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Legacies

Nicholas Georgescu-Roegen: His Bioeconomics Approach to Development and Change

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INTRODUCTION

Recent concern for 'sustainability' has attracted attention to the comprehensive theory of economic development, institutional change and biophysical constraints developed by Romanian-born economist, mathematician and statistician Nicholas Georgescu-Roegen. However, his seminal and path-breaking contributions have still not received the attention they deserve from mainstream economists. Georgescu-Roegen's early work on consumer choice theory and his innovative critique of Leontief dynamic models have never been incorporated into standard economic theory or into current behavioural and biophysical critiques of that theory. His theory of economic development is a serious critique from within the conceptual edifice of economic thought which he himself helped build. His theoretical innovations provide essential clues for a fundamental analysis of sustainability, at the level of theory as well as of policy.

Nicholas Georgescu was born in Constanta, Romania, in February 1906. He graduated from the mathematics department of Bucharest University in 1926 with the highest grade: *foarte bine*. On the advice of Traian Lelescu, a prominent Romanian mathematician, he went to study statistics at the University of Paris and obtained his PhD in 1930 with the dissertation 'On the problem of finding out the cyclical components of a phenomenon'. Having learned from the French mathematician George Darmoi some of the contributions of Karl Pearson, Georgescu-Roegen went to University College in London to study with him for two years. In 1932, he returned to Romania and became Professor of Statistics at Bucharest University. After obtaining a Rockefeller Fellowship in 1934, he went to the Harvard University Economic Barometer. Unfortunately for Georgescu-Roegen, he found that this organization had been disbanded soon after Black Tuesday — 29 October 1929 — because just the week before the crisis, it had predicted that all was in perfect order! This bad luck, however, brought Georgescu-Roegen the fortuitous opportunity to work with Joseph A. Schumpeter.

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During his stay in the US, he published four seminal articles (Georgescu-Roegen, 1935a, 1935b, 1936a, 1936b) on consumer choice theory, production theory, correction of a mathematical fallacy of Vilfredo Pareto's derivation of the indifference varieties, and a solution to a controversy between A.C. Pigou and Milton Friedman.[1] Despite Schumpeter's desire to write a definite economic analysis with him, Georgescu-Roegen returned to Bucharest in 1936. In his own words: 'The day before our sailing, Schumpeter came to New York and took us to dinner at the Waldorf Astoria to convince me to accept his outstretched hand. Only after many years was I able to comprehend how hurt he must have been by the refusal of an inconsiderate youngster' (Georgescu-Roegen, 1988a: 29). He survived for some years under the communist government but emigrated to the United States in 1948 with his wife Otilia. He obtained a professorship at Vanderbilt University in 1950 and remained there until his retirement in 1976. He died in Nashville, Tennessee, in 1994. While his most famous work is *The Entropy Law and the Economic Process* in 1971, the pinnacle of Georgescu-Roegen's theoretical contribution may well be his ambitious attempt to reformulate economic science as 'Bioeconomics'.

The broad spectrum of Georgescu-Roegen's work defies any simple classification. However, in this article I argue that his bioeconomics (mostly formulated after 1960) can be regarded as innovative and comprehensive scientific thought (see also Mayumi, 2001). In the remainder of this 'Legacy', I will therefore present some essential elements of his bioeconomics approach to development and change.

THE TWO PILLARS OF BIOECONOMICS

Georgescu-Roegen's bioeconomics rests on two pillars: the exosomatic nature of human evolution and the fundamental importance of qualitative and irreversible, truly novel changes in the economic process.

The notion of exosomatic evolution, which originated with the physical biologist A.J. Lotka (1956: 369), was developed further by Georgescu-Roegen. The idea is that humanity has transgressed the mode of biological (or endosomatic) evolution and moved into an entirely new — mechanical-industrial — mode of evolution, relying on exosomatic (external) energy and detachable (manufactured) exosomatic resources and money. Georgescu-Roegen's bioeconomics emphasizes the biological origin of the economic

1. On this controversy, Georgescu-Roegen states: '[The] verdict was against Friedman. As we all know, if you disagree with him however little, Milton Friedman would clobber you: "you are *totally* wrong". So I felt immensely gratified when Milton introduced me before a lecture at the University of Chicago as the only economist who had proved him wrong. Of course, my lecture, on Brazilian monetary inflation, "was *totally* wrong"' (Georgescu-Roegen, 1988a: 27).

process and the human problems associated with a limited amount of available resources that are unevenly located and unequally distributed. Yet, he insists that the human-mode of existence is dominated neither by biology nor by economics alone: 'my use of "bioeconomics" had not been influenced by the prevailing fashion of reducing everything to a biological basis' (Georgescu-Roegen, 1986: 249). Institutions of the market, money, credit, enterprises of all sorts, and the internal logic inherent in these institutions, emerged in response to the progressive evolution of the exosomatic nature of humankind. Georgescu-Roegen's bioeconomics is a new style of scientific thought: it is not a new branch of economics, but a new discipline that combines elements of evolutionary biology, institutional economics and biophysical analysis associated with energy and mineral resources (Mayumi, 2001; Miernyk, 1999).

