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The role of natural resources in production: Georgescu-Roegen/Daly versus Solow/Stiglitz

Quentin Couix*

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Abstract

This paper proposes a historical and epistemological account of one of the key controversy between natural resources economics and ecological economics, lasting from early 1970s to the end of 1990s. It shows that the theoretical disagreement on the scope of the economy's dependence to natural resources, such as energy and minerals, has deep methodological roots. On one hand, Solow's and Stiglitz's works are built on a "model-based methodology", where the model precedes and supports the conceptual foundations of the theory and in particular the assumption of "unbounded resources productivity". On the other hand, Georgescu-Roegen's counter-assumption of "thermodynamic limits to production", later revived by Daly, rests on a methodology of "interdisciplinary consistency" which considers thermodynamics as a relevant scientific referent for economic theory. While antagonistic, these two methodologies face similar issues regarding the conceptual foundations that arise from them, which is a source of confusion and of the difficult dialogue between paradigms.

Key words : natural resources, thermodynamics, growth, sustainability, model, theory, methodology.

JEL classification : B22, B41, Q01, Q32, Q43, Q57.

*Université Paris 1 - Centre d'économie de la Sorbonne (CES). Quentin.Couix@univ-paris1.fr.

Introduction

Modern economic thought on environmental issues has known an important revival in the 1970s. It was especially triggered by the report on *The Limits to Growth* (Meadows et al., 1972). Written by a team of engineers from the MIT and supported by the Club of Rome, a group of worldwide decision-makers, the report suggested that actual economic growth could lead to ecological collapse, due to resource depletion and the accumulation of pollutions.

Growth economists, such as Robert Solow (1973, 1974a,b) and Joseph Stiglitz (1974, 1979), criticized the report, both on methodological and theoretical ground. In parallel, they proposed their own approach, based on the neoclassical growth framework initiated by Solow (1956) and that had become very popular among economists in the 1960s (Boianovsky and Hoover, 2009). Their approach suggested a more optimistic outcome than the scenario of the Club of Rome. Among other important assumptions, their models incorporated the idea that the productivity of resources could be increased toward infinity thanks to the substitution of capital to resources and technical progress. Their contributions laid the foundations of "natural resources economics".

But inside the economic community, a research program closer to that of *The Limits to Growth* had recently emerged, around economists like Nicholas Georgescu-Roegen (1971) and Kenneth Boulding (1966). After giving important contributions to neoclassical theory, these economists formulated an epistemological criticism of its foundations. They proposed a reorientation based on references to thermodynamics and biology, placing environmental issues at the heart of their preoccupations. Georgescu-Roegen in particular took part in the debate on the limits to growth, criticizing Solow and Stiglitz's works on exhaustible resources (Georgescu-Roegen, 1975, 1979). Among other aspects, his criticism contested the relevance of the Cobb-Douglas production function and the assumption of unbounded resources productivity it encapsulates. Conversely, he argued that thermodynamic laws set limits to substitutability and technical progress.

This criticism was revived by Herman Daly almost twenty years later in an article called "Georgescu-Roegen versus Solow/Stiglitz" (1997a). Daly was a former student of Georgescu-Roegen and much influenced by him. He criticized what he perceived as a "growthmania" among economists and defended a steady-state economic policy (Daly, 1974, 1979). He played an important role in the institutionalisation of "ecological economics", an emergent school of thought, which got its own society and journal in 1989. His article of 1997 was part of an issue of *Ecological Economics* dedicated to Georgescu-Roegen, who had died in 1994 and was recognized as a precursor of ecological economics. It generated a forum debate, with neoclassical economists, like Solow and Stiglitz, and ecological economists answering each others in this issue. Compared to the sparse exchanges of the 1970s, this forum debate appears has a much more direct confrontation. The controversy as a whole, from the 1970s to the end of 1990s, is a good opportunity to better understand the divergences between these two paradigms. The purpose of the present paper is to give a detailed account of it, in order to clarify the issues at stake.

This work builds on an increasing literature on the history of economic thought on environmental issues. Natural resources economics has been the subject of surveys (Toman et al., 1995) or more specific investigations on its links to precursors such as Harold Hotelling (Erreygers, 2009). Similarly, ecological economics has been studied both for its early contributions (Ould Boye, 2014; Røpke, 2004) and for its more recent developments (Røpke, 2005). Georgescu-Roegen appears a particularly intriguing figure for the history of economic thought and his work has been the subject of recent re-examinations (Bobulescu, 2012, 2015; Missemer and Georgescu-Roegen, 2013; Missemer, 2016). Finally, some contributions have given insights on the confrontation between the two paradigms (Pezzey and Toman, 2005; Neumayer, 2013; Pottier, 2014). However, none of these contributions has fully investigated the thread that leads from the early works of Solow and Stiglitz, and their criticism by Georgescu-Roegen, to the forum debate in *Ecological Economics*. The present paper intends to fill this gap and therefore to improve the understanding of the cleavage between natural resources economics and ecological economics.

This is especially important because the opposition between these paradigms has laid the ground for two different interpretations of "sustainability", a concept that has become central during the 1990s (Neumayer, 2013). "Sustainable development" was originally defined as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (Brundtland, 1987). Given this objective, "weak sustainability" defends the possibility of substituting man-made capital to natural capital as it is depleted. The underlying idea of substitution clearly takes its roots in the work of Solow and Stiglitz. On the other hand, "strong sustainability" rejects the idea of unlimited substitution of man-made capital to natural capital. It rather advocates for the preservation of specific natural life supporting functions. This opposition has yielded different empirical indicators of sustainable development and different recommendations, used by institutions involved in environmental policy. It still frames the debates on environmental issues nowadays (Pezzey and Toman, 2005; Neumayer, 2013). Hence, the controversy at stake here offers the opportunity of exploring some of the foundations of the opposition between weak and strong sustainability.

To do so, I reconstituted the intellectual threads that lead to the 1997 debate in *Ecological Economics*. Starting from Daly's contribution (1997a) I investigated the origin of his criticism in the work of Georgescu-Roegen (1975; 1979) and identified its theoretical foundations. But the relatively few elements supporting it invited to examine other contributions of Georgescu-Roegen (1981; 1986; 1988) on natural resources, production and growth, to measure the importance he gave to it. Similarly, I reconstructed the theoretical framework underpinning Solow and Stiglitz interventions in the debate. It is constituted of both mathematical analysis (Solow, 1974b; Stiglitz, 1974) and interpretative essays of the formal results (Solow, 1974a; Stiglitz, 1979). This enables to grasp the main features of the two paradigms and to give a deeper account of the problems addressed by the debate.

The notion of paradigm (Kuhn, 1962) is used here to denote the constituents of each approach, such as definitions, illustrations, models or data, and their relations to each others. Our perspective is mainly theoretical and methodological[1]. Here, "theory" should be understood as the conceptual structure of the paradigm, the intellectual framework through which economists conceive their object of study. Concepts can be expressed through definitions and illustrations, and they are articulated together to form propositions. These propositions can have different statutes, such as "assumptions" or "conclusions", depending on their localisation in the structure of the theory. The whole conceptual structure is expressed in literary language. Therefore, we consider "models" separately from theory. These are mathematical systems constituted of variables and parameters, in which a

[1]Therefore, this approach leaves other interesting aspects aside. First, we don't deal with the few empirical elements used in the controversy, relying either on econometrics, or on technological prospective. Second, we don't consider the impact of the social and political context, apart from the publication of *The Limits to Growth.* Among interesting political aspects that could be investigated, attention could be given to the institutional positions occupied by Daly and Stiglitz. The first has served as economist in the Environmental Department of the World Bank from 1990 to 1994. While the second was just appointed chief economist of the same institution in 1997, after chairing the Council of Economic Advisers.

specific problem is formulated. Studying the logical implications of the model enables to identify conditions on the values of the parameters under which the solutions of the problem are qualitatively different. This amounts to establishing a set of relations, whether simple implications or equivalences, between different mathematical propositions. These relations shouldn't be assimilated to the kind of conceptual relations encapsulated in the theory. It is actually one the purposes of "methodology" to clarify the kind of links that exist between models and theories, but also between different theories, including from different disciplines. This is useful to understand the structure of the paradigm, to identify its ontological presuppositions, and to capture the origins of its conceptual structure. Finally, this is also helpful to confront it to various epistemological concerns, such as falsifiability or incommensurability.

This analysis shows that the theoretical disagreement on the scope of the economy's dependence to natural resources has deep methodological roots. On one hand, Solow and Stiglitz's work is built on a "model-based methodology", where the model precedes and supports the conceptual foundations of the theory. This is particularly true regarding the central the assumption of "unbounded resources productivity", which in turn cannot be given a definite meaning outside the model. On the other hand, Georgescu-Roegen's opposition, later revived by Daly, rests on a methodology of "interdisciplinary consistency" which considers thermodynamics as a relevant scientific referent for economic theory. This gives rise to the idea of "thermodynamic limits to production", considered as an outcome of Carnot's principle of the maximum efficiency of thermal engines. These strong theoretical and methodological oppositions yield incommensurability between the two paradigms. However, I argue that conceptual issues faced by both methodologies strengthened this incommensurability, while a detailed examination of these issues is an opportunity to accurately identify the subject of discord. I suggest that it resides in the relationship between natural resources, the non-material services they provide, and the value of these services, considered as more or less tight depending on which paradigm one relies on.

The article is organized in three sections. Section 1 shows how the assumption of unbounded resources productivity was integrated in Solow and Stiglitz's models under the form of capital substitution or exogenous technical progress. The model-base methodology underpinning this approach is identified, and its conceptual issues are examined. Section 2 introduces Georgescu-Roegen's thermodynamic approach of the economic process. While his critique of Solow and Stiglitz's work covers a wide range of topics, particular attention is given to the idea of thermodynamic limits and its underlying methodology of interdisciplinary consistency. Finally, section 3 shows how the 1997 forum debate reformulated this controversy in the framework of sustainability, opposing weak and strong approaches. I underline that the conceptual issues previously identified continue to influence the debate on both sides. This enables to frame more accurately the issues at stake.

1 Solow, Stiglitz, and the origins of the natural resources economics

Even though there had been work of neoclassical economists on resources before, the interest was revived by the report on *The Limits to Growth* (Meadows et al., 1972). The report was written by a team of engineers from the MIT, building on the methodology of system dynamics initiated by Jay Forrester. It displayed different set of simulations corresponding to different assumptions on population, pollution, natural resources and technological improvements. In its "business as usual" scenario, industrial growth and population were peaking at the beginning of the twenty-first century and then declining. The constraints that generated this ecological collapse were both the capacity of the environment to absorb pollutions and the depletion of resources.

The report appeared as an attack toward the insistence of economists on the benefits of growth. It triggered a large debate in which eminent economists enrolled. Robert Solow for example gave a talk at the "Symposium on the Limits to Growth" at Lehigh University, latter published in *Challenge* (1973). It was very critical of the method and assumptions of *The Limits to Growth*. Therefore, economists felt the need to study the problem with their own tools, as Solow expressed it in his Richard T. Ely lecture at the annual meeting of the American Economic Association in December 1973:

> About a year ago, having seen several of those respectable committee reports on the advancing scarcity of materials in the United States and the world, and having, like everyone else, been suckered into reading *The Limits to Growth*, I decided I ought to find out what economic theory has to say about the problems connected with exhaustible resources. I read some of the literature, including Hotelling's classic article — the theoretical literature on exhaustible resources is, fortunately, not very large — and began doing some work of my own on the problem of optimal social management of a stock of a nonrenewable but essential resource. (Solow, 1974a, p. 1-2)

The work Solow referred to was published in the "Symposium on the Economics of Exhaustible Resources", a special issue of *The Review of Economic Studies* (Solow, 1974b). Among the other papers of this special issue, that of Stiglitz (1974) also had an important influence on later works. These papers shared a similar framework and laid the foundations of the neoclassical analysis of growth with resource depletion[2], also known under the label of "natural resources economics".

1.1 General framework

Their framework builds on Solow's growth model (1956). Among the key features of this model is the notion of "production function"[3], relating the level of output Q to the level of the factors of production. Traditionnally, only aggregate capital K and labor L were considered as relevant production factors. But natural resources economics introduced a variable R, representing the flow of resources, in the production function, such that:

$$Q = F(K, R, L, t) \tag{1}$$

The notion of "resource" itself is not defined very accurately, but examples show that the Solow and Stiglitz understand it as energy sources, such as oil or coal, and minerals, such as copper or phosphorous. The important features of these resources are that they are exhaustible and taken from a finite stock S_0. Mathematically, this leads to the constraint:

$$\int_0^\infty R(t)dt \leq S_0 \tag{2}$$

[2]As underlined by Pottier (2014), by focusing on the depletion of resources, neoclassical economists put aside the question of pollutions and the link between the two, which was an important aspect of the Meadows report.

