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ARTICLE HISTORY
Compiled October 24, 2019

Abstract
This paper provides a theoretical and methodological account of an important controversy between neoclassical resources economics and ecological economics, from the early 1970s to the end of the 1990s. It shows that the assumption of unbounded resources productivity in the work of Solow and Stiglitz, and the related concepts of substitution and technical progress, rest on a model-based methodology. On the other hand, Georgescu-Roegen's assumption of thermodynamic limits to production, later revived by Daly, comes from a methodology of interdisciplinary consistency. I conclude that neither side provided a definitive proof of its own claim because both face important conceptual issues.

KEYWORDS
Nicholas Georgescu-Roegen; Robert Solow; Joseph Stiglitz; natural resources; theory of production

JEL CLASSIFICATION
B22; Q32; Q57

1. Introduction

Modern economic thought on natural resources issues has gone through an important episode in the 1970s[1]. One of the event that triggered this was the publication of the report *The Limits to Growth* (Meadows et al. 1972), which suggested that continued economic growth could lead to ecological collapse, due to resource depletion and the accumulation of pollution. Growth economists, such as Robert Solow (1973, 1974a,b) and Joseph Stiglitz (1974), strongly criticised 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 in the 1960s (Boianovsky and Hoover 2009). Among important assumptions, their models

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[1]The preoccupations regarding the depletion of natural resources had been discussed in economics before this period. See for instance Missemer (2017) for an account of the transformations of the analysis of fossil fuels exhaustion from Stanley Jevons's *The Coal Question* in 1865 to "The Economics of Exhaustible Resources" by Harold Hotelling in 1931. Even though they partially relied on these earlier works, the paradigms that emerged in the 1970s rested on new concepts and tools that considerably reframed the way questions were set.

incorporated the idea that the productivity of resources could be increased indefinitely thanks to the substitution of capital to resources or technical progress. This led to the conclusion that constant or even growing consumption could be achieved in the long run, and these contributions laid the foundations of a new branch of growth theory, here labelled as “neoclassical resources economics”.

But almost at the same time, a paradigm had emerged inside the economic community which was closer to the views of the Club of Rome. It was initiated in particular by Nicholas Georgescu-Roegen (1971), who became more and more critical of neoclassical theory after contributing to it[2]. He proposed a reorientation of economic theory based on references to thermodynamics, and placing environmental issues at the heart of its preoccupations. This naturally led him to take part in the debate on the limits to growth (Levallois 2010), criticising Solow’s and Stiglitz’s works on exhaustible resources (1975; 1979), and especially the relevance of their representation of production with unbounded resources productivity. 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). As a former student, Daly had been much influenced by Georgescu-Roegen. He played an important role in the institutionalisation of the new school of “ecological economics”, where he promoted the ideas of his mentor. In fact, his article of 1997 was part of an issue of *Ecological Economics* dedicated to Georgescu-Roegen, who had died in 1994. It generated one of the rare direct confrontations between neoclassical resources economists and ecological economists, which shows how much the underlying issues are constitutive of this opposition. Hence, studying this controversy, from the 1970s to the 1990s is a good opportunity to better understand the fundamental divergences between these two paradigms. The purpose of the present paper is to give a detailed account of it, with a focus on the theoretical and methodological issues at stake[3].

The article is organised in three sections. Section 2 shows how the assumption of unbounded resources productivity was integrated in Solow’s and Stiglitz’s models under the form of capital substitution or exogenous technical progress. I characterise the methodology underpinning this approach as model-based, and I examine the conceptual issues it raises. Section 3 introduces Georgescu-Roegen’s thermodynamic approach of the economic process. I reconstruct and critically examine his criticism of Solow’s and Stiglitz’s works, focusing on the idea of thermodynamic limits and its underlying methodology of interdisciplinary consistency. Finally, section 4 shows that the debate of 1997 rests on the same theoretical and methodological oppositions, and highlights in particular the issues related to the conceptual integration of physical and economic concepts.

2. Solow, Stiglitz, and the Origins of Neoclassical Resources Economics

As Robert Solow expressed it in his Richard T. Ely lecture in December 1973, it is the report *The Limits to Growth* (Meadows et al. 1972) that sparked his interest for natural

[2]Kenneth Boulding (1966) is another important early contributor of this new paradigm and he shares a similar intellectual trajectory.

[3]By “theory”, I mean the concepts that constitute the intellectual framework through which economists conceive their objects of study. In particular, I distinguish them from “models” as purely mathematical systems. Moreover, while in general “methodology” denotes the global articulation between the different constituents of a paradigm, here it is primarily understood as the way concepts are built.

resources:

> 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. (Solow 1974a, 1-2)

His model was presented in a "Symposium on the Economics of Exhaustible Resources", and later published in a special issue of *The Review of Economic Studies* (1974b). Together with that of Stiglitz (1974) in the same issue, his article had an important influence on later works. These papers shared a similar framework and laid the foundations of the neoclassical analysis of growth with exhaustible resources, or "neoclassical resources economics"[4].

2.1. ***Growth Models and Unbounded Resources Productivity***

The general framework is that of Solow's neoclassical growth model (1956). Among the key features of this model is the notion of "production function", relating the level of output Q to the level of the factors of production. While, traditionally, only aggregate capital K and labour L were considered as relevant production factors, neoclassical resources economists introduced a variable R representing the flow of resources in the production function:

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

The notion of "resource" itself is illustrated either by energy sources, such as oil or coal, or by minerals, such as copper or phosphorous. The important features of these resources are that they are considered exhaustible and taken from a finite stock S_0. Time t is also involved in the production function to account for "exogenous technical progress", defined most generally as variations of output that are not attributable to variations of the factors of production.

The evolution of capital and population is similar to traditional growth theory, since net investment is equal to total production minus consumption, and population grows at an exogenous rate. Given this framework, the question addressed by both Solow and Stiglitz is to know whether certain intergenerational levels of consumption can be achieved or not, but they consider slightly different configurations of this problem.

Solow (1974b) studies the case of a constant population and a constant consumption per head across generations, which he links to the notion of justice in the work of John Rawls[5]. Then, 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. [...] On the other hand, if the average product of resources is bounded, then

[4] Still in the same issue, Dasgupta and Heal (1974) provided another important contribution, which leads some authors to speak of the Dasgupta-Heal-Solow-Stiglitz (DHSS) model. I do not consider the work of Dasgupta and Heal in the present paper for two reasons: first, they did not participate actively in the subsequent controversy with ecological economists; second, their model relies on a utilitarian norm of intergenerational distribution that would require to introduce additional formal aspects but would not contribute to better understanding the controversy.

[5] See Erreygers (2009) for a discussion of this aspect.

