Economic growth and the environment

Adolfo Figueroa

ABSTRACT

The relationship between economic growth and the environment is one of the most significant problems in modern economics. Empirical data are increasingly available, but the theories behind those data remain a matter of debate. This paper presents an elementary theoretical model of the interactions between the economic process and the environment, drawing on a theory developed by Georgescu-Roegen, in which the laws of thermodynamics are applied to the economic process. The model assumes that the growth and distribution process is currently operating amid conditions of environmental distress. The model is able to predict and explain the observed relationship between economic growth and the environment, identifying new public policy implications. The paper thus aims to contribute to the debate on the choices that society must make about the future of humanity.

KEYWORDS Economic growth, environment, consumption, non-renewable resources, pollution, thermodynamics, economic aspects, environmental aspects

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I
Introduction

The relationship between economic growth and the environment has been studied from both an empirical and a theoretical perspective. The key data show that total output per person grew at an average rate of 1.4% per year in the period 1870-2000, with the highest rate (4%) recorded during the past century (Maddison, 2003). This process has been accompanied by an equally rapid degradation of the environment, including the depletion of non-renewable resources and pollution. Some studies show that certain non-renewable resources are approaching exhaustion (Clugston, 2012). The standard measure of pollution is the concentration of carbon dioxide (CO_2) in the atmosphere, measured in parts per million (ppm). According to physicist Richard Muller, "The amount of carbon dioxide was pretty constant from A.D. 800 until the late 1800s, at a level of 280 ppm. In the last century it has shot up to 380 ppm —an increase of 36%. If we continue to burn fossil fuels, we expect the carbon dioxide to keep rising […] The carbon dioxide comes from human activity, including the burning of fossil fuels and the destruction of enormous regions of forest" (Muller, 2008, pp. 265-266).

The planet's average temperature has been on the rise since the beginning of the industrial revolution, around 1850 (IPCC, 2007). Whether this global warming, and the climate change associated with it, is endogenous or exogenous to the economic process is still a matter of scientific debate. The factors affecting climate change can be summarized in three affirmations: first, human fossil-fuel burning causes CO_2 concentrations in the air to rise; second, CO_2 is a greenhouse gas; and third, the greenhouse effect increases the average global temperature. The first two are accepted by scientists, but the third is under debate.

According to some scientists, the emission of greenhouse gases leads to global warming, which results in climate change; that is, production generates waste and pollution, which triggers climate change (Aeschbach-Hertig, 2007). From their point of view, climate change is endogenous to the production process. For others, climate change is exogenous: it is caused mainly by natural variations in solar activity (Chilingar, Sorokhtin and Khilyuk, 2008, p. 1572). A third group concludes that, although climate change is a complex problem and hard to decipher with any certainty, it is likely to be endogenous to some extent (IPCC 2007, cited in Muller 2008, p. 254).

In the particular case of Latin America, some empirical evidence exists of environmental degradation in the long period of economic growth since the 1940s (Sunkel and Gligo, 1980; Gligo 1993). The negative impact of climate change upon average output and output variability has also been reported as a set of stylized facts (Galindo and Samaniego, 2010).

These are the facts, but how can they be explained? In standard economics, the paper by Robert Solow (1974) is still the classical reference; however, as will be shown below, this paper has shortcomings, which the new literature has not been able to resolve (Barro and Sala-i-Martin, 2004; Grimaud and Rouge, 2005; Lafforgue 2008). A different approach was adopted by Nicholas Georgescu-Rogen (1971), who applied the laws of thermodynamics to the economic process.

This paper presents a theoretical model using Georgescu-Rogen's framework. This model seeks to show the interactions between the economic process and the environment and thus establish the relationship between economic growth and the environment. The model attempts to explain the facts set forth above and to answer the following questions: Can economic growth go on forever? Can consumption be distributed equally between generations? What is the role of technological progress in the interactions between growth and environmental degradation?

The paper is divided into seven sections. Section II presents model A, which is based on an economic process using non-renewable natural resources. Section III examines the intergenerational consumption frontier. Section IV sets out model B, which applies the laws of thermodynamics to the economic process. Section V looks at model C, which considers the substitutability of capital, labour and natural resources. Section VI discusses the factors that could lead to changes in the intergenerational consumption frontier. Lastly, the conclusions of the study can be found in section VII.

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II

Model A: The economic process using non-renewable natural resources

This theoretical model will assume an abstract human society with given resource endowments and production technology. This society produces a single good, referred to as "good B".

With regard to the production process, the model uses the flow-fund framework of Georgescu-Roegen (1971). By definition, production is a continuous, self-perpetuating process in which two categories of production factors can be distinguished: *funds*, which act as agents, and *flows*, which are the materials being transformed into goods. In other words, funds can take the form of either inputs or outputs of the production process, whereas flows go in only one direction, either inwards or outwards.

The algorithm that will be applied in the construction of the most appropriate model begins with model A, which is based on a specific process for the production of good B. It is represented in the form of a production system as follows:

$$Q_j^* = F(K, L) \qquad (1)$$

$$Q_j^* = (1/z)\, N_j, \text{ such that } z > 0 \text{ and } \Sigma N_j \leq S_0, j=1,2,\ldots,T \qquad (2)$$

The production system (1)-(2) assumes that the flow of gross output Q^* is produced in period j using quantities of two types of production factors: the fund of services contained in the stocks of capital K and labour L —equation (1)— and the flow of material inputs N sourced from the stock of non-renewable natural resources S_0, which in this case will refer to mineral resources in the Earth's crust and will be considered the only input —equation (2). Capital stock K is composed of good B. Renewable natural resources will be ignored for the time being.