[3]The notion of production function was originally introduced by Wicksteed (1894) and later used in empirical studies by Cobb and Douglas (1928). However, until Solow's growth model, this notion was rather impopular among economists(Felipe and McCombie, 2013).

Time t is introduced in the production function to account for "exogenous technical progress". Formally, it represents variations of output that are not attributable to variations of the factors of production. An other important dynamical aspect inherited from Solow's growth model is the distribution of output between aggregate consumption C and net investment $\dot{K}$, in the form:

$$C + \dot{K} = Q \tag{3}$$

Finally, population is supposed to be growing at a constant rate n:

$$L = L_0 e^{nt} \tag{4}$$

Thanks to this framework, Solow and Stiglitz want to study the problem of the intergenerational distribution of wealth. The main issues in this prospect are the trade-off between consumption for the present generation and investment to accumulate productive capital for the coming generations, and the constraint of the finite stock of resources. Hence, they need to specify the norm of intergenerational justice they want to achieve and the properties of their production function. On both aspects, Solow and Stiglitz follow slightly different roads.

1.2 Solow's model

Regarding intergenerational justice, Solow adopts a norm of constant consumption per head across generations, that he links to the notion of justice in John Rawls's work[4]. Given this norm, he argues that some assumptions have to be made on the production function for the problem not to be trivial:

> For the problem to be interesting and substantial, R must enter in a certain way. For example,if production is possible without natural resources, then they introduce no new element. Presumably the initial stock would be used up early in the game to shore up consumption while a stock of capital is accumulated, which will then be maintained intact while the same level of consumption goes on even after the natural resource pool is all gone. [...] On the other hand, if the average product of resources is bounded, then only a finite amount of output can ever be produced from the finite pool of resources; and the only level of aggregate consumption maintainable for infinite time is zero.
>
> The interesting case is one in which $R = 0$ entails $Q = 0$, but the average product of R has no upper bound. (Solow, 1974b, p.34)

This introduces the two main characteristics of production functions advocated by neoclassical economists with regard to natural resources. First, the resource must be "essential" in the sense that production shouldn't be possible without a strictly positive flow of resources. Second, output is not absolutely limited by the flow of resources, that is the assumption "unbounded resources productivity". As acknowledged by Solow, this last one is crucial if one looks for levels of consumptions that can be maintained indefinitely. Otherwise, straightforward computation shows that consumption must decline at some point[5].

[4]See Erreygers (2009) for a discussion of the link between the two.

[5]Suppose that at any time t the product $Q(t)$ is bounded by the flow of resource $R(t)$, independently of the level of capital and labor, so that $Q(t) \leq \mu R(t)$. Then, the total consumption across generations is finite: $\int_0^\infty C(t)dt \leq \int_0^\infty Q(t)dt \leq \int_0^\infty \mu R(t)dt \leq \mu S_0$. No constant level of consumption can be maintained.

According to Solow, this justifies to use a Cobb-Douglas production function:

$$Q = e^{\lambda t} K^\alpha R^\beta L^\gamma, \ \alpha + \beta + \gamma = 1 \tag{5}$$

which fits both requirements. More precisely, the assumption of unbounded resources productivity is satisfied even if the exogenous technical progress is null[6]. In this case, it is the "substitutability" between aggregate capital and resources, encapsulated in the function, that ensures this property. The choice of the Cobb-Douglas production function, and the explicit assumption of unbounded resources productivity, will be at the heart of the following controversy with Georgescu-Roegen and Daly.

The mathematical problem now consists to determine whether the finiteness of resources, the trade-off between investment and consumption, population growth and the production function (equations 2 to 5) are compatible with a constant consumption per head:

$$C = c_0 L \tag{6}$$

To solve it, Solow turns the problem into minimizing $\int_0^\infty R(t)dt$ under the equations 3 to 6. These four equations yield one fundamental relation on K and R:

$$\dot{K}(t) = e^{(\lambda + \gamma n)t} K(t)^\alpha R(t)^\beta - c_0 e^{nt} \tag{7}$$

Whereas the minimization of $\int_0^\infty R(t)dt$ gives a second equation of evolution:

$$\frac{\dot{F}_R}{F_R} = F_K \tag{8}$$

where F_R and F_K are the marginal productivities of resources and capital. Together, these two relations form a differential system whose solutions describe the dynamics of the hypothetical economy. The goal is to know if there exists a "viable" path, that is to say a path that consumes less than the total stock of resources, as stipulated by the constraint 2.

Solow does not treat the general case and retreats on the assumptions of constant technology and constant population. In this case, the production function becomes:

$$Q = K^\alpha R^\beta L_0^\gamma \tag{9}$$

Given these restrictions of the initial problem, Solow is able to demonstrate that a viable strictly positive level of consumption exists if and only if :

$$\alpha > \beta \tag{10}$$

that is if the "output elasticity" of capital is greater than that of resources. Under this condition, he finds the minimizing path for $\int_0^\infty R(t)dt$ and gives the largest viable consumption per capita[7].

The viability of the path heavily relies on the substitution of resource flow by capital to maintain the level of production. Indeed, the optimal path exhibits monotonically

[6] Suppose $\lambda = 0$, then $\frac{Q}{R} = (\frac{K}{R})^\alpha (\frac{L}{R})^\gamma$ may be as big as one wishes, provided K is sufficiently great.

[7] The formula of the maximum viable consumption shows that it depends, among other things, on the stock of resources and on the initial stock of capital:

$$c_0 = (\alpha - \beta)^{\frac{\beta}{1-\beta}} (1-\beta) K(0)^{\frac{\alpha-\beta}{1-\beta}} S_0^{\frac{\beta}{1-\beta}} L_0^{\frac{-\alpha}{1-\beta}} \tag{11}$$

increasing capital stock and decreasing resource flow. Therefore, the structure of the Cobb-Douglas production function, and the assumption of unbounded resources productivity it encapsulates, are crucial for the result above.

1.3 Stiglitz's two models

Stiglitz (1974) uses the same equations from 2 to 5, and only diverges on the norms of intergenerational wealth distribution and the specification of the production function.

Stiglitz studies first the possibility of maintaining consumption growth at a constant rate:

$$C = C_0 e^{gt} \tag{12}$$

Equation 8 is introduced as an "efficiency condition" and the underlying minimization of $\int_0^\infty R(t)dt$ is no more explicit. He circumvents the mathematical problems encountered by Solow and finds a solution to the general case with population growth and technical progress. The necessary and sufficient condition for a viable path to exist is:

$$g < \frac{\lambda + \gamma n}{1 - \alpha} \tag{13}$$

Thanks to this condition, Stiglitz is able to answer the problem investigated by Solow. To maintain a constant consumption per capita, we need to know if $g = n$ is possible, which yields the following condition:

$$n < \frac{\lambda + \gamma n}{1 - \alpha} \Leftrightarrow n < \frac{\lambda}{\beta} \tag{14}$$

This latter condition may be interpreted as the need for "resource augmenting technical progress" to be greater than the rate of population growth[8]. The comparison between the relative productive power of capital and resources is no more a preoccupation as in condition 10. Rather than capital substituting to resources, it is now exogenous technical progress at rate λ that plays the central role in compensating the decreasing flow of resources. Here, we may interpret exogenous technical progress as an other way of ensuring the more general assumption of unbounded resources productivity[9].

As a second exploration of the general framework of natural resources economics, Stiglitz considers an other norm of intergenerational distribution of wealth, labelled as "utilitarian". It consists in maximizing the sum of discounted utilities across generations:

$$\max \int_0^\infty U(C)e^{-\delta t}dt \tag{15}$$

Utility is taken as a function of consumption per capita c, multiplied by the size of the

[8] Rewriting the production function as

$$Q = K^\alpha (Re^{\frac{\lambda}{\beta}t})^\beta L^\gamma$$

we see that $\frac{\lambda}{\beta}$ can be considered as the rate at which technical progress improves the level of resources, that is "resource augmenting technical progress".

[9] Obviously, any production function with exogenous technical progress going to infinity has unbounded resources productivity. While in the Cobb-Douglas case it was aggregate capital that compensated for resources, here it is the exponential technical progress that increases the output per unit of resource as time is passing.

population:

$$U(C) = \frac{c^v}{v} L, 0 < v < 1 \tag{16}$$

The optimization problem taking account of the constraint 2 is then solved by similar mathematical methods as above. The growth rate of consumption per capita is asymptotically constant with value:

$$\lim_{t \to \infty} g_c = \frac{\lambda - \beta\delta}{1 - \alpha - \beta v} \tag{17}$$

This limit is positive if $\frac{\lambda}{\beta} > \delta$, that is if resource augmenting technical progress is greater than the discount rate. This shows once again that technical progress plays a central role in escaping the scarcity of resources in this model. [10]

1.4 A model-based methodology

The work of Solow and Stiglitz presented above gave to natural resources economics its first impetus and its most important features. A whole literature was built on this framework, and Solow and Stiglitz made other important contributions to it. Stiglitz concentrated on the implications of competitive markets and alternative institutional structures on the allocation of resources (Stiglitz, 1976). While Solow explored elaborated version of the growth model, adding for example "extraction costs" of the resource (Solow and Wan, 1976), and used it to analyse data on the price and the availability of resources (Solow, 1978). In the latter, the assumption of unbounded resources productivity, either under the form of technical progress or substitutability, kept a central role[11].

In order to discuss the issues at stake in the contributions of Solow and Stiglitz, I use the categorization later suggested by Stiglitz himself (1979). It is exposed in a synthetic and interpretative essay on the achievements of natural resources economics by the end of the 1970s. He suggests four categories: viability, forecasting, efficiency and intertemporal equity. I will go quickly over the last two, which are of marginal interest for my purpose, and then focus on the first ones.

The "efficiency" issue deals with the "reasons that the economy might not allocate natural resources efficiently [because of] peculiarities of the private market [or] particular

[10] The special issue of *The Review of Economic Studies* in which Solow and Stiglitz's papers are published, contains a third influential paper by Dasgupta and Heal (1974). Despite it is not referred to in the subsequent debate with ecological economists, it shows the unified character of those first contributions to natural resources economics, and the omnipresence of unbounded resources productivity as a crucial assumption.

Dasgupta and Heal use a utilitarian norm, but with the larger framework of CES production functions and without technical progress. In this case, the asymptotic value of the marginal product of capital plays a central role:

$$\rho = \lim_{K \to \infty} F_K = \begin{cases} 0 \; if \; \sigma \leq 1 \\ \alpha^{\frac{\sigma}{\sigma-1}} \; if \; \sigma > 1 \end{cases} \tag{18}$$

As indicated, the value of this parameter depends on the elasticity of substitution and on the output elasticity of capital, two parameters that are closely linked to the productivity of resources. The asymptotic growth rate of consumption is then given by:

$$\lim_{t \to \infty} g_c = \frac{\rho - \delta}{1 - v} \tag{19}$$

It is therefore positive if and only if $\rho > \delta$. This is possible if the elasticity of substitution is greater than one, and the elasticity of production of capital is big enough. Both aspects underline the role of the substitution between capital and natural resources in this model.

[11] The kind of allocative approach investigated by Stiglitz is not as much dependent on this assumption since it generally resorts directly to a demand function for the resource, not relying on any production theory.

government actions". Formally, the main concern is to know if the economy satisfies equation 8. Under marginal productivity pricing, a core assumption of the neoclassical framework, this equation is interpreted as the principle that the growth rate the price of resources should be equal to the interest rate. It has been the subject of an important literature that investigates the institutional conditions, such as competitive markets or monopoly, under which this is satisfied or not. The market system is usually believed to be a sufficient condition, as Solow states it:

> [One] notices that the first of these quantities is a capital gain, the instantaneous return from leaving a dollar's worth of the resource in the ground, and the second is the instantaneous return from owning and using or renting a dollar's worth of reproducible capital.
>
> It is clear from this interpretation that some of the properties of an optimal path are easily achieved through market processes. But I can see no force - other than "Rawlsian conviction" - that will steer a market economy to constant consumption and the right [$R(0)$]. "Rawlsian conviction" here means something more than current legislation; there needs to be a kind of social contract to bind the next Congress, and the next. (Solow, 1974b, p. 36)

The latter part underlines that another institutional condition is necessary for the economy to follow the trajectories of the model. For the second equation 7 defining the differential system to be satisfied, equation 6 must be valid. As expressed by Solow, this was initially perceived as a rather coercive control on the consumption of each generation. However, this condition has later been reformulated by Hartwick (1977) as the condition that the level of investments should be equal to that of the rents from the resource.

