former factor being the most important in the amount of surplus energy delivered to society may be the ultimate limit to economic expansion:

> It will only be when we get a response from nature, in the form of greatly diminished return in the form of surplus energy, that we can expect the present [industrial] revolution to slow down (p. 31).

Cottrell (1972) explored the differences between a biophysical and so-called humanist approach to biological and cultural evolution. Like Lotka, Cottrell emphasized the most fundamental relation in nature: organisms capture the radiant energy of the sun as a means to perpetuate the patterns that differentiate them from one another. On Lotka's hypothesis that natural selection favors those who maximize the energy flux through their systems, Cottrell stated:

> The evidence for Lotka's position is not yet sufficient to make it clear that it should be formulated into a law. But the tendency it expresses...fits other evidence that ability to control energy conversation is one factor involved in the persistence of patterns that require energy for their

> replication. Certainly the patterns of observable human behavior fall into that category. Man cannot escape thermodynamics...his effectiveness in controlling energy conversion so that is serves his needs and satisfies his values is one measure of his probable survival in a habitat.

Energy technology may in some cases impose only limited restrictions on the society using it, while in others (e.g., controlled fusion and breeders) the conditions necessary to utilize an energy source may be extremely narrow and the technical and social organizations required to operate them may be extremely precise.

Writing about the same time as Cottrell was M. King Hubbert who, like Cottrell and others before him, was impressed by the remarkable correlation between the burst of human civilization and the transition to a fossil fuel economy. Hubbert, a geophysicist by trade, used his extensive knowledge of physics, mathematics and geology to revolutionize the way in which the supply of nonrenewable resources were analyzed. Hubbert (1949) was one of the first to gather empirical data on rates of energy production, discoveries and consumption in order to make predictions on future energy availability. Hubbert (1949) made the startling prediction that the fossil fuel era would be short-lived, at least relative to the time frame commonly assumed and estimated domestic oil production would peak in the late 1960s. Hubbert (1974) stated:

> ...the epoch of the fossil fuels as a major source of industrial energy can only be a transitory and ephemeral event - an event, nonetheless, which has exercised the most drastic influence very experienced by the human species during its entire biological history (p. 196).

It was the ‘drastic influence’ that energy quality and availability had on economic development that led Hubbert to criticize standard economics for its lack of a biophysical basis. Echoing the words of Soddy written almost a half-century earlier, Hubbert (1966) stated:

> One speaks of the state of growth of GNP. I haven’t the faintest idea what this means when I try to translate it onto coal, oil, iron, and the other physical quantities which are required to run an

> industry...the quantity GNP is a monetary bookkeeping entity. It obeys the laws of money. It can be expanded or diminished, created or destroyed, but it does not obey the laws of physics (p. 291).

History has proven Hubbert's (1956, 1962) petroleum supply models to be remarkably accurate, and subsequent analyses by Hubbert (1967, 1980) confirmed the general accuracy of his original mathematical models of petroleum availability. However, Cleveland and Kaufmann (1991) showed that Hubbert's models have greater explanatory power when they explicitly account for short run economic forces that affect drilling, discovery, and production. It is ironic that the timing of what may prove to be one of the most important economic events in U.S. history , the peaking of domestic oil production, was predicted most accurately by a physical scientist.

The 1970s

The environmental movement and the petroleum supply and price shocks of the 1970s made energy, and natural resources in general, and important social, economic and political issue. Virtually overnight, the amount o research devoted to energy-environment-economic interactions increased substantially.

In *Environment, Power, and* Society, Howard T. Odum (1971) developed a systematic methodology using energy flows to analyze the combined system of humans and nature (see also Odum and Odum, 1976; Odum 1983; Odum 1996). Odum combined Darwin's theory of natural selection and Lotka's (1922) hypothesis of natural selection as an energy maximizing process into a 'general energy law': maximization of useful work obtained from energy conversion is the criteria for natural selection. Odum coined this 'law' the maximum power principle. The maximum power principle, while yet to be subjected to rigorous empirical testing, rests on the principles of natural selection set forth by Darwin and Lotka. Odum observed that ecological and other systems that survive and prosper used energy at some 'optimum' rate 'better' than competing energy utilization strategies. Since human systems are subjected to the same energy constraints as any other system, Odum suggests that any ethic for the survival of humans must meet this same logical and cultural, operated on differential rates and efficiencies of energy use by ecosystems and economies.

Two of Odum's most important contributions to biophysical economics are energy quality and the countercurrent flow of energy and money in the economy. Energy quality refers to the relative ability of the economy to use different fuels to produce economic output per heat equivalent burned. Odum argued that because fuels differ in quality, societies with access to higher-quality fuels have an economic advantage over those with access to lower quality fuels. Odum also stressed the importance of matching economic tasks with fuels of appropriate quality. High-quality fuels such as electricity are best used to control the flow of larger, lower-quality flows in the economy. Electricity is well-suited to operating a computer which can perform tremendous amounts of work per kcal of electricity. Electricity used for space heating is a poor use of high-quality energy because space heat could also be provided by lower-quality fuels such as petroleum, coal or wood.