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, 34)

Here, Solow introduces the assumption of "unbounded resources productivity" which postulates that output is not absolutely limited by the flow of resources. As he acknowledges, this assumption is crucial if one looks for levels of consumption that can be maintained indefinitely, since otherwise consumption must necessarily decline at some point. Moreover, according to him, this justifies to use a Cobb-Douglas production function of the form:

$$Q = K^{\alpha} R^{\beta} L^{\gamma},\ \alpha + \beta + \gamma = 1 \tag{2}$$

In this case, it is the "substitutability" between aggregate capital and resources that ensures unbounded resources productivity[6]. Under these assumptions, Solow demonstrates that a strictly positive level of consumption can be maintained if and only if the output elasticity of capital is greater than that of resources[7]:

$$\alpha > \beta \tag{3}$$

The path that realises this constant consumption per head has monotonically increasing capital stock and decreasing resource flow. Therefore, the possibilities of substitution inherent to the Cobb-Douglas production function, and the assumption of unbounded resources productivity it encapsulates, play a central role in this result.

On his side, Stiglitz (1974) examines the case of a population growing at a constant rate n, with a Cobb-Douglas production function and exogenous technical progress at a constant rate λ, such that:

$$Q = e^{\lambda t} K^{\alpha} R^{\beta} L^{\gamma},\ \alpha + \beta + \gamma = 1 \tag{4}$$

In this framework, he shows that a constant consumption per head can be maintained

[6]Formally, this can be seen by rewriting the production function as: $\frac{Q}{R} = (\frac{K}{R})^{\alpha}(\frac{L}{R})^{\gamma}$. Under this form, if R and L are constant, the productivity of resources on the left may be as big as one wishes, provided K is sufficiently great.

[7]Solow's demonstration relies on the minimisation of $\int_0^{\infty} R(t)dt$ under the constraint of the equation governing capital accumulation $\dot{K} = Q - C$. This minimisation yields a second equation of evolution involving the marginal productivities of resources and capital, F_R and F_K:

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

Together, these two relations form a differential system whose solutions describe the dynamics of an hypothetical economy. Solow shows that there exists a path that consumes less than the total stock of resources if and only if inequality (3) is satisfied.

if and only if[8]:

$$n < \frac{\lambda}{\beta} \tag{5}$$

This condition is interpreted as the need for "resource augmenting technical progress" to be greater than the rate of demographic growth[9]. Rather than capital substituting to resources, it is now technical progress that plays the central role in compensating the decreasing flow of resources. But this is just an other way of ensuring the same assumption of unbounded resources productivity[10].

Hence, unbounded resources productivity, under the form of technical progress or substitutability, is crucial to overcome the scarcity of resources in these models. As Stiglitz himself summarises :

> 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. With technical change, at any positive rate, we can easily find paths along which aggregate output does not decline. (Stiglitz 1974, 130-131)

2.2. *A Model-Based Methodology*

The work of Solow and Stiglitz gave to neoclassical resources economics its most important features. A whole literature was built on this framework, to which Solow and Stiglitz made other important contributions[11]. Along this trend, the assumption of unbounded resources productivity, and the notions of substitution and technical progress, kept a central role. I investigate here the foundations of this assumption and the representation of production it relies on.

For this purpose, it is necessary to understand how substitution and technical progress, which are used to describe and legitimate this assumption, are conceived in neoclassical resources economics. In analytical contributions (Solow 1974b; Stiglitz 1974), these notions primarily appear as mathematical properties of production func-

[8]Stiglitz's equations of evolution are similar to that obtained by Solow, except that they introduce constant growth rates of technical progress and population. In fact, Stiglitz establishes a more general condition for aggregate consumption to grow at a constant rate g:

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

Setting $g = n$ in this inequality yields condition (5).

[9]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, which justifies the label "resource augmenting technical progress".

[10]In the second part of the same paper, Stiglitz studies another model based on a similar framework but using a utilitarian norm of intergenerational distribution, which consists in maximising the sum of discounted utilities across generations. Once again, technical progress plays a central role in escaping the scarcity of resources in this model, since the asymptotic growth rate of consumption per head is positive if and only if resource augmenting technical progress is greater than the discount rate.

[11]Stiglitz (1976) concentrated on the implications of competitive markets and alternative institutional structures on the allocation of resources. Solow and Wan (1976) explored an elaborated version of the growth model with extraction costs of the resource, and Solow (1978) analysed data on the price and the availability of resources.

tions. On the one hand, substitution describes the possibility of increasing the productivity of resources $\frac{Q}{R}$ by increasing the level of capital K. On the other hand, technical progress is concentrated in the multiplier $e^{\lambda t}$, its determinants are not specified and it is assumed to be independent of the factors of production. This endows them with well identified mathematical meanings.

However, these mathematical meanings do not give any conceptual substance to these notions. In fact, there are very few conceptual elaborations of them in the work of Solow and Stiglitz, most of which can be found in interpretative essays where these notions are described in more concrete terms (Solow 1974a; Stiglitz 1979). In this part of the literature, three different mechanisms can be identified to illustrate the notion of substitutability. First, substitution may occur between resources, for instance from oil to coal thanks to coal-liquefaction technology (Solow 1974a, 5), or from fossil fuels to "backstop technologies", such as nuclear fusion or solar energy (Solow 1974a, 11). Second, substitution can mean a change in the composition of output toward less resource-intensive goods (Solow 1978, 6). And finally, it can denote a transformation of the production process toward fuel-saving technologies (Solow 1978, 6).

The problem with these different definitions of substitution is that none of them is adequately represented by the model. Indeed, the first one is rather substitution between resources than substitution between capital and resources, but there is no variable in the model describing an alternative resource that would substitute to the exhaustible one. The second definition in turn relies on a substitution between produced goods which cannot be represented explicitly in the model because only an aggregate output is displayed. And similarly, the third one is rather substitution between different kinds of capital, whereas only an aggregate capital variable appears in the model. The fundamental issue here is that, in all these definitions, the concept of substitution relies on underlying mechanisms that are not represented explicitly in the model. This creates an important discrepancy between its conceptual meaning and its mathematical representation.

Moreover, it also blurs the true significance of the concept and in particular its distinction with the notion of technical progress. Indeed, the main illustration of technical progress in the literature is that of "natural-resource-saving technical progress" (Solow 1974a, 10), which seems very close to the third definition of substitution above. This shows that substitution and technical progress conceptually overlap and cannot be conceived in a strictly separated way, whereas this is what is done at the mathematical level where they appear as distinct and independent properties. Once again, this reveals an inconsistency between the conceptual and the mathematical levels, or between the theory and the model.

My suggestion is that this issue comes from a "model-based" methodology, by which I mean that the model precedes the conceptual structure of the theory. In this sense, the latter does not rely on a self-supporting understanding of the production process, and concepts are instead primarily forged as descriptions of the properties of the model. It is only in a second time, and in a very succinct way, that Solow and Stiglitz try to describe them in more concrete terms, which reveal that these concepts rely on mechanisms that are not explicitly represented in the model and that they tend to overlap. The underlying issue is to know how concepts that primarily arise from a model can make sense *outside of the model* and give rise to a consistent understanding of production.