This latter condition actually leads to the problem of "intergenerational equity", that is the criterion of optimal distribution of consumption between generations. The main question here is the relevance of the utilitarian norm with a strictly positive discount rate. In economics, this norm has been introduced by Frank Ramsey in the theory of optimal economic growth, and as become the convention for such questions. Stiglitz's position (1974) is rather ambiguous, since he explores both a utilitarian model and a model where a constant growth rate is imposed. However, Solow has generally stared at the utilitarian norm with a sceptical look, based on John Rawls's criticism[12].

The following issues are more directly linked to the representation of production. The "viability" issue refers to the "conditions under which growth cannot be sustained and conditions under which it can"(Stiglitz, 1979, p. 39). It is essentially an abstract problem that concerns the properties of the *mathematical models* of growth with exhaustible resources. On this topic, the results obtained by both Solow and Stiglitz are well summarized by the latter:

> The fact that there is a limited amount of natural resources and natural resources are necessary for production does not necessarily imply that the economy must eventually stagnate and then decline. Two offsetting forces have been identified: technical change and capital accumulation. Even with no technical change, capital accumulation can offset the effects of the declining inputs of natural resources, so long as capital is "more important" than natural resources, i.e. the share of capital is greater than that of natural resources.

[12] See Erreygers (2009) for a more detailed discussion. Solow has been quite constant on this point (Solow, 1986, p. 143).

> With technical change, at any positive rate, we can easily find paths along which aggregate output does not decline. For so long as the input of natural resources declines exponentially, no matter at how small a rate, provided the initial level of input is set correctly, we will just use up our resources. And the technical change can offset the effects of the slowly declining input of natural resources. To sustain a constant level of per capita consumption requires a more stringent condition on the rate of technical change. (Stiglitz, 1974, p. 130-131)

This quotation illustrates well the relationships of Solow and Stiglitz with their models. It rather appears as a description of the mechanisms of the model, than as a discourse on transformations actually happening in the economy. This is particularly true for contributions dedicated to pure mathematical models (Solow, 1974b; Stiglitz, 1974), but even interpretative essays do not give much economic substance to the fundamental concepts of their theory (Solow, 1974a; Stiglitz, 1979). For instance, the notion of "exhaustible natural resources" is not illustrated by any concrete example in the first ones, while from the others it seems to cover energy sources, such as oil and coal, or minerals, such as iron or copper. However, as Solow (1974a, p. 2) and Stiglitz (1979, p. 40) themselves hint at, this association is slightly problematical. Since minerals are partly recyclable, they are not exhaustible in the same sense that energy is, and do not play similar functions in production.

But this problem is more acute for "technical progress" and "substitutability". In the theoretical contributions, they appear only as mathematical properties of the Cobb-Douglas production function. On the one hand, substitution describes the possibility to increase the productivity of resources $\frac{Q}{R}$ by increasing the level of capital K. This mechanism plays a crucial role in the optimal trajectory identified by Solow by enabling to maintain the level of production while decreasing the flow of resources. On the other hand, technological progress is concentrated in the multiplier $e^{\lambda t}$ beside the Cobb-Douglas structure. The choice of an exponential form relative to time is not justified and its determinants are unspecified. Moreover, it appears completely independent of the factors of production. Nevertheless, the mathematical meanings of substitutability and technical progress are well identified among the properties of the production function.

Things are much less clear when it comes to relating these concepts to concrete transformations of the production process. Theoretical contributions do not give any clue on this topic, and, while interpretative essays are less silent on the subject, they reveal conceptual issues. Starting with substitutability, at least four different mechanisms can be identified in Solow's work: substitution of coal to oil by transforming one into the other through coal-liquefaction technology (1974a, p. 5); substitution of pretended infinite sources of energy by "backstop technologies", such as nuclear fusion or solar energy (1974a, p. 11); substitution of less resource-intensive goods by changes in the composition of output and substitution through fuel-saving technologies (1978, p. 6). However, these different mechanisms are problematical. The first two are rather substitution *between resources* than substitution between capital and resources. This is at odd with their models, which describe the depletion of an aggregated exhaustible resource, with no other resource coming in to substitute. Hence, theses two mechanisms do not seem consistent with the definition of substitution in the model. If we now consider the case of fuel-saving technologies, it is also used to illustrate the concept of technical progress, and is actually the only illustration one can find (1974a, p. 10). This reveals that substitution and technical progress conceptually overlap and cannot be conceived in a strictly separated way. Consider for example a baker that increases its capital by buying a second oven. To produce the same quantity of bread, he can't use less energy (either under the form of electricity or gas) to heat up the oven just because he now has two instead of one. Hence, capital accumulation has to come with some sort of technological improvement if it is to increase the productivity of resources. Reciprocally, if some newly discovered technology is to improve this productivity, it needs to be implemented through investments. Therefore, less resource-intensive production is better accounted for with technological change and capital accumulation at the same time, and the distinction between the two in the neoclassical model is a conceptual issue.

I suggest that this comes from a "model-based" methodology, where concepts first arise as description of the properties of the Cobb-Douglas production function. As a consequence, the model precedes the conceptual structure of the theory, which does not rely on a prior analysis of the nature of production. Rather, concepts are forged in describing the properties of the model, and only in a second time Solow and Stiglitz try to relate them to the actual functioning of the production process. But this second step is a difficult one, as shown by the analysis of "substitution" and "technical progress" above. First, these concepts lack a definite meaning in regard of actual production processes. Second, they tend to overlap, for example on the case of resource-saving technologies. I propose to call this the "conceptual foundations" issue, since it is at bottom the question of how concepts that arise from the model can make sense *outside the model* and give rise to a consistent understanding of production.

As the assumption of "unbounded resources productivity" is the consequence of the combined effects of technical progress and substitution, it inherits their model-based foundations. Hence, according to this analysis, the viability issue appears as a purely formal one: the mathematical conditions under which a viable path can be found (equations 10 and 14) are hardly connected with concrete transformations of the production process.

In the end, the only physical aspect of the production process considered in early natural resources economics appears to be the assumption that resources are "essential", that is that $R = 0$ implies $Q = 0$, as originally advocated to promote the Cobb-Douglas function (Solow, 1974b). However, Solow and Stiglitz tend to depart from this constraint too, as illustrated by what follows:

> The second main conclusion is that the introduction of exhaustible resources into this sort of optimization model leads to interesting results-some of which have been sketched-but to no great reversal of basic principles. This conclusion depends on the presumption that the elasticity of substitution between natural resources and labour- and-capital-goods is no less than unity-which would certainly be the educated guess at the moment.(Solow, 1974b, p. 41)

Despite he doesn't signal it clearly, at this point, Solow departs from the mathematical model he has investigated and refers to the framework of Constant Elasticity of Substitution[13] (CES) production functions of the form:

$$Q = F(K, R, L) = [\alpha K^{\frac{\sigma-1}{\sigma}} + \beta R^{\frac{\sigma-1}{\sigma}} + \gamma L^{\frac{\sigma-1}{\sigma}}]^{\frac{\sigma}{\sigma-1}} \tag{20}$$

The Cobb-Douglas is a special case of this family of functions, when the elasticity of substitution is unitary, $\sigma = 1$. When $\sigma > 1$, $R = 0$ *does not imply* $Q = 0$, that is to say that resources are *not essential* to production. In these conditions it is obviously

[13] The elasticity of substitution between factors x and y of a production function $F(x, y)$ is defined as $\sigma = \frac{d \ln y/x}{d \ln F_x/F_y}$. Under the assumption of marginal productivity pricing, it describes the evolution of the factors ratio as relative price changes.

possible to maintain a constant consumption across generations. Conversely, if $0 < \sigma < 1$, then resources are essential, but the productivity of resources is bounded. It is the other trivial case avoided by Solow's assumption of a Cobb-Douglas function. Reference to CES functions is therefore misleading, since it introduces situations that were initially rejected by Solow as uninteresting. Moreover, the condition of an elasticity of substitution greater than one, which he seems to think reasonable, is at odd with the minimal requirement of an essential resource, that himself advocated for at the beginning. In fact, inessential resources formally bring back to conventional growth theory, since capital and labour are sufficient factors of production. This is a very strange turn, since the initial endeavour was to bring resources into the analysis. I think reasonable, from the above analysis, to relate this outcome with the model-based methodology of Solow and Stiglitz. Their focus on the formal aspects of their models drives them away from physical considerations on the production process, and it enables such a paradoxical assumption as "inessential resources"[14].

The model-based methodology of natural resource economics is also of prime importance to understand the issue of "forecasting", that is the predictive power of the models. As Stiglitz acknowledges, "forecasting usually entails an extrapolation of past events into the future [which] requires certain, usually quite strong assumptions" (1979, p. 39). He distinguishes two methodologies for forecasting. On the one hand, the "engineering approach" is concerned with examining actual technologies, potential improvements across time or predictable breakthroughs. On the other hand, the "economist's approach" acts at a more aggregated level, using mathematical models that are supposed to capture essential technological possibilities. This methodology has two different extrapolation problems: that of the structure of the production function; and that of the specific values of its parameter, estimated on past data.

Let us start with the second one. In natural resources economics, two estimates are considered meaningful. First, in relation to condition 10 we might want to estimate the values of the output elasticities of capital and resources. Under the assumption of marginal productivity pricing, these output elasticities are equal to the respective factor share, that is the proportion of GDP earned by each factor. Accordingly, empirical support for the validation of condition 10 rests on the fact that capital incomes are approximately three times more than resource rents (Solow, 1974b, p. 37)[15]. Second, if we suppose a CES framework we might be interested in estimating the elasticity of substitution. On this point, Solow and Stiglitz generally refer to the estimates of Nordhaus and Tobin (1972), which support the idea of an elasticity of substitution greater than one. However, these estimates also rely on the assumption of marginal productivity pricing (Stiglitz, 1979, p. 45).

The first question behind these estimates is to know what they tell us about the past structure of the economy. The answer is a most controversial one and has been the subject of debates since the early empirical work of Cobb and Douglas (1928). Felipe and McCombie (2013) have done a survey of the debate and argue that estimates of production functions in general are mere testing of an accounting identity. However, I do not wish to investigate further this question here because Solow and Stiglitz didn't contribute much to the empirical testing of theses assumptions and generally referred to other works on

[14]Such a focus is very perceptible in Stiglitz's discussion on elasticities of substitution(1979, p. 41-43) which does not refer to any proper production process and only describes the form of the isoquants.

[15]More accurate data is presented in Solow (1978), but the conclusion is similar with natural resources representing only five percent of total GNP.

this topic[16]. Themselves concentrated on the theoretical elaboration of the paradigm. Following this outlook, another question appears of more immediate concern: what do these estimates tell us about the future structure of the economy ? The answer to this question can only rely on the the assumption that the estimated parameters will remain constant. As Stiglitz mentions it, "the crucial question is what is to be taken as a constant" (1979, p. 44). This leads to question the structure of the production function itself.

Stiglitz is well aware of the methodological problems facing the extrapolation of a production function estimated on past data. Considering the case of CES production function and the estimation of the elasticity of substitution, he concedes that "resource pessimists" could oppose that "the particular parameterization implicit in the above calculation that the elasticity of substitution is constant is not correct: for example, they might argue that as resources become scarcer, the elasticity declines" (Stiglitz, 1979, p. 45). As a first answer to the problem, he suggests to allow the elasticity to vary and test the assumption that it is constant. But I suggest that this is in no way different of the original problem: one might equally contest that, because the elasticity is constant according to past data, it will be constant under every condition of production, and in particular with little resources. If we believe that the estimates are actually able to capture the structure of the production process, we can only believe so on the spectrum of combination of factors of production that is expressed by the data. Nothing can justify the extrapolation to other very different combinations of factors. For instance, as we currently have experienced only relatively low values of the ratio of capital to resources, we cannot extrapolate estimated production functions to high values of this ratio. But it is these values that are crucial in optimal trajectories of the model, since resources go to zero and capital increases to infinity.

Stiglitz's second suggestion to solve the problem is to pursue the "analysis at a much more disaggregated level" (Stiglitz, 1979, p. 46). The different levels he points at are firms, sectors and intersectors structures of production. He notices that too little attention has been given to the mechanisms covered by the notion of substitutability, which "requires an understanding of all the possible patterns of substitution available in consumption and production" (Stiglitz, 1979, p. 46). However, this tends to blur the distinction between the "engineering approach" and the "economist's approach" initially suggested by Stiglitz.

In the absence of such understanding though, the choice of the structure of the production function, be it CES or Cobb-Douglas, appears "contingent", and its extrapolation to future conditions of production is questionable. By contingent, I mean that the preference for a specific production function among the infinitely many mathematical forms available is not grounded into an appreciation of the nature of the production process.