Odum argued that energy was the source of economic value. He pointed out that wherever a dollar flow existed in the economy, there was a requirement for an energy flow in the opposite direction. Money is used to buy goods and services, of necessity derived from energy. Each purchase operates through the economy as a feedback, stimulating more energy to the drawn from the ground and into the economy to produce additional goods and services. Money circulates in a closed loop, whereas low-entropy energy moves in from the outside, is used for economic tasks, and then leaves the economic system as degraded heat. Odum also observed that the large natural energy flows of solar radiation, water, wind etc. are essential for life, have no associated dollar flows. The costs of using these energy flows do not, therefore, enter into economic transactions directly, often leading to their misuse or the mismanagement of life-sustaining environmental services.

Empirical support for some of Odum's ideas was given by Costanza (1980, 1981) who analyzed the relationship between the direct and indirect energy used to produce a good or service in the U.S. economy and the dollar value attached to that good or service in market transactions. Costanza used the term embodied energy to describe the total energy cost of a good or service. Costanza (1980) showed that there was a strong statistical relation between the embodied energy content of a good and its dollar value if energy calculations included an estimate of the energy costs of labor and government services as well as direct fuel use. Costanza (1981) used this empirical evidence to argue for an embodied energy theory of economic value which maintains that the value of any good or service to humans is ultimately related to the quantity of energy directly and indirectly used in its production.

Like Odum's, Costanza's embodied energy theory of value was roundly criticized by many economists (Daly, 1981; Heuettner, 1982), but he defended it with a theoretical argument based on two assumptions. First, solar energy is the only net input into our closed biosphere. Second, like Lotka and Odum argued, the struggle to sequester free energy to sustain life and maintain existing cultural arrangements was the most fundamental human activity. Based on these assumptions, Costanza (1981) hypothesized that a perfectly functioning free market would, through a complex evolutionary process, arrive at prices proportional to embodied energy content. Because the market is not perfect, however, embodied energy calculations can pinpoint problems and value nonmarketed goods and services (i.e., externalities).

The late Earl Cook, a geologist and former Dean of Geosciences at Texas A & M University, was interested not only in empirical modeling of resource supply systems, but also in broader social issues associated with energy use, resource depletion, and environmental degradation (Cook, 1976a, 1976b). Cook's (1976b) book *Man, Energy, and Society* stands as one of the most complete books on the subject. Cook was concerned with the dangers associated with the apparent incompatibility of our society's fervent, almost religious devotion to economic growth, and the fact that such growth was dependent upon a finite, nonrenewable stock of fossil fuel. Cook observed that:

> Progress has depended upon the increasing control of energy...the Rhinelanders harnessed oxen, the Benedictines waterpower. The maritime nations (Spain, Portugal, the Netherlands, Great Britain) set the winds to work. We, the Americans, started with wood, switched to coal, then to petroleum in our race to the world's largest level of material affluence and national strength. Without abundant and cheap energy, Europe could not have recovered so astonishingly fast from the ravages of World War II, and Japan could not have shot to world prominence as an industrial power.

Cook argued that industrial society, and the U.S. in particular, is faced with a resource watershed unparalleled in history. With the quality of fossil fuels rapidly diminishing, industrial society has two options. The progress option, as described by Cook, is to go on believing that omnipotent technological change and so-called economic laws will rescue us from any resource-related problems. The prudence option is to adjust our values and lifestyles commensurate with energy and resource realities. Cook (1979) warns that:

> The greatest danger in our bemused drift towards the energy waterfall is that the resulting shock will find us stripped of democratic government by an opportunistic group that comes out on top in the wreckage, a group that controls us through their control of the energy systems... (p. 13).

The empirical methodology of biophysical economics was greatly enhanced by Bruce Hannon (1975, 1977), Herendeen and Bullard (1975), and others at the Energy Research Group (ERG) at the University of Illinois[4]. The ERG developed an input-output model of the U.S. economy based on the energy flows from which the direct and indirect energy cost of any good or service could be calculated.

Hannon (1977) used this information to argue that the U.S. should adopt a strong energy conservation ethic to offset diminishing supplies of domestic fossil fuels and increased reliance on foreign sources of fuel. Hannon stressed that consumers had to become more aware of the impacts their decisions had on energy demand, because different goods and services had different energy costs. For example, even if a household reduced its direct fuel use by lowering thermostats or driving less, the money saved by doing so could be respent on goods that required an equivalent amount of energy for their production, thereby negating the original act of conservation. Regarding consumer awareness of energy issues, Hannon (1977) stated:

> An awareness of the stock of available energy resources, analogous to the perception of a savings account or a woodpile stacked by the fireplace, it also needed. The absence of this awareness is the root of the problem...The ignorance of the fact that there is a finite quantity of energy available is perhaps the greatest tragedy of this age (p.99).

Hannon proposed several methods which could encourage energy conservation, the most interesting of which was an energy rationing scheme which would provide direct consumer control or energy use.