The production system (1)-(2) represents a particular notion of a production process in which Q_j^* is the output flow produced in period j, and N_j is the flow of mineral resources used in the same period. Production can continue period after period for as long as the stocks of K and L remain constant and the flow of mineral inputs is assured, until the stock S_0 is depleted.

The production system (1)-(2) assumes the use of limitational technology; that is, the first and second types of factor cannot be substituted for each other. Mineral resources cannot be substituted for capital or labour; however, K and L are substitutable factors, as indicated by equation (1). The proportion of mineral resources to gross output in the production process, represented by the coefficient z, is fixed and determined by technology.

Finally, the production system (1)-(2) also assumes given values for the length of the working period and the work intensity of production units in businesses that produce good B. The model assumes the full employment of the labour force and machinery. In a long-run analysis, such as that provided by this paper, a lengthy unit of time is used —in this case, a decade.

Some of these assumptions will be modified in the construction of two alternative models that will be presented in subsequent section of this paper. The laws of thermodynamics (on the relationship between matter and energy) will be introduced in model B; while model C will consider substitution between funds and flows. Model B will turn out to be the most appropriate of the three models.

In model A, if mineral resources are considered as redundant factors, the relevant equation in the production process is equation (1). Net output is by definition equal to gross output minus the quantity of goods allocated to the reposition of the stock K. The term "reposition" in this case refers to the quantity of good B needed to keep stock K constant; this implies securing the same stock and thus the same quantity of service funds period after period.

The coefficient of reposition of K can be represented by b, which indicates the quantity of good B needed per unit of K for the value of K to remain constant. Multiplying b by the quantity of K will give the total quantity of good B needed directly to repair the wear and tear on machinery and thus keep the stock of capital K constant period after period.

The reposition equation for any period j can be written as:

$$R_j = b\,K = r\,Q_j^*, 0 < r < 1 \quad (3)$$

In equation (3) R indicates total reposition, that is, the total quantity of good B that is needed to maintain constant the stock of K. From equation (1), it follows that given K and L, the quantity of gross output Q^* is known. Hence, the flow of reposition R can be represented as a fixed proportion of Q^*: the coefficient r. In a truly productive process, the coefficient r must be less than one.

The flow of net output Q can be written as:

$$Q_j = Q_j^* - R_j = Q_j^* - r\,Q_j^* = (1-r)\,Q_j^* \quad (4)$$

Equation (4) shows that the flow of net output Q is a fixed proportion of the flow of gross output Q^*. Because there is reposition, stock K is a *renewable* factor and net output is sustainable over time; that is, net output can be repeated period after period, as long as the mineral resources are a redundant factor. Net output may be allocated to capital accumulation or to consumption; however, the model assumes that all net output is allocated to consumption.

If society is endowed with machinery and labour in quantities K_1 and L_1, which are now the redundant factors of production, the relevant equation that applies to the production process is equation (2). The initial stock of mineral resources S_0 will decrease continuously in the production process, even if the same quantity of gross output is produced period after period. Therefore, the quantity remaining of the stock of mineral resources at the end of the period T, referred to as term S(T), can be written as:

$$S(T) = S_0 - \Sigma N_j, j=1, 2, ..., T = S_0 - \Sigma\, z\, Q_j^* = S_0 - z\,\Sigma\, Q_j^* = S_0 - z\,Q^*\,T \quad (5)$$

Equation (5) shows that if the quantity of gross output is constant, the initial stock of mineral resources declines steadily over time at the rate of $N= z\,Q^*$ per unit of time. The new stock at period T becomes S(T) according to the number of periods for which the production process was repeated.

III

The intergenerational consumption frontier

This section takes into consideration both equations of the production system (1)-(2). K_1 and L_1 shall represent the factor endowments of machinery and labour needed to produce gross output Q_1^* and render redundant the initial stock of mineral resources. The mineral resources required for the production of net output Q, as defined in equation (4), can then be included in equation (5) as follows:

$$S(T) = S_0 - z\,F(K_1, L_1)\,T = S_0 - z\,Q_1^* T = S_0 - [z/(1-r)]\,Q_1 T = S_0 - \mu\,Q_1 T, \text{ where } \mu = z/(1-r) \quad (6)$$

In equation (6) the depletion rate of the initial stock of mineral resources is now presented in terms of the net output Q_1. The stock of mineral resources declines steadily over time at the rate of $N= \mu Q_1$ per unit of time, where μ represents the technological requirement of mineral resources per unit of net output.

The period at which the stock of mineral resources is eventually depleted can be found by setting the value of equation (6) to zero, that is, $S_0 = \mu\,Q_1\,T$. This equality shows that a given initial stock and a given technological coefficient imply a fixed total output, whether that output is produced in the current period or in the future. If the net output for a given period is doubled, the number of periods over which that output can be sustained will be reduced by half. The higher the net output, the fewer the periods over which it can be repeated. A given net output level cannot be produced indefinitely.