This is not to say that this choice has no motivation. One of the motivations previously identified is to have an "interesting and substantial" problem (Solow, 1974b, p. 34). As underlined by Pottier (2014, p. 130), this must be understood as a *mathematical* problem which solutions are not trivial and therefore offers a ground for mathematical investigation. Stiglitz suggests a second motivation. He insists on the distinction between "analytical methods" and "simulations". The former consists, in a given theoretical framework, to find the critical conditions which will yield different answers to the problem. It is well illustrated by the work of Solow and Stiglitz on natural resources economics which set forth conditions 10 and 14. The latter, in a similar theoretical framework, consists to give *numerical* solutions for different values of the parameters that constitute different "scenarios". This is closer to the method of the report on "The Limits to Growth" (Meadows et al., 1972).

[16] One exception is the work on factors shares data by Solow (1978).

Stiglitz defends the superiority of analytical methods, because they enable to identify the exact conditions that imply qualitatively different behaviors of the model, while simulation can only answer the viability issue if values of the parameters are given (Stiglitz, 1979, p. 44). However, analytical methods have a condition that his not highlighted by Stiglitz: simplicity. Indeed, the analytical resolution or the qualitative analysis of differential systems generally imply intricate mathematical considerations that may become out of reach if the model is too complex. A good illustration is Solow's repeated justifications that the Cobb-Douglas "simplify the treatment of technical progress" or that "a complete analysis of [the implications of unlimited technical progress] would be laborious" (Solow, 1974b, p. 34 and 40). Along this line, the choice of production functions of the Cobb-Douglas or CES forms are implicitly linked to the simplistic representation of production they provide.

A third motivation for choosing theses kinds of production functions is the fact that this framework has become dominant in the analysis of growth in the 1960s (Boianovsky and Hoover, 2009). Although this is not stated explicitly, the continuity with the tools used in traditional neoclassical growth theory is obvious. However, it denotes at the same time the absence of a reflection on the specificity of natural resources as a production factor. The symmetric character of Cobb-Douglas or CES production functions puts capital, labour and resources on the same level. This also implies the transposition of the concepts of "substitution" or "technical progress" from the traditional theory, without much thinking about their meaning in the context of natural resources. Together with the mathematical motivations above, this theoretical continuity underpins the choice of the model. No consideration on the nature of the production processes involved and on the interrelation of resources and other factors appears as the root of this choice. This is why I suggest to call it "contingent".

To sum up, the most important lesson of our discussion of Solow and Stiglitz's work is that the assumption of "unbounded resources productivity" plays a central role, and that it is the outcome a "model-based methodology". This latter notion underlines that the model precedes and gives birth to the conceptual foundations of the theory. Hence, the choice of the production function cannot rely on a pre-existing analysis of production and is mainly justified by mathematical concerns. This "contingent production function" is the root of the other main issue identified as the "conceptual foundations". This means that fundamental concepts such as "substitution" and "technical progress" are essentially defined as properties of the Cobb-Douglas production function, and hardly linked to concrete transformations of the production process. As a consequence, the aptitude of theses models to provide useful insights into the future is weakened.

However, Stiglitz reverses the burden of proof and challenges "resource pessimists" to show that "as resources become scarcer we do not, or cannot, substitute less resource-intensive commodities for more resource-intensive commodities" and that "the prospects are bleak for technical changes that would enable us better to use what resources we have" (1979, p. 47). Among modern resource pessimists, he explicitly referred to Nicholas Georgescu-Roegen (1979, p. 36), who took up the challenge.

2 Georgescu-Roegen and thermodynamic limits to production

After dedicating his early academic career to the development of neoclassical economics, Nicholas Georgescu-Roegen made a major theoretical switch in the 1960s. The transition is well illustrated by his book *Analytical Economics*, in 1966, which contains both his most important contributions to neoclassical theory, and an introduction to his new research program. He gave a more complete view of the latter in 1971 with *The Entropy Law and The Economic Process*. As this title suggests, Georgescu-Roegen advocates, among other things, to take into account thermodynamic laws in economic theory. This perspective will have an important influence on some founding members of ecological economics (Røpke, 2004; Ould Boye, 2014). Daly in particular, in the forum debate on "Georgescu-Roegen versus Solow/Stiglitz" (Daly, 1997a), will insist on the idea that thermodynamics sets limits to substitution and technical progress. This section tries to appreciate more accurately the effective place and the development of this proposition in Georgescu-Roegen's work. To do so, it is first necessary to recall some of the main features of his thermodynamic approach of the economic process.

2.1 Thermodynamics and the economic process

Thermodynamics can be broadly defined as the science of the transformations of energy, and is essentially constituted of two principles[17], which Georgescu-Roegen illustrates on the working of a "railway engine" (1971, p.5). The first principle concerns the conservation of "energy". Though this latter concept has become familiar, it is important to understand that it is a scientific construction designed to give a common measure to very different phenomena, as illustrated by the railway engine: it starts as the chemical energy of coal, burnt to produce thermal energy (heat) in the boiler; then this heat at high temperature is transformed into heat at atmospheric temperature, when the steam goes out, and mechanical energy (movement) to propel the train; finally this mechanical energy is also transformed into heat by the frictions of the air and of the tracks. In this context, the first principle of thermodynamics states that the energy is conserved all along these transformations. Hence, we can say that energy *changes its form*, from chemical energy to thermal energy and mechanical work, but that its *quantity is conserved*.

However, thermodynamics has a second principle that specifies what are the possible transformations between the different forms of energy. Its origins are in the work on steam engines of Sadi Carnot in 1824, later reformulated in the formalism of energy by Rudolf Clausius (Georgescu-Roegen, 1971, p. 129). While mechanical energy may be fully transformed into thermal energy by friction, Carnot's work shows that the heat contained in a boiler, as in the case of the railway engine above, cannot be fully transformed into mechanical work. Carnot describes a heat engine as composed of three parts: a "hot source" at temperature T_1; a "cold sink" at temperature $T_2 < T_1$[18]; an intermediate body, such as water. It functions according to a cyclical process that transforms a flow of heat Q_1 from the hot source into mechanical work W and a flow of heat Q_2 that goes to the sink. The conservation of energy, implies that $Q_1 = W + Q_2$, and the efficiency of the engine is measured by the portion of the initial heat that has been transformed into mechanical work: $\eta = \frac{W}{Q_1} \leq 1$.

Carnot's main achievement was to prove that this efficiency has a theoretical maximum, strictly lower than one. This results from a thought experiment in which he imagines the

[17] Thermodynamics has two other principles which are not of prime interest here. See for example Poirier (2014) for a conceptual introduction to thermodynamics.

[18] In general, the sink will be the atmosphere and T_2 its average temperature.

ideal functioning of an engine[19]. This yields "Carnot's maximum efficiency" coefficient:

$$\eta_m = \frac{W_m}{Q_1} = \frac{T_1 - T_2}{T_1} \tag{21}$$

This result has multiple consequences. First, it shows that not all the thermal energy can be transformed into mechanical energy, whereas the opposite is possible. In particular, all the heat dissipated in the atmosphere, the "ultimate sink", cannot be transformed back into mechanical work. In the words of Georgescu-Roegen this dissipated heat is "latent energy" whereas "available energy" is energy that can be transformed into mechanical work (Georgescu-Roegen, 1971, p. 129). Second, this means that the possible transformations of energy are always in the sense of a "qualitative degradation". For example, when mechanical work is transformed into heat at atmospheric temperature by friction, then the mechanical work is lost forever and cannot be recovered from the heat. Georgescu-Roegen states it as follows:

> Like heat, [available] energy always dissipates by itself (and without any loss) into latent energy. The material universe, therefore, continuously undergoes a qualitative change, actually a qualitative degradation of energy. The final outcome is a state where all energy is latent, the Heat Death as it was called in the earliest thermodynamic theory. (Georgescu-Roegen, 1971, p. 129)

This statement can be reformulated using the concept of "entropy". Georgescu-Roegen never formally defines entropy, which he thinks to be unnecessarily technical. This technical aspect is the counterpart of "an analytical simplification and unification" achieved by the concept. Hence, he prefers the literal definition of entropy as "an index of the relative amount of [latent] energy in an isolated structure" (Georgescu-Roegen, 1971, p. 5)[20]. Since the initial formulation of the second principle was that latent energy tend to increase at the expense of available energy, it can be reformulated as: the entropy of an isolated system increases toward a maximum. Carnot's maximum efficiency, the qualitative degradation of energy and the "entropy law" can be considered as equivalent formulations of the second principle of thermodynamics.

This law is central in Georgescu-Roegen's understanding of the economic process, which he describes as follows:

> Even if only the physical facet of the economic process is taken into consideration, this process is not circular, but *unidirectional.* As far as this facet alone is concerned, the economic process consists of a continuous transformation of low entropy into high entropy, that is , into *irrevocable waste* or, with a topical term, into pollution. [...]

[19]In Carnot's ideal engine every heat flow happens with the intermediate body having the same temperature as the source or the sink, depending on the phase of the cycle. Just as in mechanics we try to avoid "mechanical shocks", the goal is to avoid "thermal shocks", considered *a priori* as efficiency losses. Of course, no heat transfer can happen between two bodies at the same temperature. The whole thought experiment is in fact a limit case where temperature differences are infinitely small, and the expansion of the intermediate body therefore takes infinite time. In addition, Carnot's ideal engine has an other important property: it is reversible. This means that the cycle may as well be followed in the other sense: heat going from the sink to the intermediate body, outside mechanical work compressing the latter, and finally heat being released to the source. This reversibility enables to show that no thermal engine could have a greater efficiency.

[20]I will not enter the details of the definition of entropy either. See for example Poirier (2014) for a more complete introduction to this concept.

> The conclusion is that, from the purely physical viewpoint, the economic process is entropic: it neither creates nor consumes matter or energy, but only transforms low into high entropy.(Georgescu-Roegen, 1971, p. 281, italics in the original)

Multiple features of his thought result from this understanding of the relation between the entropy law and the economic process. First, the entropy law is considered as the physical principal underpinning both the depletion of resources and the accumulation of pollution. This means that these phenomenas are two facets of a single property of the material world, and that it is not possible to have one without the other. Second, the natural resources under considerations here are both energy resources, such as coal or solar energy, and minerals, such as copper. But rather than focusing on their superficial properties of finiteness, exhaustibility or recyclability, Georgescu-Roegen intends to give the thermodynamic principles from which these properties emerge. Third, this analysis leads him to underline the radical scarcity that governs these resources and distinguishes it from the scarcity of land dear to classical economics:

> For example, land, although it cannot be consumed, derives its economic value from two facts: first, land is the only net with which we can catch the most vital form of low entropy for us, and second, the size of the net is immutable. Other things are scarce in a sense that does not apply to land, because, first , the amount of low entropy within our environment (at least) decreases continuously and irrevocably, and second, *a given amount of low entropy can be used by us only once.*
>
> Clearly, both scarcities are at work in the economic process, but it is the last one that outweighs the other. For if it were possible, say, to burn the same piece of coal over and over again *ad infinitum*, or if any piece of metal lasted for ever, then low entropy would belong to the same category as land. (Georgescu-Roegen, 1971, p. 278, italics in the original)

With this perspective, Georgescu-Roegen appears as a pioneer of environmental issues among economists, a few years before that the debate on the "limits to growth" draw more attention on the subject. However, his 1971 book, *The Entropy Law and the Economic Process* didn't reach a large audience among economists. There were multiple reviews, mostly favourables, but they didn't come from eminent economists, as Georgescu-Roegen expected from his earlier contributions and his close links with Paul Samuelson and others. He had to wait the debate on the limits to growth to find a more appropriate context. At that time, he contacted the authors of the report to propose his help to reply to the criticisms addressed by economists (Levallois, 2010). This gave him the opportunity to promote his own paradigm in a paper published in 1975 under the title "Energy and Economic Myths", which received a wider audience.

2.2 The criticism of natural resources economics

In the first three sections of this paper, Georgescu-Roegen recalls his thermodynamic approach of the economic process, and in the fourth he adds a distinction between "available" and "accessible" energy. He notes that extracting available energy from its deposit, for example in oil wells, and making it properly useful, implies to spend some energy, for instance to extract, transport or refine the resource. If the energy spent is less than the energy obtained then it is said to be accessible. Otherwise the deposit is not energetically profitable, and *a fortiori* not economically either. In this context, he uses "efficiency" to denote the ratio between what is extracted over what is spent[21], and he writes:

> To be sure, actual efficiency depends at any one time on the state of the arts. But, as we know from Carnot, in each particular situation there is a theoretical limit independent of the state of the arts, which can never be attained in actuality. In effect, we generally remain far below it. (Georgescu-Roegen, 1975, p. 355)

The above statement clearly refers to Carnot's maximum efficiency of the thermal engine 21. This principle appears as the archetype of the kind of absolute limits that thermodynamics imposes on production processes. However, the process is very different than that of a thermal engine. In such an engine, the work produced is directly a transformation of the heat coming from the hot source. Whereas in extractive activities, the energy resource extracted, oil for instance, is not a transformation of the energy spent. The latter is only used to build and run the infrastructures that will extract the former from a pre-existing deposit. Therefore, Carnot's principle does not apply to this situation.