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[4] During the 1970s and early 1980s the ERG produced over 300 papers, reports and technical documents on a wide rang of energy and economic topics. This body of research represents one of the largest, comprehensive, and consistent approaches to modeling energy-economic interactions in existence.

Under this scheme, people would work for energy coupons, each representing a specified number of energy units. These coupons would be traded for the direct and indirect energy embodied in goods and services. The national government would own the energy sources and issue new coupons to meet targeted energy use rates. While not likely to be adopted in a dollar-oriented society, Hannon's proposal is consistent with the biophysical philosophy of Soddy and the Technocrats, who believed standard economic and financial institutions were inadequate allocaters of energy and other natural resources.

Robert Ayres (1978; see also Ayres and Kneese, 1969; Ayres and Nair, 1984) was another physical scientist who used biophysical methods to gain insights into the economic process. Using a material - energy balance model, Ayres described the inconsistency of the closed, cyclic model of standard economics with the First Law of Thermodynamics, which states that what low-entropy matter and energy enters the economic process as useful raw materials must ultimately leave the process and return to nature as high entropy wastes. One immediate implication is that so-called 'externalities' are necessarily pervasive rather than exceptional characteristics of the economic process as some economic theorists had generally assumed.

Ayres used the principles of entropy and the Second Law to describe natural resources quality in physical terms. High-quality negentropy stocks (i.e., highly ordered deposits of natural resources) are those which require low amounts of fuel and other natural resources to discover, extract and process. Ayres described a thermodynamic Catch-22 related to resource depletion. The faster we deplete mineral resource negentropy stocks, the more we accelerate the demand for a depletion of fossil energy resources, since lower-quality resources require more energy for their extraction. This ratchet effect is amplified as high-quality fuels such as coal must be used, which themselves require a greater energy investment per unit energy extracted. Ayres emphasized that the standard economic model of natural resource scarcity does not account for the positive feedback between decreasing resource quality and the rate of extraction of those resources. The standard model has until recently ignored the increased environmental costs due to the build-up of high entropy wastes from increased use of energy matter.

Ayres et al. (1996) and Ayres and Martiñas (1995) propose a system of aggregating energy and materials based on exergy. Exergy measures the useful work obtainable from an energy or material, and is based on the chemical energy embodied in the material or energy based on its physical organization relative to a reference state. The physical units for exergy are the same as for energy or heat, namely kilocalories, joules, BTUs, etc. For fossil fuels, exergy is nearly equivalent to the standard heat of combustion; for other forms of energy specific calculations are needed that depend on the details of the assumed conversion process. For materials, exergy is defined jointly for a material and the reference state with which it must ultimately reach thermodynamic equilibrium (Ayres et al., 1996). Thus, exergy measures the degree to which a material is organized relative a random assemblage of material found at an average crustal abundance, an average concentration of sea water or of gases in the atmosphere. The higher the degree of concentration, the higher the exergy content.

Ayres argues that exergy has a number of useful attributes for aggregating heterogeneous energy and materials. Exergy is a property of all energy and materials and in principle can be calculated from information in handbooks of chemistry and physics (e.g. Linde 1991-1992) and secondary studies (e.g. Szargut et al. 1988). Thus, exergy can be used to measure and aggregate natural resource inputs as well as wastes. For these reasons Ayres argues that exergy forms the basis for a comprehensive resource accounting framework that could "provide policy-makers with a valuable set of indicators." One such indicator is a general measure of "technical efficiency," the efficiency with which "raw" exergy from animals or inanimate source is converted into final services. A low exergy efficiency implies room for the improvement in the efficiency of converting energy and materials into goods and services. Similarly, the ratio of exergy embodied in material wastes to exergy embodied in resource inputs is the "most general measure of pollution" (Ayres, et al. 1996). Ayres and Martiñas (1995) also argue that the exergy of waste streams is a proxy for their potential ecotoxicity or harm to the environment, at least in general terms.

In *Steady-State Economics* (1977), Herman E. Daly points out the logical inconsistencies between the emphasis placed on economic growth and the energy and environmental realities confronting us. Like Soddy (1926), Daly argued that our preoccupation with monetary flows at the expense of thermodynamics principles misleads us into believing that technological advance is limitless, and that perpetual economic growth is not only physically possible, but morally and ethically desirable as well.

One of Daly's (1985) most insightful contributions to biophysical theory was his critique of the conceptual model of the economic process found in most introductory textbooks. In this model, exchange value embodied in goods and services flows from firms to households and is called national product. A counter flow of equal value, in the form of factors of production, product. A counter flow of equal value, in the form of factors of production, flows back to firms from households and is called national income. This flow is depicted as circular, elf-feeding, and self-renewing.