By dividing equation (6) by μ, we obtain:

$$S(T)/\mu = S_0/\mu - Q_1 T \qquad (7)$$
$$Q(T) = Q_0 - Q_1 T$$

The term Q(T) shows the time path of net output, whereas Q_0 shows the quantity of net output that could be produced during the initial period. The productive capacity of mineral resources declines over time at the rate given by Q_1. This production capacity is given by the linear equation (7), in which the flow of net output Q_1, determined by the stock of machinery and labour, constitutes the (negative) slope.

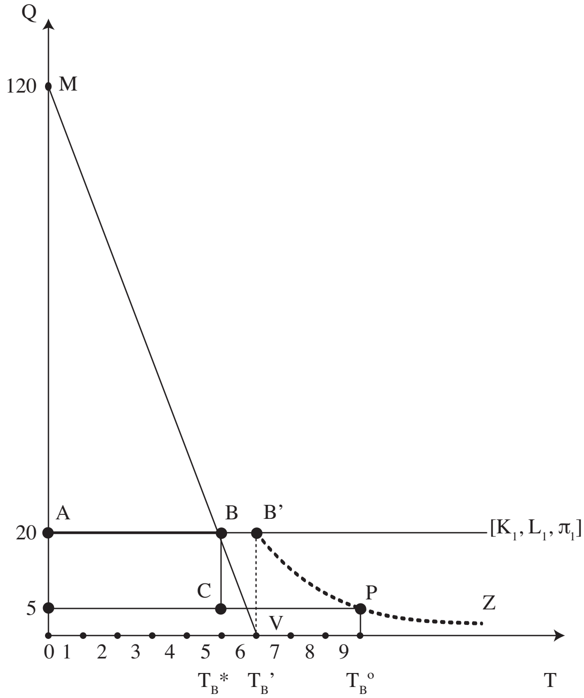
Equation (7) represents the constraints of both funds and flows in the production of net output Q_1, such that the stock of mineral resources is initially the redundant factor ($Q_0 > Q_1$). As the net output Q_1 is repeated period after period, the stock of mineral resources will decrease continuously and irrevocably, until it is ultimately depleted. By setting Q(T)=0, we can determine the period in which depletion will occur, let us call it T', at which point net output will become zero. T' implies the extinction of human society. The period in which mineral resources stop being redundant —let us call this T^*— can also be easily determined by setting $Q(T)=Q_1$. It is therefore clear that $T^*=T'-1$.

Another assumption will now be introduced into the model. Society would not readily allow nature to determine the end of its existence and would take action if confronted by the risk of extinction. We assume, therefore, that society will decide at period T^* (that is, when mineral resources are no longer redundant) to extend the duration of the remaining stock of mineral resources for more than one period by lowering the level of consumption. In that scenario, the remaining stock of mineral resources could be extended over several periods and used at the rate given by the new consumption level until these resources were depleted. We will refer to this end period, to be determined by society, as T°, such that $T^*<T'<T°$.

Equation (7) is represented in figure 1. The horizontal axis measures time and the vertical axis net output. Given the stocks of K_1 and L_1, and also given the level of technology Π_1, the corresponding flow of net output is represented by the segment OA, that is, Q_1= OA. The mineral resources constraint is represented by the line MV. OM units of net output could then initially be produced with the given stock of mineral resources; hence, mineral resources are initially redundant. But as OA units of net output are repeated period after period, the stock of mineral resources will decrease until the stock is depleted, which occurs at period T_B' (period 6 in figure 1). This is the basic nature of the flow-fund production process, as initially represented by the production system (1)-(2).

FIGURE 1

The intergenerational consumption frontier



Source: Prepared by the author.
Note: vertical axis measures consumption levels, assuming OM=120 units and OA=20 units; horizontal axis measures generations as time intervals.

Figure 1 also shows that net output is equal to consumption. At period T_B^*(period 5), when mineral resources are no longer redundant, society will decide to intervene and extend the duration of mineral resources by reducing consumption to a fraction of the current consumption level OA. Those mineral resources that have not been used at the end of that period could then last for several further periods until they are eventually depleted. This would depend, however, on the choices made by society with respect to the fraction of consumption. If consumption is reduced by half, the extension will be for two periods; if consumption is reduced to one third of current levels, the extension will be for three periods, and so on. The set of consumption possibilities is thus shown by the curve B'Z, which is an equilateral hyperbola.

The time path of the consumption possibilities may be called the *intergenerational consumption frontier*. In figure 1, it is represented by the segment AB and a particular point in the segment B'Z. The segment AB is constrained by the stocks of K_1 and L_1 and the segment B'Z by the remaining stock of mineral resources.

Let us suppose that society decides to choose point P in the segment B'Z. Beyond period T_B^*(period 5), the consumption level is given by the segment CP (the level C is one fourth of OA in figure 1) and will last for four additional periods, until mineral resources are depleted in period T_B° (period 9). The initial stocks of labour and machinery now become redundant, and the quantity of net output is limited by the available mineral resources. To simplify, we assume that the number of workers remains unchanged, even though only a proportion of them are needed in production. Some institutional changes will have to be introduced into society to accommodate the separation between workers' participation in production and in distribution. With no reposition needed, the stock of machines will be allowed to decline.