Georgescu-Roegen then discusses the different arguments used to dismiss the idea that resource depletion might be a problem for the perpetuation of economic activities. After discarding the idea that the entropy law could be circumvented or that resources would be infinite, he comes to the role of technical progress in increasing the productivity of resources. Once again he refers to Carnot's coefficient to suggest that there is a theoretical limit to technological improvement:

> Even if technology continues to progress, it will not necessarily exceed any limit; an increasing sequence may have an upper limit. In the case of technology this limit is set by the theoretical coefficient of efficiency. (Georgescu-Roegen, 1975, p. 362)

Georgescu-Roegen now claims that the production of any economic good or service requires a theoretical minimum consumption of energy. This last proposition appears as an opposition to Solow's assumption that "the average product of [resources] has no upper bound" (Solow, 1974b, p. 34). In particular, Georgescu-Roegen notes that "in Solow's hands, substitution becomes the key factor that supports technological progress even as resources become increasingly scarce." (Georgescu-Roegen, 1975, p. 362). However, the link between the idea of thermodynamic limits and the criticism of substitution in Solow's model is not straightforward at that time, especially because Georgescu-Roegen is also addressing criticisms of other economists such as Percy Bridgman.

The criticism of natural resources economics will become more direct in a 1979 paper published in *Scarcity and Growth Reconsidered*. There, he formulates a radical criticism covering the four issues identified by Stiglitz[22].

Regarding "efficiency", Georgescu-Roegen is sceptical about the ability of markets to provide an optimal allocation of resources. His main argument is that the only useful mechanism to reach the "true scarcity value" of an exhaustible resource is an auction. But, for it to be consistent, every person interested in the resource must be able to bid, and, "unfortunately, the future generation cannot be present to bid now" (1979, p. 100). However, Stiglitz had explicitly dealt with this argument. He suggested that it is the

[21] Nowadays, in energy studies, this ratio is also known as the energy return on energy invested (EROI) and used as an important indicator of the accessibility of energy sources.

[22] Georgescu-Roegen himself doesn't use these categories, but they are convenient to expose his criticism.

self-interest of every owner of a resource to anticipate these future needs, restrain the extraction of the resource and sell it to another investor to obtain his return (1979). To this argument, Georgescu-Roegen replies that "the time horizon [of owners] is limited", taking the example of early oil owners in the United-States (1979, p. 100). He then goes on asserting that what Stiglitz means by "efficiency" is not clear. However, from the original works of Solow and Stiglitz, the efficiency problem is clearly set as whether equation 21 is satisfied by the economy. If marginal productivity pricing is assumed, it is interpreted as the equality between the growth of the resource price and the interest rate. Hence, it rather appears as a short-term problem for investors rather than a question of long time-horizon, and Georgescu-Roegen's criticism misses its target on this issue.

But Georgescu-Roegen also disagrees with the criterion of optimality underlying the problem of efficiency. According to him, natural resources economics only deals with "intergenerational equity" through the "utilitarian norm" of maximizing discounted utilities. Going back to the origins of discounted utilities in the works of Jeremy Bentham and Stanley Jevons, he suggests that it was only intended to describe an irrational trait at the individual level, and that, at the social level, "discounting the future is wrong from every viewpoint" (Georgescu-Roegen, 1979, p. 101). However, he does not notice that on this point he is very close to Solow's criticism of the utilitarian norm. He is driven to think that all natural resources economics uses utilitarian norm because Stiglitz himself focuses on this topic (Georgescu-Roegen, 1979, p. 62), hiding the fact that Solow and himself also considered norms of growing or constant consumption. Therefore, the criticism of the utilitarian norm only partially affects natural resources economics.

Turning to the "forecasting" issue, we notice two remarks from Georgescu-Roegen. First, he compares econometric estimates of production functions to the "sculptor who can prove to you that there is a beautifully carved Madonna inside almost any log" (1979, p. 97). By this metaphor, he means that econometricians can almost ever determine parameters of an abstract production function (the Madonna) that fit well with empirical data (the log). Therefore, these good results are rather a mathematical artefact than a truly existing relation between production factors and output. This is somehow a more general criticism than the one which suggests that estimates of production functions capture an accounting identity (Felipe and McCombie, 2013). Second, he compares the extrapolation of past production functions into the future to the fallacy of forecasting that a single human will never develop arteriosclerosis just by observing its health until the age of thirty (1979, p. 97). This illustrates the problem of justifying the extrapolation of some constant parameters. Hence, Georgescu-Roegen anticipates many of the future debates on the empirical validation and the signification of production functions, but he stays at a very general level and does not deal with the technical details of his arguments.

Georgescu-Roegen's criticism deserves more attention when it comes to the "viability" issue. He directly criticizes the use of a Cobb-Douglas production function:

> On the paper, one can write a production function any way one likes, without regard to dimension or to other physical constraints. A good example is the famous Cobb-Douglas function, but the Solow–Stiglitz variant adds the sin of mixing flow elements with fund elements. [...]
>
> From [the Cobb-Douglas] formula it follows that with a constant labor power, L_0, one could obtain any Q_0, if the flow of natural resources satisfies the condition
>
> $$R^{\alpha_2} = \frac{Q_0}{K^{\alpha_1} L_0^{\alpha_3}}$$

> This shows that R may be as small as we wish, provided K is sufficiently large. [...] In actuality, the increase of capital implies an additional depletion of resources. And if $[K \to \infty]$, then R will rapidly be exhausted by the production of capital. Solow and Stiglitz could not have come out with their conjuring trick had they borne in mind, first, that any material process consists in the transformation of some materials into others (the flow elements) by some agents (the fund elements), and second, that natural resources are the very sap of the economic process. They are *not* just like any other production factor. A change in capital or labor can only diminish the amount of waste in the production of a commodity; no agent can create the material on which it works. Nor can capital create the stuff out of which it is made. In some cases it may also be that the same service can be provided by a design that requires less matter or energy. But even in this direction there exists a limit, unless we believe that the ultimate fate of the economic process is an earthly Garden of Eden. (Georgescu-Roegen, 1979, p. 97-98)

This criticism mixes multiple arguments whose articulation is not clear. First, Georgescu-Roegen underlines the fact that capital is itself an output of the production process and as such implies some depletion of resources. He then suggests that the increase of capital to infinity should quickly exhaust resources. Here "quickly" should be understood as "in finite time", otherwise it wouldn't contradict natural resources economics. However, Solow and Stiglitz models are consistent with the premise that the production of capital depletes resources. Indeed, the increment of capital at every time is taken on the aggregate product, itself produced thanks to resources, as formalised by the equation

$$\dot{K} = Q - C = F(K, R, L) - C \tag{22}$$

But this does not prevent capital from increasing to infinity in Solow's model, precisely because the productivity of resources increases faster, enabling the flow of resources to decrease toward zero. This model is consistent from the mathematical point of view, and this shows that Georgescu-Roegen's first argument is not relevant by itself. It can only be logically founded on other assumptions.

Among them is the distinction between flows and funds[23], which suggests a difference of nature between factors of production. While matter and energy are transformed in the process of production, capital and labour are agents of this transformation. Under this framework, the notion of substitution can appear misleading since capital cannot play the role of resources in production. The only thing it can do is to modify the production process in a way that diminishes the losses of matter and energy.

This leads to the third argument, that of a "limit" to the diminution of energy or matter requirements to provide a given service. This idea appears to be the true logical foundation of Georgescu-Roegen's first argument. Without it, the assertion that the increase of capital to infinity implies the exhaustion of resources in finite time would not be justified, as the models of Solow and Stiglitz show. It is only by assuming that there is a limit to the productivity of resources that this assertion becomes logically founded. This idea in turn is partly inspired by the distinction between flows and funds, since the output flow, consisting of production and waste, cannot be bigger than the input flow of resources. But I suggest that it is also tightly linked with the "thermodynamics limits" found in Georgescu-Roegen's 1975 paper and based on the reference to Carnot's maximum efficiency principle.

[23]This distinction was first developed by Georgescu-Roegen in order to renew the theory of production based on a criticism of production functions and Leontief's input-output tables (Georgescu-Roegen, 1970).

However, whether in that previous paper or in the 1979 one, the notion is not examined in details. Therefore, we should rather speak of an *assumption* of "thermodynamic limits", as a latent, but never fully developed, foundation of his opposition to "unbounded resources productivity". This appears as the root of the divergences on the viability issue.

2.3 A methodological opposition

Georgescu-Roegen's paper is a radical criticism of natural resources economics. On each of the four issues identified by Stiglitz, he opposes arguments to the neoclassical approach. However, some of these arguments only partially affect natural resources economics, for example on the utilitarian norm, while others are not fully developed, as is the case for thermodynamic limits. His contributions up until the beginning of the 1990s do not give much more details on these arguments. Here and there, some allusions to the work of Solow and Stiglitz can be found (Georgescu-Roegen, 1981, 1986, 1988)[24], but they are only repetitions of the arguments against market mechanisms, the utilitarian norm and the possibilities of increasing resources productivity to infinity. Paradoxically, the assumption of thermodynamic limits is not mentioned any more.

Nevertheless, it is worth examining the epistemological and methodological aspects underpinning this assumption, for at least three reasons. First, it will draw most of the attention in the following debate between ecological and neoclassical economists. Among the diverse arguments formulated by Georgescu-Roegen against natural resources economics, Hermann Daly will pick up this one to initiate the debate. Second, it appears as the real root of his criticism of the assumption of unbounded resources productivity. Without it, the idea that capital accumulation must exhaust resources in finite time is not logically founded. Even the distinction between flows and funds is not sufficient to set limits to substitution, since Georgescu-Roegen himself recognizes that technological change can reduce material and energy requirements to produce a given service. Hence, the assumption of thermodynamic limits is the most consistent theoretical answer of Georgescu-Roegen to the challenge addressed by Stiglitz to resource pessimists (Stiglitz, 1979, p. 47). Third, since it pretends to be based on the laws of thermodynamics, it is a potential answer to the problem of extrapolation faced by neoclassical models. This problem arises from the "contingent" choice of the production function, which is not established on legitimate and stable principles. Conversely, physical laws in general, and thermodynamics in particular, are among the scientific principles endowed with the strongest legitimacy and the greatest stability across time. The purpose of the present paper is not to discuss the relevance of such a scientific reputation, but to examine the ambition of building a theory of production consistent with the laws of thermodynamics. Among other aspects, this ambition appears as a methodological answer to prevent extrapolations from drifting too far away of the future conditions of production.

This drives us toward the methodological foundations of Georgescu-Roegen's approach in general, and of the assumption of thermodynamic limits in particular. Missemer has already insisted on the idea that the choice of scientific referents exterior to economics, such as thermodynamics or biology, was one pillar of Georgescu-Roegen's methodology (Missemer and Georgescu-Roegen, 2013, p. 19). He underlines that the goal is not to bring formal analogies from a discipline to the other, but to capture some properties of the objects under study thanks to the existing body of knowledge. This underlines an other important feature of scientific referents : they should share an interest into the *same*

[24] Georgescu-Roegen's archives do not contain more information. In particular, no correspondence with Solow or Stiglitz can be found.

objects. For instance, if one accepts that a theory of production should deal with the role of energy in the production process, then thermodynamics should be the relevant scientific referent , as the science of the transformations of energy. But an other implicit criterion is the scientific legitimacy of the discipline. In particular, Georgescu-Roegen often supports the high esteem he confers to the entropy law by referring to Sir Arthur Eddington, a physicist and philosopher of science:

> The law according to which the entropy increases - the second law of thermodynamics - occupies, I think, the supreme position among the laws of nature. If your theory is found to be against the second law of thermodynamics, I can give you no hope; there is nothing for it but to collapse in deepest humiliation. (Eddington, 1928, quoted in Georgescu-Roegen 1982)

This shows that, behind the theoretical opposition between the assumptions of unbounded resources productivity and thermodynamic limits to production, there is an important methodological opposition. I argued before that the methodology of natural resources economics is "model-based" in the sense that the model precedes and founds the conceptual structure of the paradigm. Similarly, I suggest to speak of "interdisciplinary consistency" for Georgescu-Roegen's methodology, to denote that the conceptual structure of his paradigm is inherited from a scientific referent, and especially from thermodynamics in what concerns us here. Therefore, from a similar starting point on what is the problem of resources about, the two paradigms give rise to two opposite assumptions. On one hand, Solow and Stiglitz are concerned with energy and mineral resources exhaustion, which they intend to analyse with their pre-existing production function framework. For mathematical purposes, this tends to privilege the assumption of unbounded resources productivity, under the twin concepts of substitution and technical progress. On the other hand, while equally interested into the role of energy and resources in production, Georgescu-Roegen understands the issue through the concepts provided by thermodynamics. The entropy law, under the form of Carnot's coefficient of maximum efficiency, is then translated into general thermodynamic limits to production processes.