Like Ayres (1978), Daly argues that the circular flow model is seriously incomplete because it focuses on the circular flow of exchange value (i.e. money) rather than the throughput of low-entropy natural resources from which all goods and services are ultimately derived (Figure 1). Daly emphasizes that the circular flow of exchange value is coupled with a physical flow of matter-energy which is not circular. The matter-energy flow is linear and unidirectional, beginning with the depletion of low-entropy resource stocks from nature and ending with the pollution of the environment with high-entropy wastes. In this view, nature is the ultimate source of the raw materials necessary to produce economic value, as well as the ultimate sink for the unavoidable by-products of the production process. Daly (1985) states:

> It is, of course, the linear throughout [of matter-energy], not the circular flow of value, that impinges on the environment in the forms of depletion and pollution. It is impossible to study the relation of economy to the ecosystem in terms of the circular flow model, because the circular flow is an isolated, self renewing system with no inlets or outlets, no possible points of contact with anything outside itself. Yet in economic theory the circular flow has the spotlight, while the concept of throughput is only dimly visible in the shadows. Consequently, the relation of the economy to its environment is a topic which economic theory has only occasionally illuminated and often obscured (p.2).

Daly (1977) argued the benefits of a steady-state economy in which the stocks of physical wealth (capital) and people (population) are held constant. The accumulation of physical wealth is controlled by controlling the rate of energy and matter use. Population is held constant by some form of birth control practice. Daly acknowledged that such controls are not palatable to most of us because we lie in a growth-oriented society. Daly believes, however, that such a transition is inevitable due to rising world population resource depletion, and environmental degradation, and that the social costs associated with a voluntary transition to a steady-state will be far less than those that would occur if environmental conditions force us into such changes.

The Contribution of Nicholas Georgescu-Roegen

Due to his enormous influence and to the theme of this volume, the work of Nicholas Georgescu-Roegen deserves more detailed discussion. Much of what follows is based on a review of his work published in a special issue of *Ecological Economics* devoted to Georgescu-Roegen (Cleveland and Ruth, 1997).

Georgescu-Roegen had a deep and thorough understanding of economic theory, economic history, and mathematics, as well as considerable knowledge of physics and the history and philosophy of science. His genius was rooted in his instincts about the relevance of biophysical principles for human economic aspirations. Georgescu had a vision of economics rooted in the physics, chemistry, and biology of human existence, and the analytical and intellectual capabilities to weave those pieces together with the humanistic tradition of economics.

Traditional economic analysis concentrates on the exchange of commodities among the members of an economy, focusing on the role of consumer preferences, technologies, and capital endowments for the existence and stability of market equilibria. Georgescu sought to ground economic analysis in the biophysical realities of the economic process. His efforts occurred independently of, and at the same time as Boulding's (1966) celebrated demonstration of the environmental implications of the mass-balance principle, Odum's (1971) energy flow analysis, Ayres and Kneese's (1969) materials balance approach, and the application of input-output techniques to the analysis of energy use in ecological and economic systems by Hannon (1973a; 1975) and Bullard and Herendeen (1975). Together, these studies influenced to a significant extent the field of biophysical and ecological economics—the questions they ask and the methodologies they applied. But what distinguishes Georgescu's contribution from the other pioneers was his ability to incorporate biophysical principles into the everyday language and models of standard economics. In doing so his work pointed towards the economic importance of the laws of conservation of mass and energy, and the entropy law.

For Georgescu, a great sin of conventional economic analysis is the confusion of funds and flows, leading to a fundamental misrepresentation of the relation between manufactured and natural capital. A glaring example of this is the standard representation of funds and flows in models such as the Cobb-Douglas production functions, namely:

$$Q = K^{\alpha_1} L^{\alpha_2} R^{\alpha_3} \tag{1}$$

where Q is output per time period, K is the stock of capital, R is the flow of natural resources, L is labor supply per time period, and a_1, a_2, a_3 are fixed parameters. As Georgescu (1979) observes, this implies that with a constant labor force L_0, one could obtain any given Q_0 if the flow of natural resources satisfies the condition

$$R^{\alpha_3} = \frac{Q_0}{K^{\alpha_1} L_0^{\alpha_2}} \tag{2}$$

Consequently, we could maintain a constant output indefinitely with an ever-diminishing amount of R if the quantity of K can be increased sufficiently. But Georgescu (1979) exposes this “conjuring trick,” charging that excessive preoccupation with “paper and pencil exercises has led to accepting these exercises without any concern for their relation to facts (p. 97).” Of course, on an economy-wide level the increase in K implies an increase in the use of R, so that if K approaches infinity, R rapidly will be exhausted by the production of capital (Christensen, 1989). Other analysts have echoed Georgescu’s point that in certain applications or interpretations, widely used models such as the Cobb-Douglas or constant elasticity of substitution (CES) production functions embody the physically impossible assumption that a given output can be maintained as energy or material inputs vanish if manufactured capital can be increased sufficiently (Dasgupta and Heal, 1979; Meshkov and Berry, 1979; Ayres and Nair, 1984; Perrings, 1987; Ruth, 1995a). The laws of conservation of mass and energy clearly dictate that no agent can create the stuff on which it operates, i.e., manufactured capital cannot create the resources it transforms and the materials it is made from.