The second pillar of Georgescu-Roegen's bioeconomics is the recognition of the fundamental importance to (economic) development of qualitative change, which standard (neoclassical) economics fails to analyse. Qualitative change, a central theme of life sciences and social sciences such as biology and economics, eludes mathematical schematization that Georgescu-Roegen (1971) terms arithmomorphism, rooted in the mechanistic epistemology of neoclassical economics. Because of incessant qualitative changes due to the emergence of novelty in economic processes, Georgescu-Roegen insists that reality can be grasped only when arithmomorphic analysis is combined with a dialectical approach, involving in particular structural and qualitative changes. This dialectical approach must use words, instead of numbers. The most important part of economic history is a storytelling in words. Dialectical reasoning can be as correct as mathematical reasoning, but very often it can be even more penetrating. The works of Adam Smith, Joseph A. Schumpeter and Simon Kuznets, among others, are special exemplars. Since the process of historical change has an infinite number of properties together with the ever-present emerging novelty, to come to grips with facts is a much more formidable task than to indulge in empty mathematical exercises. Georgescu-Roegen was among the first to defend the absolute necessity of historical and institutional studies in economic science. The evolutionary nature of the economic process precludes a grasping of all its relevant aspects only by an arithmomorphic scheme, even by a dynamic one with genuine delays (Mayumi, 2005).

It is well known that Schumpeter's unique vision of the economic process had a profound influence on Georgescu-Roegen's evolutionary views of the economic process. Georgescu-Roegen states: 'Every one of his distinctive remarks were seeds that inspired my later works. In this way Schumpeter turned me into an economist — the only true Schumpeterian, I believe. My only degree in economics is from Universitas Schumpeteriana' (Georgescu-Roegen, 1992: 130). Schumpeter excluded reversible changes from innovations: 'what we are about to consider is that kind of change arising from within the system *which so displaces its equilibrium point that the new one* *cannot be reached from the old one by infinitesimal steps*' (Schumpeter, 1951: 64). Schumpeter described the same thing in a metaphorical manner: '[add] successively as many mail coaches as you please, you will never get a railway thereby' (ibid.). In evolutionary biology a similar idea of qualitative leap was proposed by Richard Goldschmidt in 1933: the 'changes necessary for the formation of a new species are so large that the relatively small differences of the subspecies as a starting point would hardly count' (Goldschmidt, 1933: 542). Goldschmidt described the possible candidates of a new speciation as hopeful monsters that would start a new evolutionary line if fitting into a certain biological niche. Stephen J. Gould and Niles Eldredge rehabilitated Goldschmidt's theory in terms of punctuated equilibrium (Gould, 1977; Gould and Eldredge, 1977). Georgescu-Roegen mentions how a hopeful monster has become a successful monster with a qualitative leap, so to speak, referring to Japan's economic development: 'The miracle is that Japan's economy "took off" on the back of a silk moth. Other nations had the silkworm, but missed the same opportunity' (Georgescu-Roegen, 1971: 293).

EXOSOMATIC EVOLUTION AND ITS PREDICAMENTS

It is true that economic growth and advancement of science and technology through exosomatic evolution resulted in the increased material comfort typically attained by the Western World. Yet, according to Georgescu-Roegen (e.g., 1977a, 1986), the exosomatic evolution brought about three formidable predicaments to human beings.

The first predicament concerns the eventual exhaustion of fossil fuels and mineral resources associated with the accelerated addiction to the extravagant comfort provided by the exosomatic organs. The recent concern with peak oil, the most crucial fossil fuel, is not an idle question posed to human beings (e.g., Simmons, 2005; Smil, 2008). In particular developing countries in Asia are projected to have an annual economic growth rate of 5.4 per cent from 2004 to 2030 (Ito, 2007). According to Luft (2007), 58 per cent of China's oil imports come from the Middle East now and this share will grow to 70 per cent by 2015. China's concern for its growing dependence on oil imports has led to its active involvement in exploration and production in countries and regions including Kazakhstan, Russia, Venezuela, Sudan, West Africa, Iran, Saudi Arabia and Canada. But China is not the only Asian actor thirsty for oil. Other countries including India are projected to be major contributors to the world's energy demand. In fact, China and India are 'guesstimated' to account for approximately 70 per cent of the energy consumption in Asia over this 30 year time period (Ito, 2007) — which should be a cause of concern for most other energy-importing economies.