The distribution of consumption between generations can also be seen in figure 1. The consumption level of the present generation (OA for period 1) will be higher than the average consumption level of future generations (OA for four generations and OC for four generations). Consequently, there is consumption inequality between generations. The reason lies in the finite stock of mineral resources, which will not allow consumption level OA to be prolonged indefinitely.

In conclusion, when non-renewable natural resources are used in the production process, the current generation's consumption level cannot be sustained indefinitely. This is simply the result of the inevitable depletion of a given stock of exhaustible resources. Moreover, there will be a degree of inequality in the level of consumption between generations: the average consumption level of future generations will necessarily be lower than that of the current generation.

IV

Model B: Applying the laws of thermodynamics to the economic process

Environmental economics textbooks usually recognize two schools of thought in this new discipline (Hanley, Shogren and White 2001). The standard economic theory on the environment is based on neoclassical theory and the first law of thermodynamics. The other school, known as bioeconomics, was developed by Georgescu-Roegen (1971), who applied the second law of thermodynamics —the entropy law— to the economic process. Both laws of thermodynamics will now be introduced into the analysis of the production process, as well as the production system (1)-(2) and its derived relations.

So far, the effect of consumption on the environment has operated through a continuous decrease in the stock of mineral resources until its ultimate depletion. This process may be referred to as the *pure depletion effect* of a given non-renewable resource.

The laws of thermodynamics that are of interest in the economic process were put simply by Georgescu-Roegen (1971, pp. 5-6), as follows:

> "Let us take the case of an old-fashioned railway engine in which heat of the burning coal flows into the boiler and, through the escaping steam, from the boiler into the atmosphere. One obvious result of this process is some mechanical work: the train has moved from one station to another. To wit, the coal has been transformed into ashes. Yet one thing is certain: the total quantity of matter and energy has not been altered. That is the dictate of the Law of the Conservation of Matter and Energy—which is the First Law of Thermodynamics … At the beginning the chemical energy of the coal is *free*, in the sense that it is available to us for producing some mechanical work. In the process, however, the free energy loses its quality, bit by bit. Ultimately, it always dissipates completely into the whole system where it becomes *bound* energy, that is, energy which we can no longer use for the same purpose. […] In other words, high entropy means a structure in which most or all energy is bound and low entropy, a structure in which the opposite is true. […This is] the Entropy Law, which is the Second Law of Thermodynamics. All it says is that the entropy of

the universe (or of an isolated structure) increases constantly … and irrevocably. We may say that in the universe there is a *continuous* and *irrevocable* qualitative degradation of free into bound energy."

The outcome of the production process includes not only goods, but also "bads" because waste is an inevitable outcome of the production process. This constraint is set in the first law of thermodynamics: matter and energy can only be rearranged, not destroyed or created.

The first law has another implication for the production process. The production of material goods involves the transformation of inputs (the flow elements of production) by agents (the fund elements). Therefore, mineral resources are essential elements in the economic process in the sense that N=0 implies $Q^{*}=Q_{1}=0$. This property was already introduced as an assumption of the production system (1)-(2). According to the second law, waste is transformed into pollution of the biophysical environment. Depletion of resources and pollution are the two ways in which the economic process contributes to the degradation of the environment.

The production of goods is dependent upon the environment in two ways: (i) as a source of mineral resources (low entropy); and (ii) as a sink for waste (high entropy), which together degrade the environment (Daly 1996, p. 33). The Earth's size imposes limits on both components, as the given stock of mineral resources and finite capacity to absorb waste restrict our ecosystem's capacity to continue supporting human life as we know it. For the production process, the given stock of mineral resources would not be a problem if everything could be recycled, but the entropy law prevents full recycling; similarly, waste would not be a problem if our ecosystem's absorptive capacity were infinite.

Consequently, any production process, even those with a constant net output flow, implies a continuous and irrevocable depletion of mineral resources. Therefore, the economic process is a human activity that can also be seen as the transformation of low entropy (mineral resources) into high entropy (waste and pollution). Available matter and energy can be used only once in the production process. The production process thus implies degradation of free into bound energy.

Both laws of thermodynamics are very much interrelated. As economist Kenneth Boulding (1976, p.5) stated:

"In a closed system, the first law says that all that can happen is rearrangement; the second law says that if rearrangement happens, it is because there is some kind of potential for rearrangement, and as rearrangement goes on, potential is gradually reduced to zero and we get to the point where nothing further can happen."

The economic process only rearranges matter and energy, but in doing so the production capacity is qualitatively degraded. Therefore, as production is repeated period after period, the potential of the production system is continuously and irrevocably degraded. The economic process is not mechanical, but entropic.

How do the laws of thermodynamics affect the intergenerational consumption frontier? First, the effect of waste on the qualitative degradation of the biophysical environment must be taken into account. Waste will lead to environmental pollution, of water, air and soil. We may assume that pollution leads to an increase in the average global temperature and that climate change will affect the production process by making it more risky.

Second, pollution is an outcome of the production process; however, it will have a feedback effect upon the production process as it will increase the cost of replacing machinery. Owing to the direct damage inflicted by pollution upon the physical capital and the higher risk of destruction from climate change, a higher depreciation rate will now be required to keep machines both productive and durable.