One of Georgescu’s (1979b, 1982) most renowned arguments is that “matter matter’s too.” Georgescu reacted strongly against energy theories of value (e.g., Costanza, 1980; Hannon, 1973b; Odum, 1971). He argued that the principle of entropy applied to materials as well as energy. Energy and materials always are used together; we can never handle energy without a material receptor, material lever, or material transmitter (Georgescu-Roegen, 1979). Thus, Georgescu argued that there is a “dual” of the first law of thermodynamics, namely that no mechanical work can be performed without the use of some matter. He further asserted that the second law of thermodynamics, which precludes the possibility of a machine converting energy to work with 100 percent efficiency, is due to "imperfections in matter." That is, there are no frictionless materials, no perfect insulators, no perfect conductors, no perfectly elastic materials, etc. (Georgescu-Roegen, 1979). These imperfections preclude the perfect conversion of energy into mechanical work. Consequently, a full understanding of material and energy transformations requires explicit attention to matter.

The hand-in-glove relation between energy and material use produces a continuous conversion of matter from high quality to low quality state, in a manner directly analogous to the dissipation of energy. Georgescu (1979b) states:

> All over the material world there is rubbing by friction, cracking and splitting by changes in temperature or evaporation, there is clogging of pipes and membranes, there is metal fatigue and spontaneous combustion. Matter is thus continuously displaced, altered, and scattered to the four corners of the world. It thus becomes less and less available for our purposes (p. 1034).

Georgescu emphasized that "the Entropy Law in its present form states that *matter, too, is subject to an irrevocable dissipation*" (Georgescu-Roegen 1976, p.8, original emphasis). This statement is, without doubt, correct for isolated systems. All changes in the thermodynamic state of materials must be accompanied by a degradation of the quality of energy. If the system is isolated, i.e. no mass or energy flows cross its boundaries, the system will ultimately reach a state at which no gradients in temperature, pressure or material composition exist that enable the system to change its state. Such a state of the system is referred to as heat death.

In subsequent arguments Georgescu (1977) asserted that "isolated systems present only a small interest to us. If we set aside the case of the whole universe, isolated systems are set up (with some degree of tolerance) only in laboratories" (p. 267). In much of his work on the role of matter in economic processes he then focused on closed, rather than isolated systems, i.e. systems that *do* have energy flows crossing their boundaries but *do not* have material flows across their boundaries:

> Having in mind the statistical interpretation of thermodynamics, one may argue that we can certainly reassemble the pearls of a broken necklace scattered over the floor. Is not recycling such a type of operation? To see the error in extrapolating from the molar to the molecular level, let us suppose that the same pearls are first dissolved in some acid and the solution is spread over the oceans — an experiment which depicts what actually happens to one material substance after the other. Even if we had as much energy as we pleased, it will take us a fantastically long, practically infinite time, to reassemble the pearls. (Georgescu-Roegen, 1977, p. 269)

Inspired by this and similar examples, Georgescu went on to elevate his observations to a Fourth Law of Thermodynamics — or Law of Matter Entropy — describing the degradation of the organizational state of matter:

> [...]a system that can exchange only energy with its outside and performs work indefinitely at a constant rate [...] is another thermodynamic impossibility. [... S]ooner or later, some elements will become totally dissipated. (Georgescu-Roegen, 1981, pp. 53-54)

The bottom line for Georgescu is that due to material dissipation and the generally declining quality of resource utilization, materials in the end may become more crucial than energy. This leads him to criticize Boulding's (1966) claim of no law of increasing material entropy. He rejects Daly's (1973) version of a steady-state economy on the grounds that materials dissipate in a closed system such as the Earth just as energy does. Georgescu states:

> Complete recycling being impossible, even in the steady state the "transactions" between the economic process and the environment must necessarily consist of some available matter as well in order to compensate for the matter dissipated continuously and irrevocably. (SEJ, p. 1039)

Georgescu also rejects the "infinite resources" arguments made by Brown et al. (1957), Brooks and Andrews (1974) and Goeller and Weinberg (1976), because they ignore the importance of changes in the quality of matter. For example, Brooks and Andrews (1974) state that the literal notion of running out of materials is ridiculous because the entire planet is composed of minerals. Georgescu exposed the fallacy of this argument by observing that, by the same token, we could argue that we will never run out of energy because the entire planet is full of energy. Indeed, the ocean contains enough energy to support undreamed of economic activity for millennia to come. However, the temperature gradient in the ocean is so small that for all practical purposes the enormous store of energy is unavailable. Similarly, Georgescu (1979b) argues that many of the materials are in low quality deposits that for all practical purposes render them unavailable.

Georgescu's emphasis of material quality shares a common theme with the biophysical perspective of resource scarcity held by some ecological economists (Slesser, 1978; Hall et al., 1986; Gever et al., 1986; Cleveland, 1991, 1993; Peet, 1992; Ruth, 1993) and a number of physical scientists (Cook, 1976; Chapman and Roberts, 1983). The biophysical manifestation of scarcity is the use of, and often times the depletion of, increasing amounts of natural and human-made capital to deliver a unit of resource to society. A decline in the quality of the natural resource base due to cumulative depletion, an increase in the instantaneous rate of exploitation, or an increase in the scale of extraction, increases the amount of natural capital used to extract a unit of natural resource. The biophysical perspective of scarcity measures the cost of obtaining natural resources in physical terms, and thereby emphasizes the throughput of energy and materials required to extract resources, and the resultant impact of that throughput on a broad array of ecosystem services in different quantities and spatial scales.