Although these methodologies are radicaly different, they face similar issues. First, their respective sources of conceptual inspiration are not straightforwardly justified or interpreted. Regarding natural resources economics, I characterized the choice of the model as "contingent". Its justification essentially lies in the mathematically interesting problem it sets and the possibility of solving it analytically. But this does not endow it with much scientific legitimacy among other possible representations of production and weakens its long run relevance. Symmetrically, Georgescu-Roegen's methodology faces an issue of "equivocal interpretation" of thermodynamics. In particular, Georgescu-Roegen has had troubles interpreting the relations between energy, matter and entropy. He shifted from thinking that the dissipation of matter was a direct consequence of the entropy law, to suggesting that a fourth law is necessary to account for it (Georgescu-Roegen, 1977, p. 269). The assumption of thermodynamic limits itself is generally stated for both energy and matter. However, Carnot's principle, which appears as the origin of this assumption, only deals with the maximum energetic efficiency of a thermal engine. Hence, it does not involve any material consideration and does not seem to be a theoretical basis for minimum requirements of matter.

The second issue arises when the conceptual structure of each paradigm is built according to the respective methodology. For natural resources economics, I suggested to speak of a "conceptual foundations" issue to denote the difficulty of making sense of concepts such as "substitution" or "technical progress" outside the model. Similarly, I propose to speak of a "conceptual translation" issue to describe the challenges that face the prospect of translating physical knowledge, such as the laws of thermodynamics, into economic analysis. The most important example is the link between Carnot's maximum efficiency of a thermal engine and general thermodynamic limits to production. As I have shown above, Georgescu-Roegen essentially hinted at such a relation but didn't examine it in details. In particular, he didn't care much about the difference between physical and economic variables. While Carnot's principle initially applies to the transformation of heat into mechanical work, measured in energy units, Georgescu-Roegen generalised it to production as a whole, though the unit of the latter is much less clear. Without any investigation of this kind of problem, thermodynamic limits to the productivity of resources is left as an intuition whose conceptual relevance is questionable.

How should this latter issue be investigated, and in particular what should be the place of a formal representation of production ? On this point, Goeorgescu-Roegen's answer is qualified. As a component of his paradigm, he developed what he called flow-fund models. These were conceived as an alternative to existing theories of production such as Leontief's input-output matrices or the neoclassical production function(Georgescu-Roegen, 1971, Chap. 9), which he criticized on conceptual ground. However, the implications of his thermodynamic approach of production on such a formal representation are not clear. Himself didn't seem interested in going too far on the way of an integrated formal representation of economic and thermodynamic processes:

> [We] may now try to represent the economic process by a new system of equations patterned after that of thermodynamics. In principle, we can indeed write the equations of any given production or consumption process (if not in all technical details at least into a global form). [...][But] the rub is that in the long run or even in the not too long run the economic (as well as the biological) process is inevitably dominated by a qualitative change which cannot be known in advance. Life must rely on novel mutations if it is to continue its existence in an environment which it changes continuously and irrevocably. So, no system of equations can describe the development of an evolutionary process. (Georgescu-Roegen, 1971, p. 17)

The insistence on qualitative changes that could not be treated through modelling is an other pillar of Georgescu-Roegen's paradigm. This feature is partly inherited from Joseph Schumpeter (Bobulescu, 2012). Introduced by him to economics, Georgescu-Roegen retained his distinction between "growth", as a quantitative increase of production, and "development", as a qualitative transformation of production. The latter operates by deep technological breakthroughs such as passing from horse coaches to railway engines. As Missemer argued, this interest for qualitative changes is also a reason to qualify Georgescu-Roegen's association with a "degrowth" perspective, since degrowth is quantitative (Missemer, 2016). In particular, one should not think that, because he rejects the assumption of unbounded resource productivity, he thinks that production will decline as natural resources are exhausted. Conversely, in his criticism of natural resources, he notices that focusing on exhaustible resources hides the more important problem of finding new energy sources that would bring a qualitative transformation of the production process:

> The question that confronts us today is whether we are going to discover *new* sources of energy that can be safely used. No elasticities of some Cobb-Douglas function can help us to answer it. (Georgescu-Roegen, 1979, p. 98)

Even though this displaces the debate, it does not mean that the opposition between unbounded resource productivity and thermodynamic limits is not important. Whatever future source of energy will power the economy, it will abide by the laws of thermodynamics. Hence, if those imply thermodynamic limits to production, it will still be an important feature of the production process, and economic analysis should take it into account. This explains why the controversy between ecological economics and natural resources economics on this subject kept going on.

3 The forum debate in Ecological Economics

In 1997, Herman Daly initiated a forum debate in *Ecological Economics* with a paper called "Georgescu-Roegen versus Solow/Stiglitz"(1997a). Daly was a former student of Georgescu-Roegen and had been much influenced by his thermodynamic approach of the economic process. From a similar framework, he developed a more policy oriented perspective. He was particularly critical of what he perceived as a "growthmania" among economists. Himself suggested to reorient economic policies toward the stabilization of physical economic outputs and inputs, also called a "steady-state economy" (Daly, 1974, 1979).

Daly played an important role in the institutionalization of ecological economics, which got its own society and journal in 1989. He was one of the main vector of Georgescu-Roegen's influence on this new school of economics (Røpke, 2004). As a mark of this influence, in 1997, an issue of the journal was dedicated to the memory of Georgescu-Roegen, who died in 1994. Daly was the guest editor of the issue, and this is where he initiated the debate (Daly, 1997b). Therefore, this latter illustrates well the "identity formation" process of ecological economics described by Røpke (2005), and its two facets: the determination of the theoretical roots of the field and the clarification of the divergences with the competing paradigm of natural resources economics.

Daly's initial paper recalls Georgescu-Roegen's criticism of natural resources economics, based on his paper of 1979. However, he focuses the debate on the assumption of "thermodynamic limits" to production as a counterargument to "unbounded resources productivity", giving little attention to the other aspects of the criticism, such as the role of markets or the utilitarian norm. The tone of Daly's paper is polemical and it ends on a direct challenge addressed to Solow and Stiglitz:

> Toward that happy end it is appropriate to reissue Georgescu-Roegen's invitation to Solow/Stiglitz, and the whole community of neoclassical economists for whom they are distinguished spokesmen, to put an end to 'conjuring tricks' — to mathematical fun and games with infinity in the Garden of Eden — and to devote their impressive analytical powers to helping develop serious ecological economics for the real world. (Daly, 1997a, p. 265)

Solow and Stiglitz were invited to answer and they defended the assumption of unbounded resources productivity (Solow, 1997; Stiglitz, 1997). Daly replied once again, and he invited commentaries on the controversy by other ecological or natural resources economists. This invitation was followed by ten of them, whose comments varied from some clearly siding with Daly and Georgescu-Roegen arguments (Clark; Common; Opschoor; Peet; Tisdell), to some proposing a more qualified opinion (Ayres; Pearce; Castle), and others denouncing the polemical tone of the debate and advocating more open-mindedness (Turner; Perrings). Moreover, other articles were published shortly after in reaction to the debate and should also be considered (Mayumi et al., 1998; Bergh, 1999).

Before analysing what we can learn from these contributions, one more contextual aspect seems important. At that time, "sustainability" had recently become a key concept of the discussions on environmental issues. It had first appeared at the frontier of academic and political concerns, in 1987, in the report of the World Commission on environment and development, under the supervision of the United Nations (Brundtland, 1987). "Sustainable development" was then defined as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs". The notion quickly disseminated in international political sphere, through events like the Rio de Janeiro Earth Summit in 1992, but it also became a source of academic debates. In economics, two competing approaches emerged under the labels of "weak sustainability" and "strong sustainability". The former defends that man-made capital can substitute to natural capital, and suggests therefore that the relevant sustainability indicator is the aggregation of both. Solow was an important contributor of this perspective, and in particular imported the concept of substitution from the framework of natural resources economics (Solow, 1993). The latter underlines the limits to the substitution between man-made capital and natural capital, but also between the different forms of natural capital such as natural resources, climate stability or ecosystems. As a consequence, it advocates the preservation of each of the specific forms of natural capital. This approach was set forward by ecological economists and notably by Daly (1990).

Hence, the forum-debate of 1997 is clearly an important moment in the confrontation between these two approaches of sustainability. Two years later, a collective book in honour of Georgescu-Roegen is explicitly named *Bioeconomics and sustainability*, suggesting that his work could contribute to the analysis of sustainable development issues (Mayumi and Gowdy, 1999). However, recent historical and analytical accounts on the debates around sustainability, such as Neumayer (2013) or Pezzey and Toman (2005), don't devote much attention to his contribution. Neither do they study the implications of the forum-debate of 1997. Therefore, they miss the fact that Georgescu-Roegen's assumption of thermodynamic limits to production is one of the roots of the limits to substitution between natural and man-made capitals advocated by strong sustainability[25].

3.1 Time horizon and the productivity of resources

In comparison with the four issues initially set forward by Stiglitz (1979), the debate of 1997 narrower than the original criticism of Georgescu-Roegen, the issues of "efficiency" and "intergenerational equity" not being tackled. Regarding "forecasting", the first question raised by the forum debate concerns the relevant time horizon of the models. It is triggered by Stiglitz's following assertion:

> Part of the problem arises from a lack of understanding of the role of the kind of analytic models that we (and others) have formulated. They are intended to help us answer questions like, for the intermediate run—for the next 50 – 60 years, is it possible that growth can be sustained? What does this possibility entail? We write down models as if they extend out to infinity, but no one takes these limits seriously—for one thing, an exponential increase in the population presents almost unimaginable problems of congestion on our limited planet. (Stiglitz, 1997, p. 269)

This argument is discussed by a number of comments in the forum debate, which strongly deny its relevance (Daly; Clark; Opschoor; Tisdell). First, they consider that this

[25] It is only "one of the roots" because his criticism concerns only the substitution of man-made capital to natural resources, while the debate also bears on the substitution of man-made capital to biodiversity or climate stability. For these other forms of natural capital, the criticism of substitutability must be founded on other arguments.

time horizon is not suitable for ecological purposes, such as resource depletion or climate change, which have both short and long term consequences. But they also think that the argument is an *ad hoc* assumption to avoid criticisms and that had never been formulated before. Even though no one noticed it in the forum debate, this interpretation is confirmed by the fact that Solow used exactly the opposite argument to support his assumption of constant population in 1974:

> The convention of exponential population growth makes excellent sense as an approximation so long as population is well below its limit. On a time-scale appropriate to finite resources, however, exponential growth of population is an inappropriate idealization. But then we might as well treat the population as constant. (Solow, 1974b, p. 36)

This ambiguity on the time horizon of models is linked to the issue of "conceptual foundations". As in the case of "substitution" and "technical progress", it reveals the difficulty of making sense of some mathematical property, here the time variable and its boundaries, outside of the model. The multiple interpretations that arise underline the absence of a clear conceptual structure underpinning the paradigm.

Similarly, the interpretation of the entropy law and its relation to time are questioned by natural resources economists. For instance, Solow expresses doubts on the relevance of accounting for the entropy law in economic theory:

> No doubt everything is subject to the entropy law, but this is of no immediate practical importance for modelling what is, after all, a brief instant of time in a small corner of the universe. (Solow, 1997, p. 268)

Stiglitz had a very similar statement in 1979 (p. 37), which shows that both interpret the entropy law only as a long term and global driving force of the universe, with no signification for economic activities in the medium run. Conversely, Daly replies by underlining its practical consequences:

> But the entropy law has more immediate and relevant implications: that you can't burn the same lump of coal twice; that when you do burn it once you get soot, ashes, CO_2, and waste heat, as well as useful heat. The entropy law also tells us that recycling energy is always a losing proposition, that there are limits to the efficiency of conversion of energy from one form to another, and that there is a practical limit to materials recycling—all in the here and now, not just in the cosmic bye and bye.

In fact, even Solow's early writings on natural resources show that he thought the laws of thermodynamics to constrain possibilities of recycling (1974a, p. 2). Georgescu-Roegen himself made statements that supported either the long term cosmological interpretation (1971, p. 19, 231) or the practical economical consequences (1971, p. 6, 278).

