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# BIOPHYSICAL ECONOMICS: HISTORICAL PERSPECTIVE AND CURRENT RESEARCH TRENDS

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## ABSTRACT

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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 relatistic and systematic treatment of natural resources.

## INTRODUCTION

The energy and environmental events of the 1970s, and the economic disruptions resulting from them, made society acutely more aware of the connection between economic well-being and the quality and availability of natural resources. An intimate connection has always existed between the human economy and the natural environment because it is only from nature that humans derive the energy and other raw materials needed to sustain life and expand economic output. Until recently, natural resource quality and availability have been largely ignored in standard models of economic production. Consequently, resource events of the 1970s 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). Traditional economic models which had guided economic prosper-

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ity during the post-WWII era were unable to effectively manage the negative economic effects of these resource events. As a result, these models have been criticized for their lack of a sophisticated and realistic treatment of the role of natural resources in human economic affairs (Ayres and Kneese, 1969; Georgescu-Roegen, 1971; Odum, 1971; Daly, 1977; Hall et al., 1986).

Many of these critiques spring from a broad body of research known as biophysical economics [1], the basic tenets of which are the focus of this analysis. Biophysical economics differs from standard economic theory by using thermodynamic and ecological principles which emphasize the role of natural resources in the economic process, and also to identify areas of economic theory which neglect rudimentary environmental considerations. I will argue that the biophysical approach was validated by the economic consequences of the resource events mentioned above which escaped adequate prediction and explanation by standard economic theory. Recent empirical research has substantiated many points biophysical analysts have argued for more than a century, and also draws attention to the lack of empirical support for much of standard economic theory.

Biophysical economics is not, as some might think, a trendy response to recent energy and environmental events. 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 state characterized by empirical testing of some basic biophysical principles.

## ORGANIZATION OF ANALYSIS

Two themes characteristic of biophysical economics will be used to trace its development. The first is the degree of emphasis placed on the physical laws that govern the energy and matter transformations which form the basis of the production process. Biophysical analysts have argued that ignoring such constraints have prevented standard economic theory from fully accounting for the economic significance of changes in the quality of natural-resource inputs to economic production, and the basic life support services that assimilate vast quantities of wastes which inevitably result from all energy–matter transformation.

The second theme is the physical interdependence between the factors of production. The supply of capital and labor depends on inputs of low-ent-

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

ropy matter and energy since neither capital nor labor can physically create natural resources. Standard economic production functions misrepresent this important interdependence. As a result, many biophysical analysts challenge the 'omnipotent technology' hypothesis which is based in part on the factor substitution model. This hypothesis maintains that the depletion of high-quality fossil fuel and mineral deposits will not result in a decline in our per-capita material standard of living because depletion automatically sets into motion forces which counteract depletion effects. Central to the omnipotent technology hypothesis is the neoclassical model of factor substitution which describes the mechanism by which capital, labor and natural resources can be substituted for each other in response to changes in their price.

## 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 well. 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; all 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 called agriculture the 'productive' class, while manufacturing and commerce were 'unproductive' or 'sterile'. Juxtaposed between these two classes were the 'class of proprietors' consisting of the landowners, the king, and the cleargy who received in the form of rent, taxes, and tithes 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 form, economic concepts such as general equilibrium and the Leontief (1941) input–output system, both of which became widely used economic models (Meek, 1963).

The influence of the Physiocratic School peaked in the 1760s and declined rapidly thereafter. For most economists, the Physiocrats represent an historical curiosity and 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 of economic production intuitively grasped by the Physiocrats were formalized by the discovery of the laws of thermodynamics. Soon after Carnot (1867), Clausius (1824) and other 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 disparate biological and physical processes were quantified and compared. Carnot's (1824) 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 good and services.