Natural resources in a highly organized state are more economically useful because they have lower energy costs. The inverse relation between resource quality and the energy cost has been demonstrated for a wide range of minerals and fossil fuels (Page and Creasy, 1975; Chapman and Roberts, 1983; Cleveland, 1993; Ruth, 1995c). The increased effort required to develop lower grade resources also increases their environmental cost. In metal mining, for example, deterioration of ore quality in underground mines spurs the expansion of surface mining where the volume of waste material produced per ton of ore is twelve times greater (Gelb, 1984). The stripping ratio (tons of waste per ton of ore extracted) in metal, nonmetal, and coal surface mines in the U.S. has increased sharply in the last half-century (Gelb, 1984). That decline in resource quality increases the land required to produce a ton of coal which, in turn, increases the amount of degraded land that must be reclaimed and the quantity of water used in reclamation. Cleveland (1993) found that the increase in the energy cost of petroleum extraction in the U.S. also is associated with an increase in the quantities of water used and CO_2 released in the extraction process.

Georgescu's Fourth Law has been criticized by a number of analysts in economics and the physical sciences. Ayres and Miller (1980) argue that Georgescu's assertion that intrinsically scarce materials cannot be recovered (regardless of energy expenditure) from average rocks and the ocean is just plain wrong. They observe that physical dissipation of materials can never result in a distribution worse (from the standpoint of recovery) than a hypothetical homogenous regolith in which every element is present exactly in its average crustal abundance. They argue that all elements can be extracted from such a regolith provided there is enough available energy. Ayres and Miller conclude that, in theory, energy is the only resource that could ultimately limit economic growth.

It recently has been pointed out, that on a fundamental physical level, there is no such *law* as the Fourth Law of Thermodynamics stated by Georgescu (Bianciardi et al. 1993, Ruth 1995a). Whether at the molar or molecular level, in principle it is always possible to use the incoming high-quality energy to trace, collect and reassemble the dissipated elements. Well-documented counter examples to Georgescu's Fourth Law include the biogeochemical cycles—driven by the influx of solar radiation—that constantly funnel dissipated materials through a closed, global ecosystem and temporarily generate high material concentrations. It is those processes that lead to the formation of pearls from ocean water in the first place, the agglomeration of metals in ores and the formation of fossil fuels.

The theoretical flaws of Georgescu's Fourth law have led some to dismiss Georgescu's ideas or deny their significance (Månsson 1994). What should be at issue, however, is not a "categorical impossibility" of perfect recycling asserted by Georgescu (1981, 1986). More important are the relationships among the processes that lead to a dissipation of high-quality energy and degradation of material resources on the one hand and the processes that capture high quality energy and change materials from less desired to more desired thermodynamic states on the other hand. With thermodynamics, central for an assessment of these relationships are the concepts of information and time.

To be able to trace and collect dispersed materials requires not only the availability of energy but also information and time. The fundamental physical relationships among those three inputs into processes that upgrade the state of materials have been described by Szilard (1929) and applied to industrial systems by Spreng (1993), Chen (1992, 1994), Ruth and Bullard (1994) and Ruth (1993, 1995b). The role of information relative to the other inputs into production processes prompted Boulding (1982) to claim that energy itself is unimportant. What is important is the knowledge to make use of material endowments that are present in less desired forms and change their state to more desired ones. In the case of biological systems, that knowledge is embodied in their genetic make-up. In the case of economies, it is present in the capital goods, human capital, institutions and other repositories of knowledge such as computers and libraries (Ruth, 1996a).

Biological systems, however, differ markedly from economic systems with regard to the time available to trace, collect and upgrade materials. Ore deposits and fossil fuels have been formed over time periods that are far too long to be of relevance for economic decision making. The formation of ore deposits and fossil fuels is powered by the inflow of solar radiation, utilized at low efficiencies, and heat from the Earth's core. In contrast, economic systems use significant amounts of nonrenewable resources to speed up the production of goods and services. Thus, from an economic perspective, an increasing dispersal of materials is constraining as long as tracing, collecting and upgrading those materials requires expenditures of finite, costly sources of low-entropy energy.

These perspectives highlight human participation in biogeochemical cycles and the importance of thermodynamics for understanding the environmental significance of that role. For example, the price of a material produced from virgin sources or from waste is a direct function of its degree of concentration in the parent source material or its dilution in the waste stream, respectively (Allen and Behmanesh, 1994). Hence, the recycling potential for materials in hazardous waste streams is determined by their dilution, because highly dilute materials require more work, and hence higher cost, to upgrade to a desired raw material state.