In fact, both aspects are constitutive of the entropy law. Though it was first stated through the study of thermal engines by Carnot, a most practical outlook, it has quickly been interpreted as a general law of evolution of the universe. This duality is still present in the various formulations of the law, some stating it for an "isolated system", others stating it for the "universe". This underlines once again the issue of "equivocal interpretation" that is inherent to the methodology of "interdisciplinary consistency". However, these two interpretations are not contradictory one with the other, and the implications of physical laws both at the practical and at the cosmological levels is common in physics. Mechanical laws, for example, apply to the movements of planets as well as when one plays basketball.

Similarly, there is no need to choose between one interpretation of the entropy law or the other. Hence, invoking its long term signification cannot justify to put aside its immediate consequences for the economics of production.

These immediate consequences are precisely at stake in the discussions related to the "viability" issue, that is the relevance of the assumption of "unbounded resources productivity". Daly clearly focuses his criticism on this assumption :

> The Solow-Stiglitz variant includes resources explicitly, but implicitly makes a similar assumption about near perfect substitution of capital for resources — what Georgescu-Roegen aptly dismissed as a 'conjuring trick'. In the Solow-Stiglitz variant, to make a cake we need not only the cook and his kitchen, but also some non-zero amount of flour, sugar, eggs, etc. This seems a great step forward until we realize that we could make our cake a thousand times bigger with no extra ingredients, if we simply would stir faster and use bigger bowls and ovens. The conjuring trick is to give the appearance of respecting the first law of thermodynamics (material balance) without really doing so. (Daly, 1997a, p. 263)

Daly's interpretation of Georgescu-Roegen's criticism has two important implications. First, it focuses on the first law of thermodynamics rather than the entropy law. Second, it interprets this law as the conservation of mass, and therefore focuses on the role of matter in production rather than energy. Such an interpretation has later been adopted even more clearly by Bergh (1999). Its intuition is basically that the mass of matter that goes out of the production process, under the form of commodities or waste, is necessarily linked to an equal input at the entrance of the production process, that is a reformulation of the well-known maxim : "nothing is lost, nothing is created, everything is transformed". Therefore, it advocates for a theory of production that would account for this constraint between input and output. While this is certainly an interesting issue, I suggested in section 2 that Georgescu-Roegen's assumption of "thermodynamic limits" was originally related to Carnot's coefficient of maximum efficiency, that is rather to the question of energy and the entropy law. The distinction is important because the role of energy in production is very different from that of matter. For instance, energy is not incorporated in final goods and therefore the intuitive argument of equivalence between input and output is not as relevant. With this new ambiguity, the issue of "equivocal interpretation" behind Georgescu-Roegen's thermodynamic approach actually takes its full signification as we see that his followers will adopt different interpretations than himself. Hence, the ambition of accounting for thermodynamic laws in the analysis of production becomes even more complex and uncertain.

Whatever interpretation we might choose, it should take into account another important aspect of Daly's criticism. This concerns the "distinction between substitution among factors within a given set of technologies (existing state of the art), and substitution among factors made possible by a new technology (improved state of the art)" (Daly, 1997a, p. 264). Here, Daly admits that there can be a debate on whether unbounded resource productivity might be enabled by future technologies, even though he thinks Georgescu-Roegen's intuition of thermodynamic limits is right and prohibits it. However, he underlines that if the production function is supposed to represent *actual* possibilities of production, it clearly cannot exhibit such a property. No one could pretend that such a set of technologies is *already* disposable.

This remark adds to the issue of "conceptual foundations", as previously analysed. At the bottom, it is related to the difficulty of making sense of "substitution" and "technical progress" in a consistent way outside of the model. This issue presents the same characteristics in 1997 as in 1979, but appears more clearly. First, Solow asserts that "the substitution between renewable and nonrenewable resources is the essence of the matter" (Solow, 1997, p. 267). Hence,he focuses the attention on transformations of the production process that enable to produce the same output with renewable resources. This leads commentators to discuss the possibility of finding such renewable substitutes to exhaustible resources (Clark, 1997; Ayres, 2007). However, this interpretation of substitution is not consistent with Solow and Stiglitz's models, which only mentions exhaustible resources (Solow, 1974b)[26]. These models seem rather dedicated to studying transformations of the production process that enable to produce the output with the same resource but more efficiently.

However, even if considered under this latter aspect, the distinction between substitution and technical progress is not clear. For instance, Stiglitz writes:

> In this intermediate run, capital can substitute for natural resources — and this is true even though capital itself uses resources. More precise machines (made out of resources that are relatively abundant) can reduce wastage of resources that are relatively scarce. Technical change — some of which is the result of investments in R&D, a form of capital — can reduce the amounts of physical capital and resources required to produce the unit of output — where output is measured not in physical units, but in the value of the services associated with it. (Stiglitz, 1997, p. 269)

Here, the two concepts of substitution and technical progress conflate in only one broad transformation toward a more efficient production process. The root of the problem seems to be that Stiglitz analytically distinguishes two phenomena that are in fact conceptually linked to each other. Hence, more than twenty years later, the "model-based" methodology of natural resources economics faces the same issue regarding its conceptual foundations.

This emphasizes that, more than the possibility of continuous growth, what is at stake here is the construction of a consistent representation of the production process. Accordingly, one last aspect of the debate is to know whether the variable used to measure output is in physical or value units. This briefly appears at the end of Stiglitz's quotation above, where he advocates the latter. This is actually a reply to Daly's assertion that "even production functions that yield services are producing a physical output - the use of something or somebody for some period of time" (1997a, p. 264). The early works of Solow and Stiglitz on natural resources do not even mention this problem. However, if we go back to Solow's original papers on growth theory, he says that "Q represents output and K and L represent capital and labor inputs in 'physical' units" (1957, p. 312). This shows at least that the status of aggregated variables is surrounded with penumbra.

This issue deserves particular attention because it is intimately linked with the debate on the productivity of resources. As Daly recognizes, there might not be minimum energy and matter requirements to produce a unit of economic welfare. But conversely, he advocates that if services are measured in physical units Georgescu-Roegen's assumption of thermodynamic limits would be valid. Moreover, Daly asserts that "the aggregate production functions of macroeconomics may seem to be in value units because prices are used to aggregate the variables, but fundamentally a 'dollar's worth' of capital, labor, or resources is a physical quantity" (Daly, 1997a, p. 265). These two arguments together would

[26]Dasgupta and Heal (1974), in the second part of their paper, developed a model where the economy switches from an exhaustible resource technology to a renewable one. This point of comparison makes even clearer the fact that that Solow and Stiglitz's models were restricted to the former.

logically imply the negation of unbounded resource productivity in production function with aggregated variables, whether under the form of substitution or technical progress. However, not all ecological economists agree with him on this topic. Ayres for instance opposes to the first part of the argument. He agrees that "human welfare is attributable in the final analysis to non-material services" that nevertheless have "a material base". But he disagrees on the idea that "there is some finite upper limit to the service output of a given material [...] given the possibility of dematerialization, re-use, renovation, recovery and recycling" (Ayres, 1997, p. 286). Following the same line, Bergh asserts that "both the service output of materials processing and the value of this service output do not seem to be bounded by an identifiable absolute limit" (Bergh, 1999, p. 554). Ayres's argument deals with the relation between a non-material service and its material base, for example between a transportation service and the vehicle used for it. This is justified by Daly's focus on material requirements when he interprets Georgescu-Roegen's criticism. But it does not answer the question of the link between a service and its energetic base, which is more important if we interpret Georgescu-Roegen in the light of his reference to Carnot's maximum efficiency principle.

Nevertheless, this discussion enables to study more deeply the issue of "conceptual translation". It shows that the notion of production itself as to be refined to be able to assess its dependence to natural resources. More precisely, the relation between material and energetic resources, the non-material services they provide, and the value of these services is at the heart of the issue. Studying further this relation seems necessary to have a clear conceptual understanding of the respective roles of matter and energy in production.

This appears as the most important lesson we can draw from the debate in *Ecological Economics*. However, the debate also broadens the understanding of other issues, such as the interpretation of the entropy law or the conceptual foundations of substitutability and technical progress. This enables to better apprehend the implications of the controversy.

3.2 Methodological and epistemological implications

It is now time to put together the different pieces of my analysis, to propose a specific reading of the controversy opposing natural resources and ecological economics. Between the two most active periods of the controversy, in the 1970s and at the end of 1990s, the spectrum of issues at stake has narrowed. In the first period, it covered the role of markets, the relevant norm of intergenerational equity, the scope of substitution and technical progress, and the extrapolation of the structure of the economy as captured by the model. While in the second period, the discussion focused on the potential of substitution and technical progress. However, this evolution is not fortuitous. It follows from the central role played by the assumption of unbounded resources productivity in Solow and Stiglitz's representation of production, to which Georgescu-Roegen opposed the assumption of thermodynamic limits. The radical opposition between the two assumptions appeared from the beginning as the most important divergence, and the forum debate in 1997 gave it even more weight. Consequently, it simplified the structure of the controversy around the confrontation between unbounded resources productivity and thermodynamic limits to production.

Behind this theoretical opposition, there is an important methodological opposition. As I suggested the assumption of unbounded resources productivity is the outcome of a "model-based methodology". This underlines that the model precedes the conceptual structure of the theory, and actually gives rise to it. Such a methodology is confronted with the issue of choosing a model of the production process without having conceptually analysed it. Therefore, it resorts to mathematical concerns to define an interesting and analytically solvable problem, which justifies to talk of a “contingent” representation of production. However, once the model has been mathematically studied, it has to be interpreted in order to show its potential as a representation of the actual economy. This step faces the “conceptual foundations” issue of making sense of concepts such as substitution and technical progress outside of the model. In fact, the debate of 1997 shows that the confusion about these concepts is lasting over time. The interpretation of substitution as substitution *between* resources persists, though it is not consistent with the basic features of the model. While the interpretation as improved efficiency shows that the two concepts overlap, unveiling the ambiguous status of production functions as a representation of the state of the art. Even the interpretation of the time variable is questioned by the debate, in response to Stiglitz’s assertion that the model is only relevant for the intermediate run. Hence, making sense of Solow and Stiglitz’s growth models with exhaustible resources appears difficult, and this leaves uncertain the relevance of unbounded resources productivity.

On the other hand, Georgescu-Roegen’s methodology of “interdisciplinary consistency” is clearly endorsed by Daly and most other ecological economists, as shows their insistence on the role of the laws of thermodynamics. According to this approach, the conceptual structure of the paradigm is inherited from thermodynamics, considered as a relevant scientific referent. Nevertheless, it faces similar issues. First, thermodynamics is subject to “equivocal interpretations” that make uncertain its meaning as a scientific referent. In particular, Daly tends to interpret Georgescu-Roegen’s assumption of thermodynamic limits in terms of the conservation of mass, focusing the attention on matter. Conversely, I showed that it was originally formulated as a generalization of Carnot’s coefficient of maximum efficiency, orienting rather toward the role of energy. While the two perspectives might be interesting, it shows the potential dilution of the assumption into multiple interpretations. Moreover, even if we agree on one specific interpretation, there is still a step to make sense of it in the analysis of production. The “conceptual translation” issue intends to describes this step and the challenges that face the prospect of translating physical knowledge, such as the laws of thermodynamics, into economic analysis. The debate brings much light on this topic. It underlines that the understanding of production depends on the relations between natural resources, the non-material services they provide, and the value of these services. This seems a particularly relevant approach to examine in more details the link between Carnot’s maximum efficiency of a thermal engine and general thermodynamic limits to production, which Georgescu-Roegen only hinted at. Without such an investigation, the confrontation between unbounded resource productivity and thermodynamic limits cannot be settled, because the two assumptions are not based on similar representation and measure of production.

The issues analysed above prevented the controversy from setting a precise problem, on which both paradigms could agree, and a shared methodology to solve it. Norton (1995) arrives at a similar conclusion in examining the opposition between strong and weak sustainability on the issue of ecosystems valuation. There, conceptual issues arise in the definition of what is an ecological service, on the relevant boundaries to apprehend its production, and on the kind of irreversibilities it is subject to. These issues lead to disagreements on the relevant units for measuring the degree of sustainability of the economy. While weak sustainability privileges monetary measures, for example through willingness-to-pay, strong sustainability resorts to independent ecological indicators. Drawing on Thomas Kuhn’s framework, Norton speaks of an “extraparadigmatic” controversy to designate the impossibility of finding a common ground for the debate in these conditions. However, it would be closer to Kuhn's approach to speak of "incommensurability" between paradigms (Kuhn, 1962, p.148).