Physical scientists and biologists were the first individuals to use energy flows to explain social and economic development. Joseph Henry (1973), 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–philospher Herbert Spencer (1880) observed that human systems have the unique ability to temporarily hald 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 Ukranian socialist, was the first to explicitly scrutinize the economic process from a thermodynamic perspective [2]. Podolinsky was

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

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 lay 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); 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; C. 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. 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 diety, 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 human first tapped energy capital (fossil fuel stocks) rather than energy revenue (solar energy) unprecedented amounts 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 'ficticious' 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 100% reserve requirements and a statute 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 accumula-

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

tors and animals as engines which burned the stored energy in plants. For Lotka (1922), survival was a 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).

Lotka proposed that natural selection acts to preserve and increase the numbers of those organisms that maximize the total energy flux through their system, so far as such behavior is compatible with all constraints on that system. One obvious constraint is energy availability. When energy supplies are not limiting, the efficiency of energy conversions is only one of many survival criteria. When energy supplies are limiting, energy conservation and efficiency become critical factors in the selection process, according to Lotka.

The use of energy as a unifying concept for social, political and economic analysis reached a zenith with the technocratic movement in the U.S.A. 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 Technocrats forecast the day when the average laborer would need to work only four hours per day, 1965 days per year.

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 the Technocracy movement gradually waned in the 1940s as New Deal politics gained populatiry, their forecasts of economic collapse proved false, and World War II began (Berndt, 1985).

## THE 1950s

This period was an exceptional one for research on the role of energy and natural resources in social and economic development. The work of White (1949, 1959), Ayers 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 sociolosit at Miami (OH) 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 undirectional 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 such 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 (b) the use of some available energy to protect one's energy flow from others seeking to use it for their worn 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 changes 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 factor determining the surplus delivered. Cottrell (1955) stated that changes 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 is should be formulated into a law. But the tendency it expresses...fits other evidence that ability to

control energy conversion 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 it 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 ever 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 rate of growth of GNP. I haven't the faintest idea what this means when I try to translate it into 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 accuracy of his original mathematical models of petroleum availability. 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.

## BIOPHYSICAL ECONOMICS IN THE 1970s

The environmental movement and the petroleum supply and price shocks of the 1970s made energy, and natural resources in general, an important social, economic and political issue. Virtually overnight, the amount of 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 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 and efficiency which enabled them to gather resources and produce goods '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 thermodynamic requirement. Odum hypothesized that evolution, both biological 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 (1977) 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. that 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.

Odum's work is extremely diverse and often complex, necessitating familiarity which his energy circuit language in order to fully understand his economic models. Economists have generally reacted strongly against many of Odum's economic theories in large part because he believes that low-entropy energy is the ultimate source of economic value — a so-called energy theory of value which is unpalatable to neoclassical economists. Unfortunately, the debate between Odum and his colleagues and economists has been divisive to the degree that many of Odum's unique and instructive insights into economic–ecological interactions have been rejected or ignored.

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 described 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 coast 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; Huettner, 1982), but he defended it with a theoretical argument based on two assumption. [4] First, solar energy

[4] Costanza's (1980) results were also charged as being statistical and/or mathematical artifacts resulting from his model specifications (Huettner, 1982; Georgescu-Roegen, 1986). These charges are rebutted in Costanza and Herendeen (1984).

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, Constanza (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's (1976) book *Man, Energy, 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 ferverent, almost religious devotion to economic growth, and the fact that such growth was dependent upon a finite, nonrenewable stock of fossil fuel. Cook (1979) 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 industrialized society, and the U.S. in particular, is faced with a recourse 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 accept that fact that physical limits to economic growth do exist and 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 [5]. The ERG developed an input–output model of the U.S. economy based on 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. 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 service. 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 materials–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

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

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 resource quality in physical terms. High-quality negentropy stocks (i.e., highly ordered deposits of natural resources) are those which require low amount 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 an depletion of fossil energy resources, since lower-quality resources require more energy for their extraction. This ratchet effect is amplified as high-quality fuels like petroleum are depleted, because lower-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 and matter.