In thermodynamics there is the 'anthropomorphic' distinction between available and unavailable energy for human beings, indicating that only available energy can be used by humans. However, this distinction *per se* does not imply that all available energy can actually be used for human activities. Georgescu-Roegen (1975: 354), in his discussion of the quality of energy sources, proposed another important distinction between *available* and *accessible* energy: there 'certainly are oil-shales from which we could extract one ton of oil only by using more than one ton of oil. The oil in such a shale would still represent available, but not accessible energy'. For the case of oil-shale the generation of the net supply would require much more energy than is obtained. Similarly, despite their recent surge in popularity, agro-biofuels are, unfortunately, not accessible energy sources.

Georgescu-Roegen's concept of accessible energy has been reinterpreted and used by several scientists (Cleveland, 1992; Cleveland et al., 1984; Gever et al., 1991; Hall et al., 1986) as energy return on investment (EROI): the ratio between the energy delivered to society by an energy system and the quantity of energy used directly and indirectly in the delivery process over a given period of time. In our book, *The Biofuel Delusion* (Giampietro and Mayumi, 2009), we present a quantitative analysis based on data sets derived from the two most impressive large-scale agro-biofuel experiments established on this planet: ethanol production from corn in the USA and ethanol production from sugar-cane in Brazil. We show that agro-biofuels do not come close to meeting the policy goals of providing energy security against future consequences of peak oil and a reduction of GHG emission. In the case of the USA it is the low output/input ratio of energy carriers which makes the solution infeasible; in the case of Brazil it is the low power level achieved in the process of ethanol production which makes the solution unattainable.

Fossil fuels are 'optimal' in terms of the amount of matter in bulk required for energy extraction, transformation and transportation to support the modern industrial society (Mayumi, 2001). Solar energy cannot easily support current fossil-fuel based manufacturing processes; as Georgescu-Roegen argues (1979a: 1050): 'It [the necessary amount of matter for a technology] is high for weak-intensity energy (as is the solar radiation at the ground level) because such energy must be concentrated into a much higher intensity if it is to support the intensive industrial processes as those now supported by fossil fuels'. He also argues that the necessary amount of matter is high for high-intensity energy such as thermonuclear energy because high-intensity energy must be contained and controlled within a stable boundary. The conclusion that fossil fuels are superior is sometimes called Georgescu-Roegen's Fundamental Proposition (Kawamiya, 1983).

The second predicament is social conflict. As Lotka clearly recognized, the fact that control over exosomatic resources (accessible energy) is unevenly distributed among individuals, has led to 'so much of the social unrest that has accompanied the development of modern industrialism' (Lotka, 1956: 370). Since large-scale production and its distribution in human societies has to be organized socially, the social classes of 'ruler' and 'ruled' are created. Social conflict of the human species is not the result of endosomatic, but exosomatic evolution (Georgescu-Roegen, 1977a). Unfortunately, social conflict will remain part of the human lot as long as our mode of existence depends on large-scale exosomatic production and distribution. Contrary to the Marxian fundamental faith, socialization of the means of production cannot bring social conflict to an end. Because of its dependence on finite, non-renewable exosomatic (accessible) energy, which is very unevenly distributed across nations as well as between individuals, human social evolution since the widespread adoption of agriculture has been associated with large-scale conflict and social unrest. As Georgescu-Roegen puts it: 'given the nature of our proclivities the resultant social conflict between the élite and their social platform is inevitable and will last under varying forms as long as mankind remains a species living by social production and social distribution' (Georgescu-Roegen, 1988b: 320).

The last predicament — the combined result of the first and the second predicaments — is the inequality among different exosomatic 'species', for example, the difference between the developed and the underdeveloped countries (Georgescu-Roegen, 1977a). This very sad predicament is an intragenerational issue. Recent concern for sustainability invokes another type of distributional issue — the intergenerational distribution issue. On this, Georgescu-Roegen argues: '[each] generation can use as many terrestrial resources and produce as much pollution as its own bidding alone decides. Future generations are not, simply because they cannot be, present on today's market' (1975: 374). The notion of intergenerational distribution is strongly related to the proper discount rate (if any) and to the notion of sustainability, weak or strong.

Since humans seem to be so enchanted with miraculous technological achievements, we have difficulty in recognizing that exosomatic evolution has unavoidably brought about these three lasting predicaments — as well as bringing felicitous exosomatic material comfort.