In order to characterise more accurately what I mean, it may be useful to contrast this situation with the analysis of modelling practices in economic philosophy. Among the epistemic functions of models identified by Morgan (2008), the one that seems most closely related to the present subject is "modelling as theorising". In this approach, whose first methodological account is attributed to Tjalling Koopmans, models are considered useful to derive logical implications from a set of initial postulates, whose combined effect would otherwise not be self-evident. Implicitly, this presupposes that the conceptual structure of the theory, in which postulates are first formulated, pre-exists to its formalisation in a model, which is only intended to articulate it more rigorously. Conversely, in the approach of Solow and Stiglitz, the representation of substitution and technical progress in production functions is anterior to their proper conceptualisation.

The notion of "representation" provides another interesting way to investigate further the issues raised by the relations between conceptual and mathematical levels. Among other conceptions, the "structuralist" approach holds that "the structure specified by a model represents its target system if it is either structurally isomorphic or somehow similar to it" (Morgan and Knuuttila 2012, 69). Comparing this position with the way Solow and Stiglitz deal with substitution and technical progress, we may say that there is no structural consistency between their conceptual and mathematical accounts of these notions. In particular, the underlying mechanisms of substitution *among* resources, capital equipment or produced goods are not explicit in their models. Instead, the models represent substitution as a relation *between* capital and resources, which appears structurally inconsistent[12].

As the assumption of "unbounded resources productivity" is incorporated in the model either under the form of technical progress or substitution, it inherits these issues. More precisely, good definitions of these concepts are a necessary condition to make sense of this assumption, but not a sufficient one. Even if we agree that the mechanisms encompassed by these concepts allow for the rise of the productivity of resources, this rise could be limited. Hence, in order to appreciate the potential magnitude of their effects and assess the relevance of the assumption of unbounded resources productivity, we need accurate conceptual definitions.

Since the models appear to be the source of the concepts, and not the converse, it is important to understand the other reasons that determine the choice of the models of production used in neoclassical resources economics. The most interesting contribution in this respect is certainly that of Stiglitz (1979), who proposes a reflexive account of the foundations of neoclassical resources economics.

The first set of justifications of this approach relies on the empirical relevance of the production functions they use. On this point, Solow and Stiglitz generally refer to the estimates performed by Nordhaus and Tobin (1972) on constant elasticity of substitution (CES) production functions. These suggest elasticities greater than one and interpret it as a demonstration of the important possibilities of substitution between capital and resources[13]. However, Stiglitz acknowledges that "the crucial question is what is to be taken as a constant" and he concedes that "resource pessimists" could oppose that

[12]Of course, this is only a problem if the theory aims at representing the world, or at least a certain conceptual picture of the world. Following Mäki (2012), we may characterise this prerequisite as "minimally realist". If instead a purely "instrumentalist" approach constituted the underlying methodology, this structural inconsistency would not as important. But, precisely, because Solow and Stiglitz attempt in a few places to make sense of substitution and technical progress as descriptive concepts of the actual world, we may assume that this is not their position. Instead, they seem to think that their representation of production can be considered as a sufficiently good one according to some commonsense experience of the world. Hence, the issue of structural consistency seems relevant in this conception of economics as a "science of commonsensibles" (Mäki 2012).

[13]The elasticity of substitution between factors x and y of a production function $F(x, y)$ is defined as $\sigma = \frac{d \ln y/x}{d \ln F_x/F_y}$. CES production functions are of the form:

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

The Cobb-Douglas is a special case of this family of functions, when the elasticity of substitution is unitary:

"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" (44-45). To solve this problem, Stiglitz suggests to allow the elasticity to vary and test the assumption that it is constant. However, 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 a decreasing flow of resources. Hence, empirical estimates cannot provide satisfactory justifications of production functions, at least for long term purposes, and instead must ultimately rely on theoretical justifications.

This leads to another set of justifications which imply mathematical concerns. It is illustrated by Solow's claim to have an "interesting and substantial" problem whose solutions are not trivial and offer some ground for mathematical investigations (1974b, 34). This approach is also endorsed by Stiglitz (1979, 44) when he insists on the distinction between "analytical methods" and "simulations". The former looks for the conditions which determine different answers to the problem, as when neoclassical resources economists set forth conditions (3) and (5). The latter instead gives *numerical* solutions for different "scenarios" characterised by some values of the parameters, as done in the report on *The Limits to Growth* (Meadows et al. 1972). Stiglitz defends the superiority of analytical methods because they enable to identify the exact frontier separating different behaviours of the model, while simulations only answer the problem for specific values of the parameters. However, analytical methods can only apply to relatively simple models. The analytical resolution or the qualitative analysis of differential systems is generally out of reach if the model is too complex. Good illustrations of this are Solow's repeated justifications that the Cobb-Douglas "[simplifies] the treatment of technical progress" (1974b, 34) or that "a complete analysis of [the implications of unlimited technical progress] would be laborious" (40). Along this line, the choice of the Cobb-Douglas production function is implicitly linked to the simplistic representation of production it provides[14].

Finally, another implicit, but obvious, motivation for choosing theses kinds of production functions is the continuity with the tools used in traditional neoclassical growth theory, which had become dominant in the 1960s (Boianovsky and Hoover 2009). However, it denotes at the same time the absence of a reflection on the specificity of natural resources as a factor of production. The symmetric character of the Cobb-Douglas production function puts capital, labour and resources on the same level. This also implies the transposition from the traditional theory of the concepts of "substitution" or "technical progress", without adapting it to the specificity of natural resources. Hence, no consideration on the nature of the production process and on the interrelation of resources and other factors appears as the root of this choice.

Altogether, this shows that in the "model-based" methodology of Solow and Stiglitz 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, and instead is determined by modelling practices and mathematical concerns.

$\sigma = 1$. 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 possible to maintain a constant level of consumption across generations. Conversely, if $0 < \sigma < 1$, then resources are essential, but the productivity of resources is bounded and no constant level of consumption can be maintained indefinitely.

[14] Halsmayer (2014) shows that the simplicity of Solow's growth model was acknowledged by himself and conceived as an alternative to complex models, such as Leontief's input-output tables or Keynesian macro-econometric models. In this context, it was justified, on the one hand, as a "prototype" on which more refined models should be built, and, on the other hand, as a pedagogical tool in which elementary economic mechanisms could be explained transparently.

In this framework, the assumption of unbounded resources productivity should primarily be understood as a mathematical requirement without conceptual substance. The notions of technical progress and substitution used to support it are themselves first introduced as mathematical properties of production functions for which a conceptual elaboration consistent with their representation in the model is missing.