Some of the most insightful developments in biophysical economics during the 1970s are attributable to two not-so-traditional economists: Nicholas Georgescu-Roegen and Herman Daly. Georgescu-Roegen, an economist at Vanderbilt University well-versed in mathematics and thermodynamics, forcefully points out what he terms the 'philosophical bareness' of standard economic theory in *The Entropy Law and the Economic Process* (1971). Georgescu-Roegen observed that every subsequent development in thermodynamics and the physical sciences has lent additional proof of the bond between the economic process and physical lows, although such a view is entirely missing from standard economic theory. Thermodynamics is the physics of economic value. The concepts of available and unavailable energy used in thermodynamics are defined relative to economic ends, and would make little sense divorced from economic purposes. Georgescu-Roegen calls the laws of thermodynamics the "most economic of all physical laws."

For Georgescu-Roegen, the economic process is unidirectional — what goes in is valuable, low-entropy energy and matter, and what comes out is valuable goods and services plus valueless high-entropy waste heat and degraded matter. To be sure, the processes that operate between these endpoints is what is of primary importance to humans. But by focusing primarily on the circular exchange of goods and services, standard economics has lost sight of the sensitivity of economies to changes in the quality of nature's low-entropy stocks of resources and also to the degradation of basic life support processes provided gratis by nature.

Despite his emphasis of the entropic nature of human existence, Georgescu-Roegen believes that the 'true' output of the economic process is not a physical flow of waste heat, but instead the enjoyment of life by all members of society. A psychic flux — the enjoyment of life — rather than a material flow is the real end product of production. As Georgescu-Roegen (1971) stated:

> "The economic process, to be sure, is entropic in each of its fibers, but the paths along which it is woven are traced by the category of utility to man" (p. 282).

For Georgescu-Roegen, without the concept of purposive human action, we cannot be in the economic world. Thus, he sees low entropy as a necessary but not sufficient for economic value.

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, flows back to firms from households and is called national income. This flow is depicted as circular, self-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. 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 the 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 live 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.

## NATURAL RESOURCES IN ECONOMIC THEORY

Economists were largely excluded from the preceding discussion not by design but because natural resources have not played a central role in standard economic models since the time of the Physiocrats. Natural resources did not even merit classification as a distinct field of analysis in *Economic Abstracts* and the *Journal of Economic Literature* until 1969. The flurry of resource-related research by economists in the past 15 years is due in large part to criticism by biophysical analysts and changes in the supply of some key natural resources. The publication of the *Limits to Growth* study by Meadow's et al. (1972), which received considerable attention in the popular press and the academic literature, spurred considerable research. Using simple computer simulation models, LTG projected the economic and social collapse of industrial society due to a combination of rising population, increased environmental degradation, and increasing resource scarcity. The energy price shocks and resulting economic disruptions following the Arab oil embargo in 1973 and the Iranian hostage crisis in 1979–80 also stimulated research. A post-1972 review of the economic literature on natural resources reveals a common theme, namely of fervent desire to 'disprove' the notion that future economic growth was threatened by changes in natural resource quality as suggested by the *Limits to Growth* model and the energy events. In particular, economists argued that physical models could not describe the role of natural resources in production because such models did not account for the efficacy of technological change, stimulated by the price mechanism, to overcome any resource-related problems (e.g., Simon, 1981; Rees, 1986).

The absence of a biophysical basis in modern economic theory is due to a variety of reasons. One reason undoubtedly is that the U.S. was endowed with enormous quantities of high-quality, low-cost natural resources, both renewable (timber, water, agricultural land) and non-renewable (metals, fossil fuels). With natural resources very cheap and abundant relative to capital and labor, there was little incentive to include resources in economic models. Another reason for the exclusion of natural resources is the strong anthropocentric bias of economic theory since the 18th century. The driving forces in classical, neoclassical and Marxist theory have been human traits, whether they be metaphysically derived ideas, desires, morals, etc., or simply the physical contribution of human muscle power in the production process. Most economists believe that humans are so unique that no physical theory can ever explain their behaviour.