PROMETHEAN TECHNOLOGIES, JEVONS' PARADOX AND MINERAL RESOURCES

Georgescu-Roegen (1969) proposed a new theory of production together with the flow–fund model, an innovative alternative to the standard production theory based on an important difference between process in farming and process in manufacturing. Here, flows are 'materials' qualitatively transformed into a process. They are elements that enter but do not come out of the process or elements that come out of the process without having entered. Funds are agents transforming a given set of inflows into a given set of outflows. They are the elements that enter and leave the process unchanged: labour, capital and Ricardian land.[2]

A feasible recipe is a procedure that uses an available set of necessary factors for achieving a goal. Thus, a feasible recipe must specify the flow and fund elements, and their tempos, required for transformation of the inputs into outputs. Baking bread, for example, is a feasible recipe, but controlling a thermonuclear reaction is not a feasible recipe at this moment. According to Georgescu-Roegen, a 'technology' is a set of feasible recipes where any input not supplied by nature can be produced by one of the feasible recipes within the technology (Georgescu-Roegen, 1983). A Promethean technology (or a viable technology) is a technology that can maintain the two fund elements, machines and people, as long as the natural resources and the environmental services (including sinks) are forthcoming. Surprisingly enough, according to Georgescu-Roegen (1992) there are only three Promethean technologies in human history: (a) husbandry (agriculture); (b) the mastery of fire; and (c) the steam engine (or more generally the mastery of internal combustion engines) coupled to fossil energy. These three technologies share a common explosive characteristic: 'with just the spark of a match we can set on fire a whole forest. This property, although not as violent, characterizes the other two Promethean [technologies]' as well (ibid.: 150). Fertile land (not Ricardian land) is the special fuel for agriculture. Fossil fuels are the special fuels for modern industry. Due to the explosive nature of Promethean technology, humans quickly fell into the Malthusian instability trap by depleting the special stocks of 'fuels' associated with these different technologies. In particular, the explosive characteristic of the petroleum-based metabolism of modern society, due to the abundant supply of high quality oil during the past hundred years or so and the continuous supply of technological efficiency improvements, has been boosting the phenomena associated with Jevons' paradox worldwide — as Georgescu-Roegen forcefully argued.

In *The Coal Question* of 1865, William Stanley Jevons examined the trend of future coal consumption and argued against the contemporary predictions of reduction in future coal consumption triggered by technological progress (Jevons, 1865). He explained an intrinsic human addiction to the comfort offered by exosomatic instruments. Increase in efficiency in using a resource leads to increased use of that resource rather than to a reduction in its use: it 'is the very economy of its use which leads to its extensive consumption. It has been so in the past, and it will be so in the future. Nor is it difficult to see how this paradox arises' (ibid.: 141). Although Georgescu-Roegen does not mention the phenomenon of Jevons' paradox, he praises Jevons' book highly and states: 'if we reinterpret his basic point of departure in the

2. Ricardian land is an indestructible space, according to David Ricardo: 'Rent is that portion of the produce of the earth, which is paid to the landlord for the use of the original and *indestructible* powers of the soil' (Ricardo, 1951: 67, emphasis added).

light of some of his side remarks, we find it now vindicated by the principles of thermodynamics. The conclusion is far stronger than that which Jevons reached for coal' (Georgescu-Roegen, 1971: 295–6).

Jevons' paradox has proven to be true not only regarding demand for coal and other fossil energy resources but also regarding demand for resources in general. Doubling the efficiency of food production per hectare over the last fifty years due to the Green Revolution did not solve the problem of hunger. The increase in efficiency increased production and worsened hunger because of the resulting increase in population (Giampietro, 1994). More energy efficient automobiles were produced, motivated by rising oil prices, but leisure driving increased (Cherfas, 1991). The number of miles driven increased at the same time that car performance improved. Now, Americans are driving bigger and more sophisticated vehicles such as SUVs, pick-up trucks and four-wheel drive vehicles. Building new roads did not solve the traffic problems due to increased use of personal vehicles (Newman, 1991). In a similar way, technological efficiency improvements in refrigeration led to the creation of much bigger refrigerators, resulting in more overall electricity consumption (Khazzoom, 1987).[3]

We know that matter in bulk, various mineral resources in particular, as well as energy, are indispensable to the economic process. However, the familiar bias in favour of energy seems to have been accentuated since the oil embargo in 1973 and continues to survive because of people's concern for peak oil and climate change. At first sight this is understandable because matter can be seen as a particular form of energy from a purely theoretical point of view, based on the Einstein equivalence between mass and energy. The most salient example of this point of view, the modern energetic dogma, is represented by the following statement: it is possible 'to recycle almost any waste, to extract, transport and return to nature when necessary all materials in an acceptable form, in an acceptable amount, and in an acceptable place so that the natural environment will remain natural and will support the continued growth and evolution of all forms of life' (Seaborg, 1972: 138).

Georgescu-Roegen, on the other hand, emphatically objected to the equivalence of energy and matter in bulk, stressing a peculiar attribute of the modern economic process:

> [as] far as the economic process itself is concerned, we must not ignore the substantial dissipation of matter caused not by purely natural phenomena but by some activities of living creatures, of mankind's, above all. It is the dissipation of some vital elements by man's consumption of food and timber in places far away from the farm and the forest that produced those items. (Georgescu-Roegen, 1979a: 1040).