As a result, more mineral resources will be required to maintain the same level of net output. Because the flow of pollution *accumulates* in the environment, as the same net output is produced period after period, the feedback effect will compound over time, and thus the technological coefficient of mineral resources required per unit of net output will increase over time; that is, the value of the coefficient μ will rise continuously over time.

The initial assumption on the production process indicated by the system (1)-(2) will now be modified. Given the values $K=K_{1}$, $L=L_{1}$ and $\pi = \pi_{1}$, the flow of gross output $Q^{*}=Q_{1}^{*}$ will be determined, provided that mineral resources flow in the quantity of N, which now includes the requirements of both direct material inputs and the indirect inputs induced by the level of pollution (P). The level in period T can be written as:

$$P(T) = \Sigma P_{j} = \Sigma\beta N_{j} = \beta z \Sigma Q^{*}_{j}, j = 1, 2, \ldots, T \quad (8)$$

The coefficient β indicates the pollution rate from burning minerals in the production process or the rate of greenhouse gas emissions from using energy from mineral resources.

We can determine the total coefficient of mineral resources required per unit of net output as follows. First, the costs associated with the reposition of machinery R are now:

$$\begin{aligned} R(T) &= r\, Q_1^* + r'\, P(T) = r\, Q_1^* + r'\, \beta\, z\, \Sigma\, Q_j^* \\ &= r\, Q_1^* + r'\, \beta\, z\, Q_1^*\, T = (r + r'\beta\, z\, T)\, Q_1^* \\ &= \lambda(T)\, Q_1^* \end{aligned} \quad (9)$$

$$\begin{aligned} Q(T) &= Q_1^* - R(T) \\ &= Q_1^*\, [1 - \lambda\, (T)], \end{aligned} \quad (10)$$

where $[1 - \lambda]>0$, and $\lambda'(T)>0$

In equation (9), the first term shows the usual reposition cost, which is equal to the proportion r of total gross output, plus the costs of reposition due to the pollution effect on the machinery, which is equal to the proportion (r') of the level of pollution. Therefore, the coefficient of total reposition per unit of gross output is represented by λ, which increases over time, and, as a function of time T, is represented by λ(T). Equation (10) shows the new relationship between net output and gross output.

The quantity of mineral resources required per unit of net output is then obtained from equation (10) as follows:

$$\begin{aligned} N(T) &= z\, Q_1^* \\ &= (z/[1 - \lambda\, (T)])\, Q_1 \\ &= \varepsilon\, (T)\, Q_1, \end{aligned} \quad (11)$$

where $\varepsilon(T)= z/[1 - \lambda(T)]$, $\varepsilon'(T)>0$, and $\varepsilon(0)=z/(1 - r)= \mu$.

The coefficient ε represents the quantity of mineral resources required per unit of net output, the value of which includes the feedback effect of pollution on the production process; moreover, the value of this coefficient increases over time owing to the cumulative effect that production has on pollution.

In order to derive the time path of the consumption possibilities frontier, equation (6) has to be rewritten to take into account the new relations that have become apparent:

$$\begin{aligned} S\, (T) &= S_0 - \Sigma\, N_j = S_0 - z\, \Sigma\, Q_j^* = S_0 - z\, Q_1^* T \\ &= S_0 - (z\, /[1 - \lambda\, (T)])\, Q_1 T \\ &= S_0 - \varepsilon\, (T)\, Q_1 T \end{aligned} \quad (12)$$

$$Q\, (T) = [S_0\, /\, \varepsilon\, (T)] - Q_1\, T \quad (13)$$

Equation (12) shows the time path of the stock of mineral resources, which at the point in time T is equal to the initial stock S_0 minus the quantity used up to that period. Equation (13) is the result of dividing equation (12) by the coefficient ε, which increases over time.

Equation (13) shows the entropic production process. It integrates flows and funds, as well as the interactions between the economic process and the biophysical environment. The quantity of net output Q_1, determined by the funds, the stock of machinery and labour, takes into account the constraint imposed by the stock of mineral resources. As T increases the requirement of mineral resources per unit of net output (the coefficient ε) also increases, which implies a continuous downward shift of the intercept of the frontier curve. The production time path, determined by the mineral resources constraint, is now non-linear, a convex curve. Thus, the same net output will lead to a more rapid depletion of mineral resources than in the previous case, which ignored the pollution feedback in the production process.

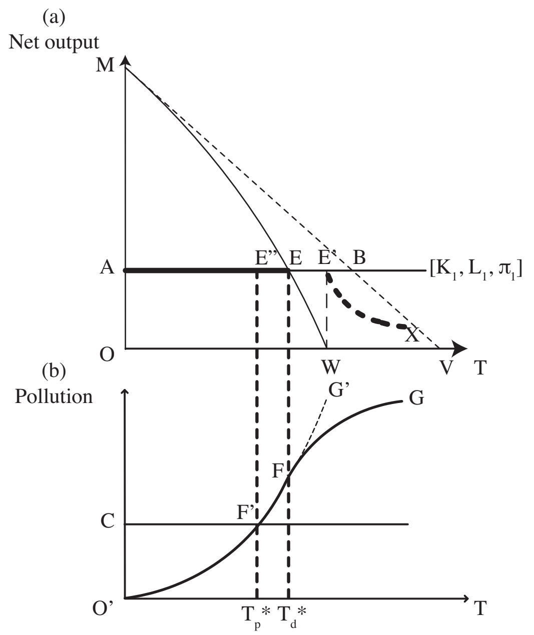
The entropic production process is represented in figure 2, with the depletion effect shown in panel (a). The straight line MV assumes a constant technological coefficient of mineral resources required per unit of net output (as in figure 1). This line represents the initial period. Since the coefficient ε increases over time, the line MV will shift continuously inwards and the new production frontier will be represented by the convex curve MW, which will transect the segment AB at point E. The entropic production process implies a more rapid depletion rate of mineral resources, as shown by the curve MW.