For these reasons an economic theory of natural resources has developed which has as its cornerstone one fundamental premise: in general natural resource scarcity cannot be a serious long-term problem because technological change responds to resource-related problems by extending the life of resources, either by increasing the efficiency of their use or by locating new deposits, and also by developing comparably priced substitutes for scarce resources (Smith, 1980).

Justification for downplaying or even ignoring the role of natural resources in the economic process seemed to be provided by empirical and theoretical analyses by prominent economists. In *Scarcity and Growth*, the most important neoclassical analysis of resource scarcity, Barnett and Morse (1963) showed that resource extraction costs, measured in direct capital and labor inputs per unit output, generally declined from the late 19th century through the late 1950s [6]. The authors attributed most of the cost reduction to 'self-generating' technological change which in a mechanistic way continually and automatically augmented the resource base, enabling costs to decline or remain stable despite the continuous move to lower quality deposits.

Further support for downplaying natural resources was provided by Robert Solow (1974), who demonstrated in a theoretical analysis that a constant per-capita income could be maintained in the face of increasing resource scarcity by substituting capital for natural resources in the produc-

[6] There has been substantial research on resource scarcity since Barnett and Morse's pathbreaking research (see Pindyck, 1978; Smith, 1979; Johnson et al., 1980; Devarajan and Fisher, 1981; Slade, 1982; D.C. Hall and J.V. Hall, 1984; Farrow, 1985). As Norgaard (1985) observed, however, no new major and conceptual or empirical analyses of scarcity have been undertaken since Barnett and Morse. Their analysis, therefore, is still representative of the neoclassical approach to modeling scarcity.

tion process. Solow's conclusions hinge on certain seemingly reasonable assumptions about the size of the initial capital stock and the elasticity of substitution between capital–labor inputs and resources. At root, Solow relies on the same assumption used by Barnett and Morse — that resource scarcity sows the very seeds for its amelioration. Scarcity-induced technological change will always find a 'cure' for any scarcity induced economic problem via the price mechanism in the market. Both Barnett and Morse's and Solow's models have been challenged by recent advances in biophysical economic theory.

## RECENT ADVANCES

Recent research in biophysical economics has in many ways added theoretical and empirical support to the work of Podolinsky, Soddy, Cottrell, Odum and others described earlier. The work of Costanza (1980), Ayres and Nair (1984), Cleveland et al. (1984) and C. Hall et al. (1986) substantiates the usefulness of a biophysical perspective and identifies more clearly some of the shortcomings of standard economic treatment of natural resources. Recent empirical research has challenged the assumptions, methods and results obtained by Barnett and Morse and Solow. Hannon (1986) concluded that both Barnett and Morse's and Solow's arguments have fallen on the same sword: technical progress and factor substitution depend on natural resources and hence are constrained by the physical laws which govern all resource transformations. The conclusions of Barnett and Morse and Solow are less reassuring than they appear because they neglect or misrepresent basic physical realities.

Regarding resource scarcity, Ayres (1978), Georgescu-Roegen (1979) and Cleveland et al. (1984) point out important omissions in Barnett and Morse's analysis: massive quantities of natural resources are used to harvest natural resources themselves. Following Cottrell's (1955) lead, Cleveland et al. defined technical progress as the ability to empower the efforts of labor with greater quantities of high-quality fuel, thereby increasing labor productivity and decreasing the quantity of labor required to produce a unit of resource. Cleveland et al. empirically demonstrated the close relation between changes in labor productivity in U.S. manufacturing and changes in the amount of fuel used per worker hour, and the ways both declined between 1973 and 1983. By measuring only capital and labor inputs, Barnett and Morse and others miss the increasing quantity of cheap, abundant energy and other natural resources used to displace labor in the extractive sectors. Labor and capital unit costs declined, but the energy cost per ton of metal and per kcal of fossil fuel have risen dramatically since the 1930s (Cleveland et al., 1984). Hall et al. (1986) found that the energy surplus delivered by the U.S. petroleum industry declined from more than 100 kcal of fuel delivered per kcal of energy invested in the 1930s to about 10–20 kcal returned per kcal invested by 1980.