3. For more on Jevons' paradox see Giampietro (1994); Giampietro and Mayumi (1998); Jevons (1990); Mayumi et al. (1998); Polimeni et al. (2008). Jevons' paradox is revived in the energy literature as the 'rebound effect' (see, e.g., Brookes, 1979; Khazzoon, 1980).

In thermodynamics the entropy law refers only to available energy dissipation tendency, not available material dissipation.[4] However, Georgescu-Roegen correctly indicates that modern agriculture tends to destroy harmonious material circulation mechanisms. He shares this view with the great agronomist, Justus von Liebig. Liebig emphasized the importance of material circulation in agricultural fields. The principle of his agronomy consists in his view that the circulation of matter in agricultural fields must be maintained with manure in so far as agricultural products are consumed in cities, and fundamental elements of soils are never returned (Liebig, 1859).

With respect to material circulation, Georgescu-Roegen proposed the 'Fourth Law of Thermodynamics' through his genuine concern with ecological salvation: complete recycling is impossible in a closed system (such as the Earth) (Georgescu-Roegen, 1977b). A closed system can exchange energy (but not matter) with the environment. The fourth law says that *even with an unlimited amount of energy available* it is impossible to recycle matter completely. It seems that Georgescu-Roegen tried to establish this alleged law as a dual to the second law of thermodynamics that refers to energy. However, I have shown elsewhere that (a) his formulation is not compatible with the framework of thermodynamics, and (b) 'material entropy' is not entropy in physics, depending on factors such as heterogeneity of matter, available technology, the multi-dimensional value system of humans and the overall availability of resources (Mayumi, 2001). Nevertheless, even though Georgescu-Roegen's 'Fourth Law of Thermodynamics' cannot be accepted as a law of physics, his concern is important because matter in bulk and energy are not convertible into each other. Therefore it is impossible to judge which equivalent recovering technology, one with more energy and less matter, or one with less energy and more matter, is ecologically preferable. It is necessary to have a general quantitative flow–fund matrix representing macro-global and micro-local economic systems to tackle formidable issues concerning integrated technological assessment. Because the Earth is a closed system, waste materials tend to remain unless there is an effective mechanism to transform waste materials into waste heat. Furthermore, the economic process depends not only on biological organs but also, to a much greater extent, on exosomatic organs. Unfortunately, there are no truly effective devices for recycling waste materials that also maintain the structure of the economic process. Flows of dissipated matter in bulk increase with the size of the economic process and there is great difficulty in maintaining these large-scale material structures in modern industrial society. Georgescu-Roegen's concern is a matter of vital importance for sustainability.

Herbert F. Bormann (1972) and Preston Cloud (1978), two contemporaries of Georgescu-Roegen, strongly supported his idea of ecological salvation,

4. For our present purpose we may be satisfied with the definition of entropy as an index of the amounts of unavailable energy in a given system at a given moment.

arguing that if the current rates of consumption of useful metals continue, about half of the known reserves might be exhausted by 2050. In fact, mineral resources, and particularly the geologically scarce metals, have been becoming increasingly important. By the geologically scarce metals we mean those metals with crustal abundances below 0.1 per cent (Skinner, 1986). It is surprising to see that such common metals as copper, lead, zinc and nickel, all of which have large and growing rates of production, belong to this category. 'Most experts believe that it is in this group of metals that shortages are likely to develop first and that these are apt to pose a serious challenge to technological development' (Skinner, 1986: 94). Cloud's caution that by the year 2050 several important scarce metals (e.g., molybdenum, nickel, copper and silver) would be in serious shortage is a fundamental technological challenge. In fact, silver and gold production already fall short of present demand, and stockpiles and savings from past mining are being drawn upon. In 2005, for example, world silver production amounted to 20,200 tons while world silver consumption reached 28,364 tons (US Geological Survey, 2005).

LIMITATIONS OF ANALYTICAL REPRESENTATIONS: QUALITATIVE CHANGE IN THE ECONOMIC PROCESS

Georgescu-Roegen's work remains very relevant to the present day not only because of its novel bioeconomic approach to economic processes and the fundamental insights resulting from this approach, but also because of the particular epistemology employed. According to Georgescu-Roegen, nature consists only of what can be perceived. Beyond that, there are only hypothesized abstractions. His ideas about the relation between nature and human perception of nature led to an epistemology concerned mainly with *valid analytical representations* of relations among facts. For Georgescu-Roegen, any worthwhile economic theory must be a logically ordered description of a reality's mode of functioning.