The increase in entropy from energy use can be compared to the decrease in entropy that results from upgrading the state of materials either from virgin ores or waste residuals to arrive at a physical measure of the efficiency of economic processes. Comparisons of this measure over time provide insight into the ability of technical change—that itself requires materials and energy to take place—to counteract depletion and pollution (Ruth 1996b, Ayres et al. 1996). An advantage of these measures over traditional economic measures of efficiency is their ability to make judgments that are irrespective of changes in consumer preferences, market forms or other institutional settings that mask the physical reality of production and consumption processes.

Despite the flaws in Georgescu's definition of a Fourth Law, his insistence on the importance of materials for production and consumption processes highlighted the differences between economic processes and "natural" processes. The wide-ranging impact of his work is evident in a number of ways. Economists and ecological economists continue to discuss and debate important details of Georgescu's work (e.g. Tang et al., 1976; Khalil, 1990; Lozada, 1991; Khalil, 1991; Bianciardi et al. 1993; Gowdy, 1993; Daly, 1995), and they debate conventional economists about the usefulness of thermodynamics in economic analysis (e.g. Young, 1991; Daly, 1992). Numerous studies of material and energy flows across the economy-environment boundary applied mass and energy balances to account for those flows and their contribution to economic production (Ayres and Kneese, 1969; Odum, 1971; Daly, 1973; Slesser, 1978; Ayres, 1978). Others have expanded on the use of mass and energy balances to account for changes in the quality of the material and energy flows as production and consumption occur (Costanza, 1980; Cleveland et al., 1984; Hall et al., 1986; Faber et al., 1985; Gever et al., 1986; Peet, 1992; Perrings, 1987; Ruth, 1993; Ruth and Bullard 1994; O'Connor, 1991; Binswanger, 1993). Georgescu's focus on the dispersal of materials and limits on recycling foreshadowed the development of the fields of industrial metabolism (Ayres and Simonis, 1994) and industrial ecology (Graedel and Allenby, 1995) in which the analysis of material cycles is used to understand how production and consumption impact the environment, and how to design new technologies that reduce such impacts. Finally, the importance of the entropic perspective advanced by Georgescu and the other pioneers is evidenced by the prominent attention devoted to it in histories of thought (Martinez-Alier, 1987; Cleveland, 1987), surveys of ecological economics (Krishnan et al., 1995; Costanza et al., 1997), and this volume in his honor.

Ecological Economics and Industrial Ecology

Concepts and methods in biophysical economics have become cornerstones of the new fields of ecological economics and industrial ecology. The International Society of Ecological Economics (ISEE) was formed in 1989 with the goal of integrating ecology and economics and other fields into a transdiscipline aimed at developing a sustainable world. Specific research areas include ecological modeling, ecological limits to growth, integrated assessment of climate change, biodiversity, valuation of natural capital, and ecological tax reform.

The basic points of consensus in the ecological economics vision are: (Costanza et al., 1997)

1. The vision of the earth as a thermodynamically closed and nonmaterially growing system, with the human economy as a subsystem of the global ecosystem. This implies that there are limits to biophysical throughput of resources from the ecosystem, through the economic subsystem, and back to the ecosystem as wastes;
2. the future vision of a sustainable planet with a high quality of life for all of its citizens (both humans and other species) within the material constraints imposed by 1;
3. the recognition that in the analysis of complex systems like the earth at all space and time scales, fundamental uncertainty is large and irreducible and certain processes are irreversible, requiring a fundamentally precautionary stance; and
4. that institutions and management should be proactive rather than reactive and should result in simple, adaptive, and implementable policies based on a sophisticated understanding on the underlying systems which fully acknowledges the unerlying uncertainties. This forms the basis for policy implementation which is itself sustainable.

Note that the basic tenets of biophysical economics form the basis for point 1. Histories and surveys also emphasize the biophysical underpinnings of ecological economics (Martinez-Alier, 1987; Cleveland, 1987; Krishnan et al., 1995; Costanza et al., 1998),

As of 1998, ISEE has more than 1300 members in 60 nations with regional chapters in Australia, Russia, Brazil, Europe and Canada. It has sponsored major international meetings with attendance in the thousands, as well as invited sessions at meetings of the Ecological Society of American and the American Economics Association. Edward Elgar Publishing has established a series in Ecological Economics in their International Library of Critical Writings in Economics, joining series in other areas of conventional economics. Specific research topics within Ecological Economics have generated special issues in journals such as *Ecological Applications* and *Environment and Development Economics*. Thus, in academic circles ecological economics seems to be having a significant impact (Costanza, 1996).

Industrial ecology examines local, regional and global materials and energy uses and flows in products, processes, industrial sectors and economies (Leifset, 1997; Ayres, 1989; Socolow et al., 1994; Graedel and Allenby, 1995). It focuses on the potential role of industry in reducing environmental burdens throughout the product life cycle from the extraction of raw materials, to the production of goods, to the use of those goods and to the management of the resulting wastes. Industrial ecology is ecological in that it views human activity -- industry in the very broadest sense -- in the larger context of the biophysical environment with which we exchange energy and material flows, and (2) looks to the natural world for models of highly efficient use of resources, energy and byproducts. Topics include material and energy flows studies ("industrial metabolism"), dematerialization and decarbonization, life cycle planning, design and assessment, design for the environment, extended producer responsibility ("product stewardship"), eco-industrial parks ("industrial symbiosis"), and product-oriented environmental policy.