Hall et al. also emphasized the danger in relying solely on economic scarcity measures because they usually ignore the energy used to recover and process new amounts of energy. The quantity of energy required to deliver a new kcal of fuel in the U.S. has increased dramatically because lower- and lower-quality deposits are being brought into production deposite (and often because of) impressive technical advances in the extractive sectors. Hall et al. and Ayres (1978) also noted that the declining energy surplus delivered by the energy sectors undermines a basic economic strategy used in the extractive sectors of subsidizing labor with increasing quantities of high quality fuel.

Recent research by biophysical analysts also challenges another cornerstone of standard economic theory: factor substitution. As described above, Solow (1974) presented a theoretical model which suggested that a constant level of output could be maintained indefinitely if the elasticity of substitution of capital plus labor for natural resource is greater than unity. As Solow states:

> "If it is easy to substitute other factors for (exhaustible) natural resources, then there is, in principle, no problem. The world can, in effect, get along without natural resources. Exhaustion is an event, not a catastrophe... If, on the other hand, output per unit of resources is effectively bounded — cannot exceed some upper limit of productivity which is, in turn, not too far from where we are now — then catastrophe is unavoidable... Fortunately, what little evidence there is suggests that there is quite a lot of substitutability between exhaustible resources and renewable or reproducible resources."

Solow and other economists have used this theory to argue that natural resources are not important because production can be maintained indefinitely at the same level if capital (or some other factor) is continually substituted for natural resources.

Georgescu-Roegen (1979), Ayres and Nair (1984) and Cleveland et al. (1984) argue that Solow's pronouncements regarding resources may be incorrect because they are based on production functions that violate the laws of physics. Standard production functions such as the Cobb–Douglas or CES treat resources no differently than other factors of production. This specification is inaccurate because low-entropy matter–energy is required to upgrade and maintain all ordered structures, including capital and laborers, against the ravages of entropy. Equally important is that neither capital nor labor can create the low-entropy matter–energy from which they are derived and upon which they operate. Building and maintaining an increase in the capital stock requires increased depletion of low entropy stocks of matter–energy. The First Law of Thermodynamics clearly implies that aluminum can be substituted for copper in electrical applications as the latter resource becomes scarcer, but that it's physically impossible to substitute labor or capital for materials (i.e., aluminum or copper). Ayres and Nair (1984) summarize the incompatibility of Solow's model with basic physical laws:

> "One can define mass and energy as explicit factors of production, but this does not eliminate the difficulty...[standard production functions suggest that] one could reduce the input of materials to zero, substitute sufficient capital and labor, and still produce the same quantity of goods. Clearly, this is physically impossible. Both the final goods produced by the economy and the capital stock used to produce them embody a certain amount of mass and energy. Mass and energy cannot be created by labor or capital... Economic theorists, at least briefly, seem to have reinvented the perpetual motion machine..." (p. 68).

Georgescu-Roegen (1979) and Cleveland et al. (1984) concluded that use of the neoclassical economic assumptions to down play the role of natural resources is incorrect because such assumptions ignore the physical interdependence of capital, labor, and natural resources. Although the neoclassical model of substitution model may accurately reflect substitution possibilities at the microeconomic level, it fails at the macroeconomic level because it ignores the physical relation between the factors of production.