Following his epistemological preoccupation, Georgescu-Roegen proposed an alternative analytical representation of the production function. Neoclassical production functions, whether for individual firms or the aggregate economy, assume that any factor can always be substituted for any other factor. The implication of this assumption is that an increase in the input of any factor always yields an increase in output. This is the basis for Solow's contention that '[t]he world can, in effect, get along without natural resources' (Solow, 1974). However, those neoclassical economists adopting the substitution assumption have not paid due attention to the essential distinction between flows and funds in the material production process (Georgescu-Roegen, 1971). Neglecting this distinction results in a systematic indifference to the biophysical foundation of economic activities. In fact, according to Georgescu-Roegen (1990), when designing a blueprint of a factory process a designer has to consider a set of three relationships: (a) the normal rate of output (q, not the capacity of output rate) determined by the structure of Ricardian land and capital funds to be used; (b) the relation between inflow rates (energy and materials, r; the products of other industries, i; the waste, w) and the rate of output; (c) the structure of fund elements, i.e., a certain number of workers to be employed (H) corresponding to the size of Ricardian land (L) and capital (K) funds to be used.

Thus, the analytical representation of a real production process should be in the following form (ibid.: 215):

$$q = q(\mathrm{L}, \mathrm{K}) = F(\mathrm{r}, \mathrm{i}, \mathrm{w}) \quad \text{and} \quad H = H(\mathrm{L}, \mathrm{K}). \tag{1}$$

We can see from this representation that any actual material production process is limitational (first introduced by Ragnar Frisch in 1931, cited in Georgescu-Roegen, 1935a) in the sense that within the same factory process we cannot compensate a decrease in output due to a decrease in a fund element (e.g. capital) by an increase in a flow input (e.g. natural resources). Using the example given by Daly (1992), having access to more timber is useless if the sawmill's capacity is the limiting factor or, conversely, if the bottleneck is with the supply of wood. In general, when changing the structure of a production process, it is not guaranteed that either functions like F(r,i,w) or funds (K or L) remain the same and even the inflows (r,i,w) themselves might change. Thus, the representation of isoquants, the concept of elasticity of substitution and time derivative of the same function by technological improvements, all found in the neoclassical theory of production, lose any operational and empirical meaning. Hence, David Pearce's claim that 'the [substitution] issue is an empirical one' (Pearce, 1997: 295) is untenable unless the production process is correctly formulated. The expression of heterogeneous factors in monetary units in aggregate production functions (Solow, 1957) makes the situation worse, as Herman Daly (1997) aptly observed. This homogenization of inputs hides the biophysical constraints of production activities and clouds the issue of sustainability (Gowdy, 1997). This misconception introduced by a description of the production process in monetary terms is inherent in the definition of weak sustainability usually adopted by neoclassical economists: 'the total value [in monetary terms] of all capital stocks be held constant, man-made and natural' (Pearce et al., 1990).

However, Georgescu-Roegen noticed a much more serious 'analytical and conceptual fallacy' (than an analytical representation of production) within the neoclassical treatment for the development process: 'It is high time, I believe, for us to recognize that the essence of development consists of the organizational and flexible power to create new processes rather than the power to produce commodities by materially crystallized plants' (Georgescu-Roegen, 1971: 275). He calls this power 'a Π-sector': 'an economy can "take off" when and only when it has succeeded in developing a Π-sector'.

This issue of a Π-sector is related to the issue of what is produced in the economic process. Some of those studying the functioning of socioeconomic processes seem to be confused by what is produced by the economic process. According to Georgescu-Roegen the economic process does not produce goods and services, but it produces a reproducible system, via the establishment of an integrated process of production and consumption of goods and services. When dealing with the analysis of the economic sectors — those producing added value — they not only produce goods and services, but also produce those processes required to produce goods and services. When considering the whole socioeconomic system, it is the integrated action of the productive economic sector and the sector of final consumption which has to be considered. Using Georgescu-Roegen's terminology, the economic process has the goal of reproducing and expanding the various fund elements defined simultaneously across different levels and scales, by using disposable flows. Following Georgescu-Roegen, then, we can conclude that *an economy not only produces goods and services, but more importantly produces the processes required for producing and consuming goods and services*.[5]

We can find an analogy of production and consumption in terms of metabolic patterns within ecological theory. In his analysis of ecosystem structure, Ulanowicz (1986) finds that the network of matter and energy flows making up an ecosystem can be divided into two parts: one that generates a hypercycle and another that has a purely dissipative nature. The former part is a net energy producer for the rest of the system. The hypercyclic part is required to keep the dissipative system in a situation of non-equilibrium (Eigen, 1971). Since some dissipation is always 'necessary to build and maintain structures at the sub-compartment level' (Ulanowicz, 1986: 119), the net energy producing part comprises activities that generate a positive feedback by taking advantage of sources of free energy outside the system (such as solar energy). The role of the hypercyclic part is to drive and keep the whole system away from thermodynamic equilibrium. The latter part comprises activities that are net energy degraders. However, this dissipative part is not useless for the system: rather, it has the role of providing control over the entire process of energy degradation and stabilizing the whole system. An ecosystem made of a hypercyclic part alone cannot be stable in time. Without the stabilizing effect of the dissipative part, a positive feedback 'will be reflected upon itself without attenuation, and eventually the upward