This is all the more important because Stiglitz himself sets the problem at a conceptual level when he 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, 47). Since he explicitly includes Georgescu-Roegen among those "resource pessimists", it is no surprise that the latter took up the challenge. The next section examines his own approach and his criticism of neoclassical resources economics.

3. Georgescu-Roegen and Thermodynamic Limits to Production

After dedicating his early academic career to analytical issues in neoclassical theories of consumption and production, Nicholas Georgescu-Roegen became increasingly disatisfied with this framework during the 1960s[15], which culminated with his book *The Entropy Law and The Economic Process* (1971). As this title suggests, Georgescu-Roegen advocates, among other things, to account for thermodynamic laws in economic theory[16], and it is on this basis that he later criticised neoclassical resources economics.

3.1. *Thermodynamics and the Economic Process*

Thermodynamics can be broadly defined as the science of the transformations of energy, and rests on two main principles[17]. The first principle states the "energy" of an isolated system can change its form but its quantity is conserved. Georgescu-Roegen (1971, 5) illustrates this principle with the functioning of a "railway engine", where the chemical energy of coal is first transformed in thermal energy (heat) at high temperature and then in mechanical energy (movement) plus thermal energy at low temperature, but the total amount of energy is constant across the process.

The second principle of thermodynamics specifies what are the possible transformations between the different forms of energy. It stems from the work on thermal engines of Sadi Carnot in 1824, later reformulated in the formalism of energy by Rudolf Clausius. Carnot's main achievement was to prove that the efficiency of a thermal engine, such as the one used in the railway example above, has a theoretical maximum. This result means that a given amount of thermal energy cannot be fully transformed into mechanical energy[18], whereas the opposite is possible by friction. This is why Georgescu-Roegen

[15]The transition is well illustrated by his book *Analytical Economics* (1966), which contains both his most important contributions to neoclassical theory, and an introduction to his new research program. However, historical accounts of the evolution of Georgescu-Roegen's thought underline that he has had a critical look on the foundations of neoclassical theory since the beginning of his career (Gowdy and Mesner 1998). Moreover, this trajectory is best understood under the light of the influence that Joseph Schumpeter had on him (Bobulescu 2012).

[16]This idea had had precursors before Georgescu-Roegen, such as Sergeï Podolinsky and Frederick Soddy, but they are less well known and himself seemed not to be aware of them when he first suggested it. See Martinez-Alier (1987) for an account of these antecedents.

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

[18]More precisely, if the source of the heat flow Q_1 is at temperature T_1, if it is in an environment at temperature

distinguishes "available energy" that can be transformed into mechanical work from "latent energy" that cannot. According to this distinction, Carnot's principle implies that "[available] energy always dissipates by itself (and without any loss) into latent energy", which is considered as a "qualitative degradation of energy" (1971, 129). For instance, when mechanical work is transformed into heat at atmospheric temperature, it is lost forever and cannot be recovered.

This statement can be reformulated using the concept of "entropy", which achieves an "analytical simplification and unification". However, Georgescu-Roegen never formally defines entropy, which he considers to be unnecessarily technical, and prefers the literal definition as "an index of the relative amount of [latent] energy in an isolated structure" (1971, 5)[19]. This is why the second principle of thermodynamics is also known as the entropy law, which states that the entropy of an isolated system increases toward a maximum.

These two laws are primarily concerned with the properties of energy. However, Georgescu-Roegen considers that they are also relevant for matter. Regarding the first law, this simply leads him to interpret it more broadly as the conservation of energy and matter, *separately* (1971, 5). But he also suggests that matter is subject to a qualitative degradation equivalent to that of energy[20]. Hence, according to him, conservation and degradation are characteristics of both energy and matter.

These laws are central in Georgescu-Roegen's understanding of the economic process, which he describes as "a continuous transformation of low entropy into high entropy, that is, into *irrevocable waste*" (1971, 281, italics in the original). As a consequence, the entropy law is considered as the physical principal underpinning the depletion of natural resources. For Georgescu-Roegen, this is true for energy resources, such as coal or solar energy, but also for minerals, such as copper. This leads him to underline the radical scarcity that governs these resources 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*" (1971, 278, italics in the original).

With this perspective, Georgescu-Roegen has been an important contributor of the renewed interest for natural resources issues in economics in the 1970s. However, *The Entropy Law and the Economic Process* didn't reach a large audience and he had to wait the debate on the limits to growth to find a more favourable context.

3.2. *Georgescu-Roegen's Criticism of Neoclassical Resources Economics*

When the debate started, Georgescu-Roegen offered his help to answer the criticisms addressed by economists to the report (Levallois 2010). This led to his paper "Energy and Economic Myths" (1975) and was an opportunity to promote his own paradigm.

In this paper, after recalling his thermodynamic approach of the economic process, Georgescu-Roegen suggests to distinguish between "available" and "accessible" energy.

$T_0 < T_1$, and if W is the amount of work produced, then the efficiency of the engine $\eta = \frac{W}{Q_1}$ is bounded by Carnot's coefficient:

$$\eta_m = \frac{T_1 - T_0}{T_1} < 1$$

[19] See for example Poirier (2014) for a more complete introduction to this concept.

[20] On this topic, Georgescu-Roegen went from believing that the dissipation of matter is a direct consequence of the entropy law, to the idea that it has been ignored by thermodynamics and deserves the status of a fourth law. This has become one of his most controversial claim and it has raised many comments in ecological economics. See for instance Cleveland and Ruth (1997), or Ayres (1999).

He notes that extracting available energy from its deposit, for example in oil wells, and making it properly useful, implies to spend some energy to extract, transport or refine the resource. If the energy spent in this process is less than the energy obtained then the resource is said to be accessible, otherwise, the deposit is not energetically profitable. In this context, he calls “efficiency” the ratio of the energy extracted over the energy 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, 355)

This statement is the first occurrence of the idea of thermodynamic limits in Georgescu-Roegen’s work. It clearly refers to Carnot’s maximum efficiency of thermal engines, which is presented as the typical kind of limits that thermodynamics may impose on production processes, and in particular here on energy extraction. But Georgescu-Roegen goes further and suggests that Carnot’s coefficient implies thermodynamic limits to technical progress in general:

> 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, 362)

This proposition can be interpreted as the idea that the production of any economic good or service requires a theoretical minimum consumption of energy. At that time, this idea is presented as a general counter-argument to the technological optimism of the economists that criticise the report *The Limits to Growth*. Georgescu-Roegen notices in particular that “in Solow’s hands, substitution becomes the key factor that supports technological progress even as resources become increasingly scarce” (1975, 362). But the analytical framework of neoclassical resources economics and the assumption of “unbounded resources productivity” are not discussed in details.

The relation becomes more direct in 1979, when Georgescu-Roegen formulates a criticism of the work of Solow and Stiglitz, and especially of the analytical representation of production on which it rests[22]. Focusing on the assumption of unbounded resources productivity incorporated in the Cobb-Douglas production function, he puts forward different arguments against it, which I critically examine here.