## CONCLUSIONS

The majority of economists, both neoclassical and Marxist, summarily reject biophysical economic models (Engels, 1882; Kaysen, 1972; Simon, 1981; Rees, 1986). The charge most frequently made against biophysical models is that they ignore or underestimate the ability of human ideas, manifested in new technologies, to offset changes in resource quality quickly and effectively enough to prevent a long-term slowing of per capita wealth. Many economists argue that there is no limit to technological change because it is a function of human ideas and there is no a priori reason to believe the rate of generation of new ideas will decline in the future. Knowledge, therefore, is the 'ultimate resource', as Simon (1981) acclaimed. The economic literature is replete with references to technological change as 'automatic' self-generating and 'exponentially growing'. This view is epitomized by Barnett and Morse (1963) who stated in a chapter entitled Self-generating Technological Change:

> "...a strong case can be made for the view that the cumulation of knowledge and technological progress is automatic and selfreproducing, and obeys a law of increasing returns" (p. 236).

The philosophy is still prevalent today. Rees (1986) stated:

> "...natural resources are products of the human mind; their limits are not physical, but are set by human demands, institutions, imagination, and ingenuity" (p. 396).

The biophysical economic perspective knowledges the importance of human ideas, but argues that the implementation of ideas through technology is a physical process governed by the same physical and ecological constraints as other work processes. Knowledge often must take physical shape in capital structures to be economically useful. Capital can therefore be described as knowledge imposed on the physical world in the form of thermodynamically improbable arrangements (Boulding, 1966). But as Daly (1985) stated:

> "...improbable arrangements cannot be imposed on dust and ashes by an intermittent breeze. It requires concentrated minerals and available energy. Low entropy matter–energy is required to embody knowledge in physical structures. High entropy matter–energy cannot be stamped with the imprint of human knowledge. That's what makes it waste. We should be wary of elevating knowledge to a universal substitute for resources" (p. 23).

For Daly and other biophysical analysts, the seeds of technological change are sown in the human mind, but it's roots are firmly planted in the biophysical world.

Hall et al. (1986) echoed this point by arguing that the seductive notion of self-correcting, self-generating technological change is too simplistic in light of the empirical observation that a large component of technological change has relied on increased use of fossil fuels per laborer. This connection differentiates current changes in resources quality from those in early times. The growing natural resource cost of resources themselves diminished the economy's ability to subsidize further the efforts of labor. Hall et al. argued that the ability to achieve rates of technological comparable to those of the last half-century depends in part on the ability of alternative fuel sources to deliver energy surpluses comparable to fossil fuels. It is not clear yet wheter this is likely or even possible to achieve. Currently, most solar energy systems deliver low-energy surpluses, if any at all, although there have been some improvements in technologies such as photovoltaics (Cleveland et al., 1984). The magnitude of the surplus obtainable from breeder of fusion power is unknown due to formidable unresolved technical problems. The energy surplus may be enormous, but the awesome potential of these sources must be tempered by our experience with the relatively tame fission technology, the costs and reliability of which we grossly miscalculated.

Despite increased public awareness about environmental affairs during the past 20 years, our society remains relatively complacent about its natural resource base. Concern for environmental degradation and energy availability waxes and wanes, tracking very closely large scale eco-disasters or the price of oil. Oil embargoes, dioxin contamination of Times Beach, MO, and the nuclear accidents at Three Mile Island and Chernobyl garner front page headlines, but seem to have little long-term impact on the public's attitude toward and knowledge about natural resources. For example, the severe recession precipitated by the 1973 Arab oil embargo was followed by increased oil use and record high rates of oil imports in the late 1970s. This set the stage for an even more severe recession following the 1979–180 oil price shocks.

A biophysical perspective suggests that standard economic models need to pay greater attention to the economic impacts of changes in natural resource quality, and, in turn, how resource quality is affected by human economic activity. Nature has upped the ante we must pay for low-entropy raw materials in the form of increased resource costs of resources themselves. Economics can no longer afford to ignore, downplay, or misrepresent the role of natural resources in the economic process. In the final analysis, natural resource quality sets broad but distinct limits on what is and is not economically possible. Ignoring such limits leads to the euphoric delusion that the only limits to economic expansion exist in our own minds.

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