5. Georgescu-Roegen shared his idea of 'production of processes' with another profound thinker, George K. Zipf. In his analysis of the organizational pattern of societies, seen as bio-social organisms, Zipf (1941) introduces for the first time the notion of critical organization: 'any change in kind or amount of goods or of processes within a social-economy will necessitate a restriction within that social-economy itself. This was true of the discovery of steam, oil, and the like, and it will also be true of the "discovery" of leisure time [that enhances consumption activities]' (ibid.: 324).

spiral will exceed any conceivable bounds' (ibid.: 57). Therefore, a subtle balance between the hypercyclic part and the dissipative part is essential for *reproducing* the stable ecosystem network. So when the ecosystem is stable, the overall metabolic balance indicates that the various elements are *produced and consumed over the food chain of the network at an expected pace*: herbivores eat plants, tigers eat herbivores and when tigers die, their bodies are 'consumed' by other living creatures in order to close the nutrient cycles. In analogous terms, therefore, a hypercyclic part is compared to production of production process and a dissipative part is compared to production of consumption process.

Since the true products in the economic process are productions of production and consumption processes, new means and ends are continually invented, new economic wants are created, and new distributive rules are introduced. The evolutionary pace of economic 'species' — means, ends, wants and various relations — is far more rapid than that of the biological species. No analytical model can deal with the emergence of novelty, for everything that can be derived from such a model can only concern quantitative variations. Besides, nothing can be derived from an analytical model that is not logically contained in its axiomatic basis where there is clear dichotomy between variables and parameters. There are numberless qualities of chemical components that cannot be logically deduced from the properties of their elements (Georgescu-Roegen, 1979b). Novelty is characterized by the fact that even after it has occurred it is as a rule impossible to explain it with known phenomenal laws.

For this reason, we should expect a systemic failure when using a model, whose formal structure is given and not changing in time (based on a given set of types), to predict the emergence of new functions and structures in an evolving system. Here we should recall Georgescu-Roegen's severe verdict on the usefulness of econometric models to make predictions about the future:

> Even more crucial is the absence of any concern for whether the formula thus obtained will also fit other observations. It is this concern that is responsible for the success natural scientists have with their formulae. The fact that econometric models of the most refined and complex kind have generally failed to fit future data — which means that they failed to be predictive — finds a ready, yet self-defeating, excuse: history has changed the parameters. If history is so cunning, why persist in predicting it? (Georgescu-Roegen, 1976: xxi-xxii)

Even Tjalling Koopmans, a staunch defender of mathematical models in economics, shares this view concerning the deficiencies of econometric model for predicting future events: 'We must face the fact that models using elaborate theoretical and statistical tools and concepts have not done decisively better, in the majority of available tests, than the most simple-minded and mechanical extrapolation formulae' (Koopmans, 1957: 212). This statement refers to the success of the models in predicting future events, not in fitting the past observations used in estimating the parameters. There is no shortage of econometric tools aided by computers by which an economist can carve as good a fit as she or he may please.[6]

However, we should note that Georgescu-Roegen did endorse the legitimate use of mathematics in economic science that can lead to valid analytical representation. In fact, he indicated two situations where mathematical models play an important role in economic science: (a) engineering economics; and (b) for the purpose of facilitating communication and detecting possible logical errors (Georgescu-Roegen, 1979b, 1981). Engineering economics deals with circumscribed conditions, *known* prices and *known* coefficients of production, and seeks to find an optimal solution. The typical example is the case of linear programming initiated by George Danzig and further developed by Koopmans. The second situation refers to a simile of dialectical reasoning with a solid external reference to a relevant economic problem before constructing a mathematical model.

Although Georgescu-Roegen was a firm believer in the proper use of mathematics, he had a serious concern with the abuse of mathematics. This argument can be reinforced by noting that even in natural sciences the severe limitations of mathematical treatment are recognized by the authorities of this field. For instance: 'even though the physicist's most dreadful weapon, mathematical deduction, would hardly be utilized. The reason for this was rather it was much too involved to be fully accessible to mathematics' (Schrödinger, 1967: 3) and it 'is the mathematics made by us which is imperfect and not our knowledge of nature' (Bridgman, 1960: 62).

CONCLUSION

In this Legacy, I have touched upon some of Georgescu-Roegen's fundamental ideas with respect to development and change. By way of conclusion, his view on climate change should be mentioned to appreciate his farsighted theoretical consideration.