The point at which social intervention takes place occurs when the curve MW transects horizontal line AB at point E, referred to as period T_d^*. Beyond this period, the consumption possibilities for the remaining mineral resources will be given by the curve E'X. Then, social choice will determine a particular point along this curve. The intergenerational consumption frontier is more limited than the comparable curve shown in figure 1 because of the effect of the entropy law.

Panel b of figure 2 depicts the pollution effect. As the same quantity of net output is repeated over time, waste and pollution accumulate in the environment, as represented by the curve O'G. The curve rises sharply up to the period T_d^* when mineral resources become scarce. Beyond that point, at which society intervenes, the level of pollution continues to rise but at a slower rate, following the path FG rather than FG'; that is, as consumption levels fall, the rate of increase of pollution also falls, but the level of pollution increases continuously and irrevocably, in line with the law of entropy. Society can modify the rate of degradation, but cannot prevent degradation altogether.

FIGURE 2

Natural-resource depletion and pollution in the production process



Source: Prepared by the author.

Figure 2 thus shows the two laws of thermodynamics in action. These laws impose constraints on the production process through depletion and pollution and, as suggested in the figure, these effects are interrelated. The effect of the depletion of mineral resources sets a time limit on the production of a given net output: output OA can be repeated until period T_d^*. Pollution will have the same property. Our ecosystem has a limited capacity to absorb waste if it is to maintain its capacity to support human life. That limited capacity can be represented as a threshold, given by the level O'C, which occurs in period T_p^*. If atmospheric pollution exceeds this threshold, the preservation of human life, as we know it, cannot be guaranteed. The segment F'G of the rising pollution curve O'G will result in a steady decline in people's quality of life owing to food source pollution and on the deterioration of human health. At that stage humans will have to make qualitative changes and adopt adaptation measures since, for example, low oxygen levels in the air could result in a kind of anaerobic human existence.

The effects of resource depletion and pollution will impose different threshold periods on the human species, depending on which of the two effects occurs first. In figure 2, for instance, our model assumes that the pollution threshold (T_p^*) will be reached before depletion (T_d^*). The relevant constraint of the environment is, in this case, the capacity of the ecological system to support human society, not the depletion of mineral resources. This ecological capacity is the ultimate element of scarcity in the economic process. Everything can be produced or substituted, except ecological capacity. We humans cannot generate another ecological environment with which to sustain our existence. In this case, the intergenerational consumption frontier will trace the path of AE" only. The model assumes that human society will be motivated to take action when confronted with the risk of extinction. In such a situation, humans will need to achieve technological and institutional innovations to move to another age. Just as humans evolved out of the stone age despite the continuing existence of stones, the use of mineral resources will be abandoned before they become exhausted.

Figure 2 clearly indicates that the ecological challenges faced by humanity will persist even if consumption levels remain steady, that is, even if we had a zero-growth society, in terms of output and population. Certainly, the problem will be more acute if society embarks on a process of economic growth, as will be shown below.

The role of renewable natural resources in the economic process has been disregarded in the entropic model. The implicit assumption that these resources were abundant will now be revised. For this purpose, two sources of energy must now be distinguished in the production process: (i) the finite and therefore exhaustible mineral resources in the Earth's crust; (ii) the sun's energy, in the form of solar radiation, which provides the Earth with a source of energy for renewable natural resources, such as forests and fish stocks.

The Earth is a closed thermodynamic system, inasmuch as it obtains energy from the sun but does not exchange matter with outer space (Baumgärtner 2004, p. 320). The scarcity of renewable natural resources comes from the Earth's limited size as a trap for solar energy. As agricultural soil is limited and subject to erosion, it belongs in the category of non-renewable resources.

Fish stocks, forests and other biological resources may, however, be subject to depletion if the rate of biological reposition is slower than the rate at which they are exploited by humans. When renewable natural resources are not renewed, they become depleted in the same way as mineral resources. In this case, renewable natural resources can also be included in the coefficients that determine the model's intergenerational consumption frontier. Those renewable natural resources that are in fact renewed may be considered as redundant factors in the model and may thus be ignored in the analysis.

In panel (a) of figure 2, the production frontier as constrained by solar energy, considered an absolute redundant factor of production, can be introduced as a horizontal line starting from above point M. Under this assumption, the segment AE and the social choice of one, and only one, point in the segment E'X can still represent the intergenerational consumption frontier, which is now determined by non-renewable resources and by those renewable resources that human production activity has made non-renewable.