First, Georgescu-Roegen underlines that “the increase of capital implies an additional depletion of resources” and suggests that if capital increases toward infinity, then “[resources] will rapidly be exhausted by the production of capital” (1979, 97). However, Solow’s and Stiglitz’s works are consistent with the premise that the production of capital depletes resources. In their models, the increment of capital at every time is taken on the aggregate product, itself produced thanks to resources. This does not prevent capital from increasing to infinity in Solow’s model, precisely because the productivity of resources increases faster and enables the flow of resources to decrease toward zero. Hence, this model is consistent from the mathematical point of view, and Georgescu-Roegen’s first argument by itself is not sufficient.

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

[22] Georgescu-Roegen’s criticism concerns other aspects of neoclassical resources economics as well. For instance, he denies that the appropriate intergenerational distribution may be achieved by market processes alone or questions the relevance of empirical estimates of production functions. However, these topics have not been tackled in the 1997 debate, and therefore are less interesting to understand the opposition between ecological economists and neoclassical resources economists.

This leads to the second argument, according to which “any material process consists in the transformation of some materials into others (the flow elements) by some agents (the fund elements)”. The distinction between flows and funds in this statement suggests a difference of nature between the different factors of production[23]. While natural resources are transformed in the process of production, capital and labour are agents of this transformation. In this framework, the notion of substitution appears misleading in the sense that capital cannot play the same role as resources in production. According to Georgescu-Roegen, “a change in capital or labor can only diminish the amount of waste in the production of a commodity” (1979, 97). However, this truly represents a limit only for material requirements, and if it is assumed that goods remain qualitatively identical.

In order to generalise his argument beyond this restricted case, Georgescu-Roegen rests once again on the idea of a limit to the productivity of resources:

> 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, 97-98, I emphasise)

This idea appears to be the true logical foundation of Georgescu-Roegen’s criticism. Without it, the assertion that the increase of capital to infinity implies the exhaustion of resources is not justified. However, compared to the initial statement in 1975, which focused on energy, this time Georgescu-Roegen suggests that this kind of limit applies to both energy and matter. Once again, the underlying idea is that the laws of thermodynamics set constraints on the use of natural resources[24].

3.3. *Interdisciplinary Consistency*

From the various contributions of Georgescu-Roegen examined above, there emerges an assumption of thermodynamic limits to the productivity of resources. It appears as the logical foundation of his criticism of the assumption of unbounded resources productivity and his most consistent theoretical answer to the challenge addressed by Stiglitz to “resource pessimists” (1979, 47). In order to better understand the nature of this opposition, it is worth examining the methodological foundations underpinning this assumption.

Missemer (2013, 19) has already insisted on the idea that the choice of scientific referents exterior to economics, such as thermodynamics or biology, is one pillar of Georgescu-Roegen’s methodology. He underlines that the goal is not to bring formal analogies from one discipline to the other, but to capture some essential properties of the objects under study thanks to the existing body of knowledge. If we refer to the taxonomy of disciplinary exchanges established by Klein (2010), this corresponds to the idea of “theoretical interdisciplinarity”, in the sense that it implies strong interactions

[23] This distinction is the cornerstone of Georgescu-Roegen’s theory of production, known as the flow-fund model and formulated as a criticism of both neoclassical production functions and Leontief’s input-output tables (1971, chap. IX). However, apart from the succinct argument above, this alternative model is not mobilised, either by Georgescu-Roegen or other ecological economists, to formulate more analytically their criticism of neoclassical resources economics.

[24] Georgescu-Roegen’s later contributions 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), but the assumption of thermodynamic limits is not even mentioned any more. Moreover, neither Georgescu-Roegen’s nor Solow’s archives contain correspondence related to these issues.

between disciplines in order to build new conceptual foundations[25].

An important additional aspect of the interaction between thermodynamics and economics in Georgescu-Roegen's approach is that it goes one way: thermodynamics is used as a source of conceptual inspiration in order to reform the foundations of economics. The implicit idea behind this kind of interdisciplinarity is that thermodynamics is a mature and reliable science, whereas economics is an unsatisfying intellectual edifice. The former in particular is well illustrated by Georgescu-Roegen's reference to Sir Arthur Eddington, a physicist and philosopher of science, who considers that the entropy law occupies "the supreme position among the laws of nature", and that if a theory is not consistent with it, "there is nothing for it but to collapse in deepest humiliation" (Eddington 1928, quoted in Georgescu-Roegen [1982] 2011, 197). This is why I suggest to speak of "interdisciplinary consistency" to describe Georgescu-Roegen's methodology, because it implies an asymmetrical relationship in which economics is required to become consistent with the laws of thermodynamics.

Of course these characteristics of Georgescu-Roegen's methodology make sense only if we also presuppose an other implicit condition, which is more of an ontological nature: both disciplines share, at least partially, an interest into the *same objects*. In the present case, this requirement is supported by the idea that economics should deal with the physical facet of economic activities, and more precisely with the role of energy and matter. If this idea is accepted, then, since thermodynamics is one of the branches of physics concerned with the transformations of energy and matter, economics should account for its relevant theoretical consequences.

Therefore, we may summarise the features of Georgescu-Roegen's methodology as follows: sameness of object; reliability of the scientific referent; and conceptual integration. This approach in turn appears quite antithetical with respect to the model-based methodology of Solow and Stiglitz. It insists on the necessity to understand first the physical features that characterise the production process, in order to build conceptual and analytical tools that are consistent with this view. Hence, behind the theoretical opposition between the assumptions of unbounded resources productivity and thermodynamic limits to production, there is an important methodological opposition.

Moreover, these methodological insights are also useful to point out the issues that Georgescu-Roegen's approach faces. Starting with the question of the sameness of objects, we may notice that Georgescu-Roegen's focus on the physical aspects of the economic process, even though it is not unfamiliar in the history of economic thought, is considerably original and not easily acceptable for most economists. While classical economists, such as Ricardo, Malthus and Marx, were interested in the material aspects related to agriculture and other natural resources issues (Belloc et al. 2008), the marginalist revolution has been identified with a trend of "dematerialisation" in economic theory (Pottier 2014). The figure of Stanley Jevons is particularly interesting. While his book *The Coal Question* warned about the consequences of coal depletion on the economic supremacy of Great Britain, natural resources were absent of his contribution to the foundations of neoclassical theory. Moreover, even when some neoclassi-

[25]This taxonomy distinguishes first between "multidisplinarity", as a mere juxtaposition of analysis on the same problem from separated disciplines, and "interdisciplinarity", which implies that some kind of interactions transform one or more of the disciplines. Then, "theoretical interdisciplinarity" as above is distinguished from "methodological interdisciplinarity", involving only the transfer of methods or tools from one discipline to another.