Climate change usually refers to global warming in the context of environmental policy. However, by the early 1980s, some natural scientists believed that global *cooling* was occurring. In fact, Stephen H. Schneider, one of the influential members of the Intergovernmental Panel on Climate Change (IPCC), supported global cooling in an article published in the prestigious journal, *Science* (Ichtiaque and Schneider, 1971). Carbon dioxide was predicted to have a minor role for global warming. Regardless of whether or not global warming is caused mainly by economic activities through massive

6. In mathematics there is a famous theorem called the Weierstrass Approximation Theorem (e.g., Randolph, 1968: 317): a real-valued continuous function on an interval can be approximated *uniformly* by a polynomial. So, it is rather easy to have a polynomial approximation that can fit perfectly well for past data using computer programming. Unfortunately this polynomial approximation has no power to predict a future full of novelties!

use of fossil fuels,[7] the following statement made by Georgescu-Roegen in 1975 deserves special attention with respect to the threat of heat pollution at a fundamental level:

> The *additional* heat into which all energy of terrestrial origin is ultimately transformed when used by man is apt to upset the delicate thermodynamic balance of the globe in two ways. First, the islands of heat created by power plants not only disturb the local fauna and flora of rivers, lakes, and even coastal seas, but they may also alter climatic patterns. One nuclear plant alone may heat up the water in the Hudson River by as much as 7°F. Then again the sorry plight of where to build the next plant, and the next, is a formidable problem. Second, the additional global heat at the site of the plant and at the place where power is used may increase the temperature of the earth to the point at which the icecaps would melt — an event of cataclysmic consequences. Since *the Entropy Law allows no way to cool a continuously heated planet*, *thermal pollution could prove to be a more crucial obstacle to growth than the finiteness of accessible resources*. (Georgescu-Roegen, 1975: 358; emphasis in last sentence added)

This quote is very valuable in two respects for our debate on sustainability. First, Georgescu-Roegen suggests that thermal pollution could be more serious than the scarcity of energy and mineral resources for sustainability. Secondly, he argues that nuclear power plants could be a real threat to global warming. We might recall that many governments are planning the construction of nuclear power plants due to high oil prices and — ironically — to fight global warming.

I believe that Georgescu-Roegen's seminal and path-breaking contributions have not yet received the attention they deserve from mainstream

7. This situation can be regarded as 'Post-Normal' (Funtowicz and Ravetz, 1990) in which uncertainty, stakeholders and their value conflicts play a central role in the process of complex decision making. Post-normal indicates a departure from curiosity-driven and puzzle-solving exercises of normal science in the Kuhnian sense (Kuhn, 1962). Normal science, so successfully extended from the laboratory of core science to the conquest of nature through applied science, seems no longer suitable for dealing with sustainability issues full of uncertainty. The social, technical and ecological dimensions of sustainability issues are so deeply connected that it is simply impossible to consider these various dimensions as separated into conventional disciplinary fields. Developments in astrophysics reveal that *solar variability* triggered by internal fusion processes together with changes in the alignments of Jupiter and Saturn seems to have had considerable effects on the earth's climate within the solar system (Gribbin, 1980). Unfortunately, however, due to serious uncertainty concerning how these changes proceed and their effects, it is impossible for us to know exactly the long-term consequences of these changes, let alone short-term influences, on the earth's climate. So, we do not have any substantive scientific evidence regarding the true cause of climatic changes. The situation facing us is indeed post-normal. Concerning the recent global warming bandwagon, the vast majority of people, including economists, seem to believe that global warming is caused mainly by GHGs, particularly by CO_2 from economic activities. But the models economists use, for example, the Stern Report, have not taken the above-mentioned investigation of the sun's variability into their analyses and assessments. The issue at hand seems to be much more complex and formidable than economists allegedly claim it to be.

economists.[8] His theory's innovative aspects may give essential clues to investigating deep theoretical and policy implications for sustainability. Close examination of the entire spectrum of his work, and new theoretical and empirical studies based on that work, are absolutely necessary. As the last student of Georgescu-Roegen, I do hope that this article will trigger a more systematic investigation of his work and a fruitful discussion on this truly profound thinker.

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8. Daly (1995) wrote that Georgescu-Roegen's later years were marked by bitterness and withdrawal. In my view, the economics profession did not give Georgescu-Roegen the recognition he merited. I once received a fax from Georgescu-Roegen in which the readers can really appreciate his bitter feeling and loneliness at the last stage of his life:

> I am afraid that this letter may come too late to you, so late that you may feel like not even reading it. But, my dear Kozo, you are still very young for being aware of the conjuring tricks used by many cliques of 'scholars'. Why, today many economists and ecologists are amassing money over money by selling two kinds of snake oils: one sings the lullaby of sustainable growth for abundant funding, the other sells to the still unaware nation the simplest econometric models of growth that have been duly exposed and overexposed. Drop me a line, even two, if you can forgive the faults of the old man with whom you once wanted to discuss things and problems as well. (Pers. comm., Georgescu-Roegen, 9 September 1992)

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