V

Model C: Substitutability between funds and flows

Another set of assumptions about the production process, according to standard economics, are covered by the concept of *production function*, which can be represented as follows:

$$Q = F(K, L, N) \qquad (14)$$

Standard economics thus assumes that the quantity of output produced depends upon the stocks of machinery, labour and natural resources, and that all of these factors of production can be substituted for one another (Solow 1974, p.34). This simple equation implicitly suggests that the three factors play the same role in the production process. In such a scenario, net output could be produced with machinery and workers alone, thereby making it possible to sustain the level of net output indefinitely. Note the difference with the flow-fund approach, which was represented as a *production system* in equations (1)-(2), rather than as a production function.

A consequence of the standard economics assumption about the production process is that the production of a given net output can go on forever. Therefore, output growth can also go on forever. There are no limits to the production of goods. This view was established by Solow in his seminal paper of 1974 and updated by Lafforgue (2008, p. 541) as follows:

> "It is now generally accepted that the limited supply of non-renewable resources does not necessarily imply a limit to growth. In particular, the neoclassical theory gives rise to three main possibilities: (i) substitution of the resource by other inputs, such as capital; (ii) improvement of resource efficiency; and (iii) development of backstop technologies. However, without any technical change, none of these outcomes will balance the resource exhaustion and continue to sustain some positive growth in the long run."

According to this view, a way to introduce substitution between machinery and mineral resources would be to assume that the technological coefficient of mineral resources per unit of net output will fall as machinery stocks increase. This substitution would be induced by changes in the relative prices of minerals, that is, as mineral resources become more expensive.

Even accepting the possibility of substitution, the question remains: Where would the new machines come from? They would have to be produced and that would require more mineral resources. The net effect of substitution and the savings of mineral resources would be smaller than if a pure substitution effect were to take place; for example, windmills can substitute oil in generating energy, but building windmills requires minerals and other inputs. In addition, the net output is a material good, which cannot be totally dematerialized, according to the first law of thermodynamics, thus setting a limit on the possibilities of substitution.

In figure 1, if a quantity of capital can substitute mineral resources, then the line MV could shift outwards, to another line that could be referred to as M''V'' (not drawn). But producing that quantity of capital would require mineral resources and would also imply reposition costs in terms of mineral resources. So, the net effect of substituting minerals would be smaller than the initial effect (a change from line MV to, say, line M'V', which would be drawn below line M''V''). If we assume that the net effect is positive, the curve representing the intergenerational consumption frontier would shift outwards. That would extend period T^*, though it would remain finite. More substitution could proceed, until the limit was reached. If the line MV represents the limit of substitution possibilities, the model will have captured the substitution effect.

In sum, in the entropic production process, substitution between fund and flow factors is possible —but only to a certain extent. This is in line with the assumption that mineral resources are essential factors of production, which is consistent with the laws of thermodynamics. However, these substitution effects will not eliminate the intergenerational consumption frontier. Even with substitution, if a given net output is repeated period after period, mineral resources will eventually become scarce and depleted and pollution will increase. Therefore, as long as mineral resources are essential factors in the production process, this conclusion will hold true. In short, the conclusions reached so far using the entropic model B retain their validity.

By comparison, standard economics has developed a large body of literature on growth theory. The models presented in popular textbooks predict that economic growth can proceed indefinitely and that the role of non-renewable natural resources can be ignored (Barro and Sala-i-Martin 2004). Given the rates of savings, population growth and technological progress, and assuming that K grows by 5%, L by 2% and π by 3%, in a dynamic equilibrium total output will grow by 5%, and so the output per person will increase by 3% (the difference between 5% and 2%). This could be repeated period after period, indefinitely. In these models, there are no constraints on growth.

Some neoclassical models do deal with non-renewable natural resources and an even smaller number with the problem of pollution, which is treated as simply a problem of externalities, and thus amenable to solution via Pigouvian taxes (Grimaud and Rouge, 2005). The neoclassical models that include natural resources in the economic process are still mechanical, and the qualitative consequences of economic growth for the environment (via the entropy law) are ignored. In this regard, Baumgärtner (2004, p. 308) affirmed that, "[neoclassical theory assumes that] on the whole thermodynamic constraints are simply irrelevant for economics".

VI

Changes in the intergenerational consumption frontier

The concept of the intergenerational consumption frontier has been constructed on the basis of a series of givens. The exogenous variables of model B include technology and the endowments of machinery, labour and mineral resources. It is time to analyse the effect of changes in these exogenous variables on the intergenerational consumption frontier.

An exogenous increase in the stocks of machinery and labour, together with any technological changes incorporated in new physical and human capital investments, will boost the current flow of gross output and net output; hence, the consumption level of the current generation will also increase. But that will lead to a concomitant rise in the rate of depletion of mineral resources, which will in turn increase the rate of pollution. In figure 2, higher stocks of K and L, and a higher level of π, will modify the intergenerational consumption frontier as follows: the level of consumption OA will shift upwards, leading to an inward shift of the curve MW representing the depletion of mineral resources and also an upward shift of the pollution curve O'G. Thus, the critical periods T' and T^* will occur sooner.