This latter notion appears fruitful to understand the controversy between ecological and natural resources economics. It underlines that the methodological opposition behind this controversy gives rise to radically different conceptual structures. While neoclassical economics understands substitution and technical progress through their mathematical model, ecological economics confronts it with its thermodynamic approach. Each approach yields a specific perspective on production, the former focusing on its aggregated economic value, whereas the latter underlines the material and energetic flows on which it relies. Hence, the respective assumptions of unbounded resource productivity and thermodynamic limits, though intuitively logically opposed to each other, are formulated in such different frameworks that they are not easily confronted.

Neumayer, in a broad review of the disagreements between weak and strong sustainability, defends an even stronger epistemological thesis. He suggests that "both paradigms rest on certain assumptions as well as hypotheses and claims about the (distant) future that are non-falsifiable" (Neumayer, 2013, p. 94). And he insists that this would hold even if the two paradigms could find a common methodological and conceptual ground for the discussion. However, this thesis is less consonant with my analysis of the controversy between ecological and natural resources economics. First, the reference to falsifiability implies some empirical testing of the theory, while the present debate mainly focused on theoretical concerns. Second, it imposes a more or less popperian epistemology as reading grid. This might be relevant for natural resources economics, for instance when it considers econometric estimates of production functions as empirical tests. Nevertheless, it does seem appropriate for Georgescu-Roegen's methodology, which pretends to draw epistemological validity from its consistency with thermodynamics, considered as a relevant and legitimate body of knowledge. In this outlook, the assumption of thermodynamic limits to production is true because it is considered as a consequence of the laws of thermodynamics, which will constrain the production process at any point in the future. While the neoclassical approach meets important issues for the extrapolation of the structure of its production function, this methodology relies on the stability of physical laws to promote its own view of long term constraints on production. Empirical tests are not considered necessary because the laws of thermodynamics are already built on physical facts and link the theory to actual production processes. Hence, even though it might be relevant for other aspects of the confrontation between weak and strong sustainability, the issue of falsifiability does not seem appropriate here. Attention should rather be dedicated to the delimitation of a conceptual framework to investigate further the opposition between unbounded resources productivity and thermodynamic limits.

3.3 Proposition for a conceptual framework

In order to examine the analytical relevance of both assumptions, we must first dissipate the confusion generated by the conceptual issues previously identified. First, the objective is to investigate the limits that the laws of thermodynamics may set on the improvement of resource productivity. It is their signification for production processes at any time that is interesting, not their very long term consequences for the universe. Secondly, I consider only energy resources and their role in production processes. More precisely, the issue is to know whether Carnot's maximum efficiency and the second law of thermodynamics logically give rise to general limits to production, and in what sense. Hence, I leave aside the implications of the conservation of mass as well as the consequences of the entropy law for matter, which has been a controversial issue but should not be tackled here (Cleveland and Ruth, 1997; Ayres, 1999). Thirdly, I consider the potential of increasing energy's efficient use, not the potential of substitution of actual energy sources, mainly fossil fuels, by other sources, for example solar energy. Under this perspective, the analytical distinction between substitution of capital to resources and exogenous technical progress does not seem appropriate. These two aspects are intimately linked in a transformation of the production process where capital is accumulated under qualitatively different forms.

I suggest that with these delimitations we have an interesting and substantial problem. It is not interesting in the mathematical sense, as in natural resources economics, but as a physical feature of production with implications for economic theory. Even though this question was already perceptible in the controversy, it was not precisely identified and investigated because of the conceptual issues on both sides. Of course, other interpretations could set forward other issues, such as the impact of the conservation of mass or the substitution between different energy sources. But I pretend that this question is the most relevant regarding the original statements of Georgescu-Roegen on one side, hinting at Carnot's maximum efficiency, and the models of Solow and Stiglitz on the other side, which only deal with one exhaustible resource and not with a transition from one resource to another.

In order to examine this question we need to introduce the notion of "exergy". This thermodynamic concept is more directly understandable than entropy and Georgescu-Roegen's approach is clarified thanks to it, even though himself did not resort to it very often. In particular, it enables to understand more accurately the implications of Carnot's maximum efficiency. Carnot's coefficient shows that not all the thermal energy in an engine can be transformed into mechanical energy. Therefore, we may define different *qualities* among the multiple forms of energy : mechanical and electrical energy is of the highest quality, that is it can be completely transformed in any other form of energy ; whereas heat and electromagnetic energy (light for example) have lower quality, and can be only be partially converted in mechanical energy. For every physical system containing a quantity of energy U, their exists a coefficient $0 \leq x \leq 1$, depending of the form of the energy, such that $E = xU$ is the maximum quantity of U that can be transformed into mechanical work. E is called the exergy of the system.

By construction, every possible transformation implies a loss of exergy. Consider for example a quantity U of mechanical energy under the form of movement[27]. At this point, the exergy of the system is $E_1 = U$. Then, the mechanical energy may be fully transformed into heat by friction. Once this is done, the thermal energy cannot be fully transformed back into mechanical energy, according to Carnot's principle. The exergy of the system then becomes $E_2 = xU = \eta_m U < E_1$, where η_m is Carnot's maximum efficiency as defined in 21. Therefore, the second principle of thermodynamics can be reformulated as: the exergy of an isolated system can only decrease. This statement is more general than Carnot's maximum efficiency, because it deals also with other forms of energy such as electrical and electromagnetic energy.

This concept sheds light on the relations between energetic aspects of production and the non-material services they provide. I suggest to distinguish three levels of the production process: the initial exergy E_i that enters in production, for example under the form of fossil fuels; the final exergy E_f that is delivered either to a producer or a consumer, for example under the form of mechanical work, heat or light; and the actual economic service it generates, such as transportation, maintaining a room at a certain temperature or lighting a place.

[27] Remember that a body of mass m moving at speed v has a kinetic energy $U = \frac{1}{2}mv^2$.

What does the second law of thermodynamics say in this context? It states that final exergy is necessarily less than the initial exergy: $E_f < E_i$. This can be regarded as a straightforward thermodynamic limit to production. However, the actual loss of exergy depends on the technical features of the process that has transformed initial exergy into final exergy. For example, if we consider the transportation of the electricity from a thermal power plant to a lamp, there have been many exergy losses, especially due to heat generated by electric wires (Joule's effect). But the entropy law does not set a minimum to these losses.

Could it be reduced to zero? To answer this question we can go back to Carnot's analysis of thermal engines. By definition, the exergy of the heat contained in the engine is exactly the mechanical energy it could produce if it worked as Carnot's ideal engine. In this latter, every heat flow is supposed to happen with the intermediate body having the same temperature as the source or the sink[28]. But this is an idealisation. In actual processes, heat transfer cannot really happen if temperatures are equal, because such an engine would take infinite time to generate mechanical work. This indicates a trade-off between power, that is the rate of mechanical work produced per unit of time, and efficiency. For instance, we can consider a Carnot engine where heat transfers happen with unequal temperatures (Callen, 1985, p. 125). If we look for the maximum power that can be generated by such an engine, then the efficiency at this maximum power is given by:

$$\eta = \frac{\sqrt{T_1} - \sqrt{T_2}}{\sqrt{T_1}} < \frac{T_1 - T_2}{T_1} = \eta_m \tag{23}$$

The economic meaning of this trade-off between power and efficiency is that if the economy is more preoccupied with power, that is with producing as much as possible in a unit of time, then the efficiency of the energetic transformations in the production process will certainly be much lower than Carnot's maximum efficiency. Or, to state it in an other way, final exergy will be much lower than initial exergy. However, this does not prevent from consuming little initial exergy, especially if E_f can approach 0 while delivering the same final economic service.

Is that latter case possible or are there thermodynamic limits too? This question can be examined more closely on the example of a train propelled by electricity. The final exergy is delivered under the form of mechanical work E_f. This exergy is really lost through frictions that transform the mechanical energy into heat. These frictions are generated by the contact with the railway, the resistance of air, and when the train brakes to stop. Nevertheless, frictions with the railway may be diminished, for example with magnetic levitation technologies[29], air resistance can be reduced by aerodynamic design, and kinetic energy can be recovered and reused thanks to regenerative braking (Koseki, 2010). Hence, no thermodynamic law seems to set a minimum to these exergy loss. However, there might be other physical principles setting limits. For instance, given some comfort requirements, we may define an optimal design with a strictly positive air resistance that will imply a minimum exergy loss E_f and therefore a minimum initial exergy $E_i > E_f$.

This example illustrates the intricate relationship between the service and its value V. The issue stems from the fact that the service of transportation has at least three dimensions : the distance travelled, the average speed at which it is travelled, and the level of comfort. If one dimension is allowed to vary, then there might be no minimum

[28]See section 2.

[29]However, magnetic levitation generates new energy expenditures and is used to increase trains speed. It is therefore difficult to assess its real potential of energy savings (Spielmann et al., 2008)

final exergy. For instance, if a requirement on the speed and distance is set, the final exergy might be decreased toward zero by making the vehicle more and more aerodynamic. But this certainly implies less and less space for the passenger and hence less comfort. The problem is that the value of the service would then certainly go toward zero too because no one would want such a vehicle. This illustrates that the value of the service is an economically constructed *quantity* that depends on the three *qualitatively* different dimensions of the service. Both the final exergy and the value of the service are positively linked with each of the dimensions. As a consequence, their comparative behaviour is not straightforward.

In particular, it is not clear if the productivity of exergy, that is the ratio $\frac{V}{E_f}$, has a maximum. In this framework, "unbounded resources productivity" would be equivalent to say that no such maximum exists. While we should rather speak of "physical limits" if it does, since it now concerns other physical aspects than thermodynamics. In fact, here the kind of limits that might arise are more linked to other physical domains, such as fluid dynamics, than to thermodynamics. To balance the respective relevance of theses assumptions, this framework suggests to evaluate as accurately as possible the relation of final exergy and value with the three dimensions of the service.

Moreover, to give a full picture of the problem, a similar analysis should be applied to the different kind of energy services, such as lighting or heating. In each case the multiple dimensions of the service should be identified and related to both final exergy and value. This would shed light on the respective relevance of the two assumptions in each context. Once this is done, we may also wonder if this methodology can unveil any interesting feature at the aggregated level. If this is possible, then this perspective offers an interesting way to better understand the global dependence of the economy to energy in the long run.

Conclusion

This paper proposes a comprehensive account of the controversy between natural resources economics and ecological economics. Regarding the former, it shows that the work of Solow and Stiglitz in the 1970's is built on a "model-based methodology". This underlines that the model precedes and gives birth to the conceptual foundations of the theory. Hence, no pre-existing conceptual analysis of production underpines the choice of the production function. The preference for Cobb-Douglas or CES forms mainly relies on mathematical concerns and the historical development of neoclassical growth theory, deserving the characterization of "contingent production function". As a consequence, important concepts such as "substitution" and "technical progress" are first defined as mathematical properties of the contingent production function. It appears difficult to make sense of it outside the model, in a way that would be consistent with the actual transformations of the production process it pretends to describe. This issue of "conceptual foundations" makes the central assumption of "unbounded resources productivity" controversial, because it relies on both substitution and technical progress.

On the other hand, Georgescu-Roegen's criticism of natural resources economics was based on his methodology of "interdisciplinary consistency". The conceptual structure of his paradigm is based on thermodynamics, considered as a relevant scientific referent for economic theory. But this interdisciplinary ambition also faces conceptual issues. First, thermodynamics is subject to "equivocal interpretations" that make uncertain its meaning as a scientific referent. In particular, the assumption of "thermodynamic limits" to production may be interpreted either in terms of the conservation of mass, focusing the attention on matter, or in term of Carnot's coefficient of maximum efficiency, focusing on the role of energy. Moreover, even if one specific interpretation is chosen, a "conceptual translation" issue faces the prospect of translating physical knowledge, such as the laws of thermodynamics, into economic analysis.

The debate in *Ecological Economics*, more than twenty years after the original contributions to the controversy, shows that the problem resides in the understanding of the relations between natural resources, the non-material services they provide, and the value of these services. Further investigation in this direction appears necessary to overcome the incommensurability arising from the very different conceptions of production underpinning each paradigm. I propose such a step with a framework that studies the relation between three levels of the production process: initial exergy, final exergy, and the final economic service performed. On one hand, Carnot's maximum efficiency, and more generally the second law of thermodynamics, directly sets a constraint on the relation between the first two levels. On the other hand, the relation between the last two levels requires a multidimensional analysis of the service, including for instance the amplitude, the speed and the comfort with which it is performed. This analysis implies physical aspects that are not reducible to thermodynamics, and it orients toward disaggregated examinations of the final services performed by energy. Hence, it could enable to overcome some of the issues met by both paradigms and give a better understanding of the energetic foundations of the economic process.

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