Conclusions

Biophysical economics is based on a conceptual model of the economy connected to, and sustained by, a flow of energy, materials, and ecosystem services. That simple but fundamental principle has formed the basis for wide-ranging research on the economy-environment relationship by a analysts from a variety of disciplines. The power of the biophysical perspective is evidenced not only by the long history it has enjoyed, but also by the fact that the analysis of energy and material flows is central to current issues about sustainability, environmental quality, and economic development.

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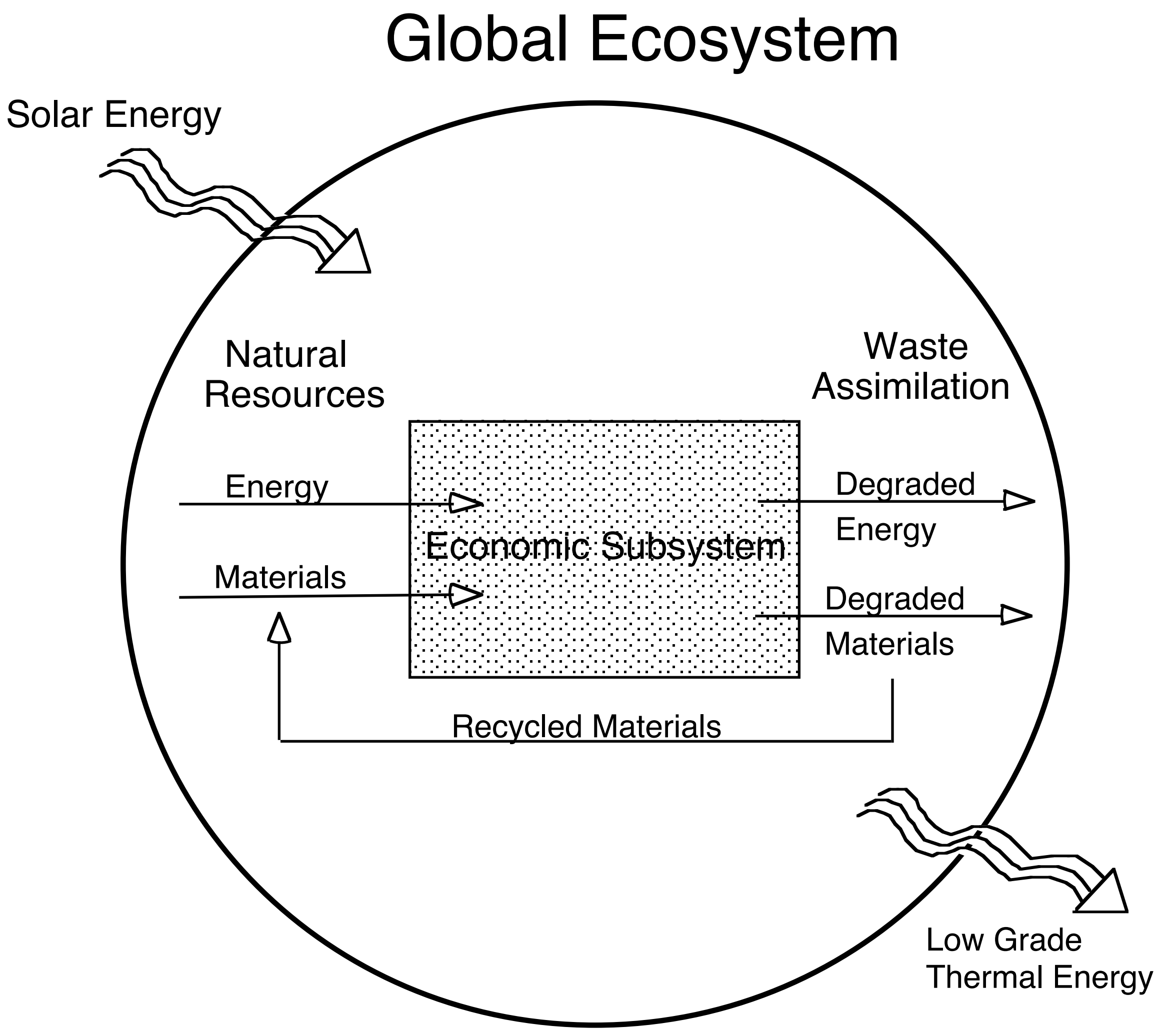
Figure Legends

Figure 1. The economy is an open subsystem of the larger closed environmental system. The economic process is sustained by the irreversible, unidirectional flow of low entropy energy and materials from the environment, through the economic system, and back to the environment in the form of high entropy, unavailable energy and materials (Modified from Hall et al., 1986 and Goodland et al., 1991).


Global Ecosystem
Solar Energy
Natural
Resources
Waste
Assimilation
Energy
Materials
Economic Subsystem
Degraded
Energy
Degraded
Materials
Recycled Materials
Low Grade
Thermal Energy