Another consequence is that the degree of intergenerational inequality will be higher: the consumption level of the present generation will increase, but the average consumption level of future generations will fall. In other words, economic growth implies greater intergenerational inequality. Therefore, the only choice society has is how to distribute the consumption level and the corresponding non-renewable resources between generations. A higher consumption level allocated to the current generation will mean that less mineral resources will be left for future generations, whose total consumption level will therefore be lower.

Consider now an exogenous technological change that leads to a decrease in the initial coefficient of mineral resources per unit of net output, the coefficient ε, which is determined by the initial coefficients z and λ, as shown in equation (11). A reduction in the value of this technological coefficient is equivalent to an increase in the initial stock of mineral resources. This is a mineral-resource-saving technological change. Therefore, the intergenerational consumption frontier will shift outwards and the pollution curve will shift downwards.

These effects can be visualized using figure 2. With new technologies that save mineral resources per unit of net output, the intercept of the mineral resources constraint curve will move upwards, above point M; the curve MEW will shift outwards and so, consequently, will the intergenerational consumption frontier. The pollution curve O'G will shift downwards. From equations (8) and (10), we can see that the reason for this shift is that the curve O'G is determined by the flow of net output (Q_1=OA), which remains unchanged, and also by the technological coefficients, which will be lower. As a result, the critical periods T' and T^* will occur later.

It is still true, however, that the current level of consumption cannot be repeated period after period indefinitely; consequently, technological progress cannot eliminate the intergenerational consumption frontier—it can only move it to another level. At each new level of technology, there will be a new intergenerational consumption frontier; moreover, this new frontier will reduce the degree of inequality between generations. This is assuming that technological change is cost-free. Taking into account the cost of mineral resources in research and development (R&D), the net effect would be smaller.

Could technological change be efficient enough in saving mineral resources to make a given consumption level sustainable indefinitely? If we assume that technological change is endogenous and cost-free, it is possible to imagine a scenario in which, following the depletion by half of mineral resources in a given period of production, technological change could occur immediately and reduce the technological coefficient of minerals per unit of net output by half, which would be equivalent to doubling the remaining mineral resources. As a consequence, the stock of mineral resources would remain constant over time, that is, the mineral resources would have become *renewable* natural resources. If that were the case, the consumption level OA in figure 2 could be repeated forever. Along this horizontal line, machines and minerals would become renewable resources thanks to technological change.

However, the lower panel of figure 2 must also be considered: pollution will inevitably continue to have an impact. Mineral resources will be used up to produce Q_1 in the first period; and even if the stock of mineral resources were recovered economically through technological change, the mineral resources used up will have generated pollution. In the next period, net output will be repeated and new mineral resources will be used up; and even if the stock of mineral resources were recovered economically, the pollution caused will inevitably have had an impact and will now have accumulated for two periods, and so it would continue. The curve O'G will then become linear. In this case, pollution, not depletion, would be the limiting factor in the economic process. Technological change would now have to eliminate the build-up of pollution to achieve a non-entropic production process and would therefore have to solve two problems: depletion of natural resources and pollution. In the most favourable scenario, it is unlikely that technological change can subvert the laws of thermodynamics.

Economic growth combined with mineral-resource-saving technological change seem to have an ambiguous effect on the threshold periods, T' and T^*. The growth effect reduces the length of those threshold periods, whereas the technology effect extends them. However, given the argument set forth above about the limits of technological change, the economic growth effect will prevail and the time thresholds will be shorter. In sum, this suggests that economic growth will curtail the survival of human society, as we know it.

VII
Conclusions

Of the three theoretical models presented in this paper, model B, the entropic model, applies the laws of thermodynamics to the economic process and focuses on the interactions between the economic process and the biophysical environment. The outcomes of these interactions include consumption patterns, the depletion of natural resources and pollution of the environment. This examination of consumption patterns allows us to trace an intergenerational consumption frontier: any consumption level can be maintained for only a finite number of periods.

The exogenous variables of the entropic model include the initial stocks of capital, labour and mineral resources together with technology. Increases in the stocks of capital and labour, as well as new labour-saving technology, reduce the finite number of periods of the intergenerational consumption frontier, whereas technological progress that leads to savings in non-renewable natural resources increases this number.

The entropic model is able to predict the observed relationship between economic growth and environmental degradation. Thus, the empirical observation that increased world CO_2 concentrations in the air have coincided with a period of rapid economic growth, as described in the introduction, has a scientific explanation.

The entropic model has several implications for public policies. First, since any given consumption level can be sustained for a finite number of periods only, a higher consumption level will go on for fewer periods; that is, economic growth cannot go on indefinitely. Second, economic growth exacerbates the inequality in the intergenerational distribution of consumption. Third, technological progress can only reduce the rate at which environmental degradation takes place, since that degradation itself is continuous and irrevocable. Fourth, the conflict in relation to growth exists not only between generations, but also within the current generation: less developed countries will have more limited ecological space to grow if the most developed countries and a few emerging economies keep growing. In this regard, Edward Wilson, a Harvard biologist, concluded that, "To raise the whole world to the US [present living standard] level with existing technology would require two more planet Earths" (Wilson 1998, p. 282).

These relationships cannot be ignored in the debate on public policy alternatives, at both the national and international levels. These are the fundamental economic problems of our time and can be attributed to the fact that the economic processes of growth and distribution are currently taking place amid conditions of environmental distress, as explained by the entropic model presented in this paper.

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