Moreover, theoretical interdisciplinarity is more explicitly endorsed by recent contributions dealing with the philosophical foundations of ecological economics (Baumgärtner et al. 2008; Spash 2012), where it appears tightly linked with the influence of Georgescu-Roegen on this school.

cal economists were interested in resources, their perspective has been "reductionist" (Missemer 2017). They analysed them only as a specific isolated market on which to apply neoclassical tools, not as a fundamental factor of production with potentially important consequences on growth. In this context, Georgescu-Roegen's insistence on the role of energy and matter in the economic process, and as a result the necessity to account for the laws of thermodynamics in economic theory, appears as a radical divergence with the implicit ontology that dominates economics at the time[26]. However, this does not characterise an internal issue inherent to his approach, but rather a strong disagreement with the rest of the economic community.

Conversely, the way Georgescu-Roegen interprets the laws of thermodynamics reveals shortcomings that are proper to his perspective. First, in his original mention of the idea of thermodynamic limits, he relates it to Carnot's maximum efficiency of thermal engines. When doing so, he considers the process of extracting energy resources from their deposit. But this process is very different from that of a thermal engine, where the mechanical energy produced is a direct transformation of the thermal energy. In energy production, the resource extracted, oil for instance, is not a transformation of the energy spent, which is only used to build and run the infrastructures that will extract the former from a pre-existing deposit. Therefore, Carnot's principle cannot be straightforwardly applied in this context, and the proposition would at least need some more arguments to be convincing.

Second, Georgescu-Roegen's various presentations of the idea of thermodynamic limits reveal an ambiguity on which entities and which laws should be considered. The first mention in 1975 focuses on energy and attributes the limits to Carnot's principle, that is to the second law of thermodynamics. But in 1979, both matter and energy requirements for production are assumed to have a lower limit, and there is no explicit reference to a particular law of thermodynamics. This shows that thermodynamics, as reliable a scientific referent as it may be, needs to be interpreted in order to be incorporated in economics. This in turn needs some accurate analysis of what exactly is relevant for this purpose, an issue on which Georgescu-Roegen is not sufficiently clear.

Finally, whatever the laws of thermodynamics supporting the idea of limit, the conceptual integration, inherent to Georgescu-Roegen's methodology of interdisciplinary consistency, would require a detailed examination of the relations between thermodynamic and economic concepts. This is particularly obvious in 1975, when Carnot's maximum efficiency is assumed to set a general limit to "technological progress". But it is also perceptible in the statement of 1979, where the limit applies to the "services" that can be provided by material and energy flows. In both cases, the idea of limit involves a mix of thermodynamic and economic concepts, whose relations have not been comprehensively investigated. In this context, thermodynamic limits to the productivity of resources appear rather as an intuition asking for more elaborate developments.

4. The Direct Confrontation between Paradigms

In 1997, an issue of the journal *Ecological Economics* was dedicated to Georgescu-Roegen, who had died three years before. On this occasion, Herman Daly revived his

[26]Of course, Georgescu-Roegen's paradigm emerges in a rather favourable social context, marked by the rise of environmental preoccupations, oil shocks that question the dependence of the economy to energy, and intellectual debates such as the one triggered by the report *The Limits to Growth*. But as it appears from Solow's work for instance, this is not interpreted as the necessity for economists to revise the conceptual foundations of their theory, but rather to consider these issues from the point of view of their pre-established theory.

criticism of neoclassical resources economics with a paper called "Georgescu-Roegen versus Solow/Stiglitz" (1997a), and focused the debate on the assumption of "thermodynamic limits" to production as a counterargument to "unbounded resources productivity". In their replies, Solow and Stiglitz defended the assumption of unbounded resources productivity (Solow 1997; Stiglitz 1997), while comments from other ecological or neoclassical resources economists varied from some clearly siding with Daly's and Georgescu-Roegen's arguments (Clark; Common; Opschoor; Peet; Tisdell), to some proposing a more nuanced opinion (Ayres; Pearce; Castle), and others denouncing the polemical tone and advocating more open-mindedness (Turner; Perrings). This debate remains one of the few direct confrontations between these two paradigms and shows the importance of the issues at stake to understand this opposition. As a result, it appears as a landmark in the related literature, which very often refers to it, but a comprehensive account of the issues raised by the controversy is missing. This is the reason why it appeared necessary to examine the original works on which the debate is built, in order to apprehend what remains the same and what changes between the two periods.

Before proceeding with this investigation, it is important to notice that the debate of 1997 happened in a new intellectual context, that crystallised around the concept of "sustainability". 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), the idea of sustainable development had become central for environmental issues in the early 1990s. In economics, it became the new battleground of neoclassical resources economists and ecological economists, which provided two opposing interpretations of sustainability. On the one hand, "weak sustainability" argued for the possibility of substituting man-made capital to natural capital as it is depleted. Solow (1993) was an important and early contributor of this approach, which appears as an extension of the concept of substitution as developed in growth models with exhaustible resources[27]. On the other hand, ecological economists, especially Daly (1990), supported the idea of "strong sustainability", according to which, there are limits to substitution of man-made capital to natural capital and specific natural life supporting functions must be preserved. This opposition has framed the debates on environmental issues until nowadays, each side promoting its own empirical indicators of sustainable development and policy recommendations (Pezzey and Toman 2005; Neumayer 2013). Hence, the controversy at stake here offers the opportunity of exploring some of its foundations.

4.1. *Time Horizon of Models and the Laws of Thermodynamics*

The first question raised by the debate concerns the relevant interpretation of the time horizon of models. It is triggered by Stiglitz's assertion that their models are only meaningful "for the intermediate run", that is "for the next 50 − 60 years", and that they are written "as if they extend out to infinity, but no one takes these limits seriously" (1997, 269). This argument is discussed by a number of comments in the debate, which strongly deny its relevance (Daly; Clark; Opschoor; Tisdell). They consider that this 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* interpretation put forward to avoid criticisms and that it had

[27]This use of the concept of substitution is an extension because it concerns natural capital as a whole, which is broader than natural resources since it includes various other life supporting functions, such as climate stability or ecosystems.

never been formulated before.

Even though no one noticed it in the debate, this last opinion is vindicated by the fact that Solow and Stiglitz have supported quite opposite positions on this topic. Indeed, Stiglitz notices that "an exponential increase in the population presents almost unimaginable problems of congestion on our limited planet" (1997, 269), as a justification for his medium run interpretation of the time horizon of models. On the other hand, Solow had asserted that "on a time-scale appropriate to finite resources [...] exponential growth of population is an inappropriate idealization" (1974b, 36), which implicitly suggests a long run interpretation. Hence, similarly to what has been identified in the case of "substitution" and "technical progress" in section 2, this shows that there is no proper conceptualisation of the role of time in these models. Time is first and for all a mathematical variable, whose meaning outside of the models is not stabilised. The multiple interpretations that arise, and vary across time, happen to be in contradiction with each other and at odd with the basic features of the models.

Reciprocally, the interpretation of the entropy law and the relevant time horizon to apprehend its consequences are questioned by neoclassical resources economists. For instance, Solow suggests that it is "of no immediate practical importance for modelling what is, after all, a brief instant of time in a small corner of the universe" (1997, 268), an assertion that had already been supported before by Stiglitz (1979, 37). This shows that both interpret the entropy law only as a long term and global driving force of the physical world, with no signification for economic activities. This point of view is criticised by Daly, who underlines the practical consequences of the entropy law, for instance "that you can't burn the same lump of coal twice", or "that there are limits to the efficiency of conversion of energy" (1997b, 273).

In fact, both aspects are constitutive of the entropy law[28]. 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. In an interdisciplinary perspective, this duality becomes confusing as different authors privilege one interpretation or the other. However, these two interpretations are not contradictory and the implications of physical laws both at the practical and at the cosmological levels are common in physics[29]. Therefore, invoking the long term signification of the entropy law cannot by itself justify to put aside more immediate consequences for economic activities.

These immediate consequences are precisely at stake in the confrontation between the assumptions of "unbounded resources productivity" and "thermodynamic limits", which is the central subject of the debate. Relying on Georgescu-Roegen's 1979 criticism, Daly presents the issue as follows:

> In the Solow-Stiglitz variant [of production function], 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, 263)

Here, Daly's interpretation of Georgescu-Roegen has two important implications. First, it focuses on the first law of thermodynamics rather than the entropy law. Second,

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[28]Even Solow (1974a, 2) wrote once that the laws of thermodynamics constrain possibilities of recycling. Georgescu-Roegen in turn made statements that supported either the long term cosmological interpretation (1971, 19, 231) or the practical economical consequences (1971, 6, 278).

[29]The laws of mechanics, for instance, apply to the movements of planets as well as when one plays basketball.

it interprets this law as the conservation of mass, and therefore reduces the debate to the role of matter in production rather than energy. According to this perspective, thermodynamic limits rest on the fact that the mass of matter that goes out of the production process, under the form of commodities or waste, is equal to the input of matter at the entrance of the production process. Hence the mass of input matter is necessarily greater or equal to the mass of output commodities, and this defines the minimum requirement of matter.

If we consider the historical account of the idea of thermodynamic limits in Georgescu-Roegen's work, as presented in section 3, this interpretation appears as a complete reversal. Indeed, the original statements in 1975 clearly referred to Carnot's coefficient of maximum efficiency, that is rather to the question of energy and the entropy law. Even in the 1979 paper, which is the main source of Daly, Georgescu-Roegen mentioned both matter and energy, without precision on the laws involved, so that this interpretation is at least reductionist. This outcome in turn is partially explained by the fact that Georgescu-Roegen's own interpretation of the practical consequences of the laws of thermodynamics was not sufficiently clear. As a result, most subsequent work that investigated further the idea of thermodynamic limits to production and tried to put it on a more analytical level seem to have followed Daly's interpretation (van den Bergh 1999; Baumgärtner 2004)[30]. The only author that adopted a more general interpretation and tried to include both energy and matter conservation, as well as the entropy law, in a formal model seems to be Krysiak (2006).

4.2. *Thermodynamics, Economics, and their Conceptual Integration*

However, even this last perspective is not satisfying because it misses another important aspect of the controversy: the necessity of conceptual integration inherent to Georgescu-Roegen's methodology of interdisciplinary consistency. In the debate of 1997, this issue is raised again in relation with the question of the relevant units for measuring production. Indeed, Daly's criticism is based on the idea that "even production functions that yield services are producing a physical output - the use of something or somebody for some period of time" (1997a, 264), to which Stiglitz replies that "output is measured not in physical units, but in the value of the services associated with it" (1997, 269)[31]. Moreover, even some ecological economists are sceptical about Daly's assertion. Ayres for instance admits that "human welfare is attributable in the final analysis to non-material services" that have "a material base", but he denies 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" (1997, 286)[32].

From this point of view, the attempts to incorporate thermodynamic laws in economic models and criticise the assumptions of neoclassical resources economics on this ground (Baumgärtner 2004; Krysiak 2006) tend to hide the issue by simply considering that produced commodities are measured according to their mass and energy content. Conservation laws lead to inequalities of the form $Q \leq R$, which are interpreted as

[30]In fact, the integration of mass conservation in a production function in order to question the relevance of the representation of production in neoclassical resources economics had been suggested before 1997 and goes back at least to Anderson (1987), who explicitly refers to Georgescu-Roegen's criticism.

[31]This question is not mentioned in the early works of Solow and Stiglitz on natural resources. I could only find an allusion in one of Solow's original paper on growth theory, where he states that "Q represents output and K and L represent capital and labor inputs in 'physical' units" (1957, 312), which shows at least that the appropriate units for production is uncertain.

[32]Following the same line, van den 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" (1999, 554).

incompatible with the assumption of unbounded resources productivity. But of course, this is not satisfying from an economic point of view as long as mass and energy units cannot be connected to some economic concepts such as services or values, which are swept out of the picture by these approaches.

This highlights that the necessity of conceptual integration, previously identified in Georgescu-Roegen's methodology of interdisciplinary consistency, still awaits a satisfying answer. Even though they do not completely solve this issue, contributions of ecological economists that care for economic concepts, such as Ayres above, help locating more accurately where the problem stands. They show that the notion of production itself has to be refined to be able to assess its dependence to natural resources. More precisely, the relations between material and energy resources, the goods they enable to produce, and the non-material services these provide, appear at the heart of the issue. In addition, the debate highlights that, since the idea of limits presupposes a quantitative relation, the units according to which concepts are measured matter. While thermodynamics relies on energy or mass units, production of goods and services have usually been associated with a value measure in economics, and it is necessary to articulate both together.

On the other side of the controversy, Solow and Stiglitz are also confronted with the same issues raised by their "model-based" methodology as they were in the 1970s, and in particular with that of making sense of "substitution" and "technical progress" outside of their models. For instance, Solow asserts that "the substitution between renewable and nonrenewable resources is the essence of the matter" (1997, 267), a question which is perceived as an important aspect of the debate by some ecological economists too (Clark 1997; Ayres 2007). However, the problem is that this interpretation of substitution is still not consistent with Solow's and Stiglitz's original models, where no such renewable resources come in to substitute to the exhaustible ones.

Stiglitz in turn suggests that the substitution between capital and resources is about "more precise machines (made out of resources that are relatively abundant) [that] can reduce wastage of resources that are relatively scarce". This shows that there is no agreement on what is the important feature behind the idea of substitution, and this interpretation too is hardly consistent with the models, whose aggregate variables do not enable to represent a change in the nature of capital goods. Moreover, substitution still overlaps with technical progress, which is defined by Stiglitz as enabling to "reduce the amounts of physical capital and resources required to produce the unit of output" (1997, 269). Hence, an overall confusion remains about the meaning of substitution and technical progress, and their relations with the corresponding properties in the models.

This is underlying Daly's criticism of the lack of "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)" (1997a, 264). This distinction aims at a more direct argument against unbounded resources productivity. It underlines that if the production function is supposed to represent actual possibilities of production, then the productivity is bounded because the set of technologies available at every time is necessarily limited. However, for Daly, Georgescu-Roegen's intuition of thermodynamic limits remains a relevant constraint for future technologies.

Unfortunately, Solow and Stiglitz have not considered this issue in their replies. However, we can analyse what this distinction would change in the conceptual issues they face. From this point of view, since technical progress depends on time in their models, it fits best with the idea of improved state of art. Conversely, substitution between capital and resources is independent of time in production functions, and therefore would correspond to the idea of an existing state of the art. Hence, this could improve the conceptual distinction between substitution and technical progress. But this would imply that neoclassical resources economists also accept Daly's proposition that the former cannot provide unbounded productivity of resources. Analytically, it means that at every given time the productivity of resources should be bounded from above, and therefore that the Cobb-Douglas structure is not satisfying. This would particularly affect the relevance of Solow's model. But a time-dependent factor of technical progress would be admissible, and Stiglitz's results could potentially be maintained with another production function because they mainly depend on this factor. However, this would not solve the whole debate, since the issue of whether technical progress enables to achieve unbounded resources productivity or is constrained by thermodynamic limits would remain.

The issues raised by this debate have later been well captured by Mayumi, Giampietro, and Gowdy (1998) and van den Bergh (1999). The latter in particular underlines that the use of aggregate variables in neoclassical models prevents from accounting more precisely of the possibilities of substitution. He suggests instead to distinguish direct substitution, between production factors "having the same function", from indirect substitution, between "multiple categories of production factors, which fulfill different, and often complementary, functions" (549). This distinction is used to provide a classification of the different substitutions that may affect the use of energy, materials, capital and labour in the economic process. It does not tell which are the more relevant *a priori*, but instead is presented as a conceptual framework for further empirical investigations of the issue.

Moreover, van den Bergh adequately acknowledges that focusing only on the physical dimension of the economic process does not solve the issue more than the conventional neoclassical approach. He underlines instead that "the interaction between physical and value dimensions, which is at the heart of the matter, is not really touched upon in either approach" (552). While this diagnostic is interesting, the answer he proposes seems less fruitful. Indeed, Van Den Bergh uses an aggregate model of production very similar to those of neoclassical economists, whose main innovation consists in introducing a "transformation function" between physical and value measures. Hence, the initial debate between unbounded resources productivity and thermodynamic limits is only reformulated under the question of whether this function can produce a constant or growing value with a decreasing physical flow going through the production process. With this question, most of the conceptual issues regarding the integration of economic and thermodynamic concepts remain.

5. Conclusion

The analysis above shows that between its two most active periods, in the 1970s and at the end of 1990s, the controversy between natural resources and ecological economics rested on the same theoretical and methodological oppositions, even though the more direct confrontation in the second phase unveils new features. The central theoretical problem is the conflict between the assumptions of "unbounded resources productivity" and "thermodynamic limits", which are associated with two different methodologies respectively characterised as "model-based" and "interdisciplinary consistency". Overall, the conclusion is that neither side has been able to provide a definitive proof of the validity of its own claim because both face important conceptual issues.

On the one hand, in Solow's and Stiglitz's works, the assumption of unbounded resources productivity rests on the concepts of "substitution" and "technical progress". But these concepts are first associated with mathematical properties of production functions, because, in the model-based methodology, the model precedes the conceptual structure of the theory. It is only at a second stage, and in a very succinct way, that Solow and Stiglitz relate substitution and technical progress to various mechanisms implying changes in the type of resource, capital or produced goods. But the issue is that these mechanisms are not explicitly represented in their models, and that, according to these definitions, substitution and technical progress tend to overlap. This reveals the difficulty for concepts that primarily arise from a model of making sense outside of the model. In this respect, the debate of 1997 brought forward the distinction between actual and improved state of the art, suggested by Daly, which may clarify some aspects of the question, at the price of forsaking the Cobb-Douglas function. But overall, the confusion surrounding those concepts lasted over time, leaving uncertain the relevance of the assumption 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. They insist on the necessity to account for thermodynamic constraints on the economic process, but they do not solve the conceptual issues that this involves. First, this approach presupposes a clear interpretation of thermodynamics and of which laws are relevant for this purpose. Georgescu-Roegen had not been clear about this issue and hinted to various possible interpretations, involving either matter or energy, and either the first or the second law of thermodynamics. In this context, Daly's interpretation that limits are set by the law of conservation of mass is at least reductionist, if not a complete reversal regarding Georgescu-Roegen's original reference to Carnot's principle, that is to energy and the second law. A more cautionary approach would be to considers all possible interpretations and examine their respective relevance. But this assessment in turn requires to consider a second issue, concerned with the conceptual integration between economic and thermodynamic concepts. While Georgescu-Roegen had left this question unanswered, the debate of 1997 underlines that the notion of production itself needs to be questioned, and in particular that the relations between natural resources, produced goods, and the non-material services they provide, are at the heart of the issue.

All along this controversy, the question of how models may appropriately represent theoretical concepts appears as a central preoccupation. In particular, the controversy raises many questions about production functions, some of which go beyond the case of exhaustible resources and reveal more general issues regarding the neoclassical theory of production. Paradoxically, ecological economists seem unable to escape from this analytical representation of production and do not provide a clear alternative to this model. By the end of his paper, Daly suggests that "Georgescu's fund-flow model of the production process is superior to the neoclassical production function" (1997a, 265), and Georgescu-Roegen himself had mentioned it in his criticism of neoclassical resources economics. But the relevance of the flow-fund model is never examined in more details, nor used to formalise the issues at stake.

This is all the more important because the issues underlying this controversy have perpetuated until nowadays through the opposition between "weak" and "strong" sustainability. In fact, the debate of 1997 happens at a moment were this new way of presenting the opposition has just crystallised and therefore is an important landmark in the confrontation between these two approaches. It underlines in particular the importance of theories and models of production for the analysis of sustainability, and the challenges that this represents for economic thought.

Acknowledgements

I would like to thank Robert Dimand, Christophe Goupil, Jérôme Lallement, Antoine Missemer, Antonin Pottier, and Fatma Rostom for helpful comments and suggestions on earlier versions of this paper. I am also grateful to the participants of the Albert O. Hirschman Seminar, the 2017 Max Weber Seminar, the 2018 Science and Energy Seminar, and the Young Scholars Seminar of the 2018 ESHET Conference.

Disclosure Statement

No potential conflict of interest was reported by the author.

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