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APRESENTAÇÃO

Um dos temas recentes que vem obtendo maior destaque no estudo da economia, principalmente entre aqueles que não seguem a corrente de pensamento dominante é a Economia Ecológica.

Estudos econômicos que incorporam em sua análise as questões do meio ambiente são de fundamental importância se um país pretende atingir um nível de crescimento alto e sustentável.

Os modelos convencionais equivocadamente, não se preocupam com questões ambientais e ecológicas. Além disso, os modelos que tratam de questões relacionadas ao meio ambiente e recursos naturais acabam sendo marginalizados e não fazem parte do núcleo duro da discussão acadêmica entre os principais economistas de grande universidades.

A falta de tratamento de questões ecológicas me parece ser uma falha na construção do conhecimento e da ciência econômica. Este livro é muito bem vindo, pois colabora com a discussão da economia e da incorporação do tema meio ambiente e ecologia nas decisões econômicas e nos estudos científicos.

Neste livro podemos encontrar diversos trabalhos que incorporam na discussão econômica os aspectos ecológicos e ambientais das decisões econômicas e trazem ao centro o debate sobre economia, o meio ambiente, e como as decisões econômicas podem afetá-lo hoje e no futuro. As formas de se cumprir esta tarefa são variadas, podemos citar os trabalho que tratam de índices de desenvolvimento sustentável ou ambiental, descrevendo sua evolução ao longo do tempo para o Brasil ou regiões. Tais índices também são analisados espacialmente, destacando a localização dos municípios conforme seu nível de desenvolvimento ambiental.

Os aspectos teóricos também fazem parte dos temas abordados neste livro, comparando os conceitos da economia neoclássica e economia ecológica ou ambiental e inserindo também discussões jurídicas que abordam este assunto. Portanto, este livro contribui imensamente com a discussão da economia ecológica e ambiental apresentando diversos trabalhos das mais variadas metodologias e objetivos de pesquisa. Propiciando ao seu leitor uma rica variedade de estudos que incorporam questões tão importantes como o meio ambiente, ecologia e recursos naturais aos estudos da ciência econômica.

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SUMÁRIO

CAPÍTULO 9

THE GEORGESCU-ROEGEN VERSUS SOLOW/ STIGLITZ FORUM AS THE EPITOME OF THE THERMODYNAMIC CRITICISM TO GROWTH THEORY

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ABSTRACT: This article seeks to shed light on the controversy between thermoeconomists and mainstream growth theorists, ongoing since the 1960s. It consists mainly in a theoretical objection to continued growth based on the laws of modern thermodynamics, put forward by Nicholas Georgescu-Roegen in his well-known book *The Entropy Law and The Economic Process*. It is argued that such developments can be fairly represented by an exchange of papers between Herman Daly, Robert Solow and Joseph Stiglitz, with contributions of several other authors, published in a 1997 special issue of the *Ecological Economics Journal* dedicated to the memory of Georgescu-Roegen. The article describes its main contents, especially those which can be historically related to the broader controversy. Among other issues, the debate focused on the substitutability between natural and man-made capital and the thermodynamic implications for practical economic purposes.
KEYWORDS: economic growth theory; thermoeconomics; Georgescu-Roegen; natural resources; entropy law.

RESUMO: O presente trabalho traz à tona a controvérsia entre termoeconomistas e teóricos neoclássicos do crescimento econômico, iniciada nos anos 1960. Tal controvérsia consistiu basicamente em uma objeção teórica à ideia de crescimento continuado, calcada nas leis da termodinâmica moderna, tal como exposto por Nicholas Georgescu-Roegen no seu renomado livro "A Lei da Entropia e o Processo Econômico". Defende-se que tais acontecimentos podem ser razoavelmente representados por uma troca de artigos ocorrida entre Herman Daly, Robert Solow e Joseph Stiglitz, com contribuições de inúmeros outros autores, publicada em 1997, em uma edição especial da revista *Ecological Economics* dedicada à memória de Georgescu-Roegen. Descreve-se seu conteúdo principal, focando nos elementos relacionados à controvérsia de um ponto de vista histórico. Entre outros aspectos, o debate abordou a substituibilidade entre capital natural e manufaturado e as implicações termodinâmicas aplicadas a propósitos econômicos na prática.
PALAVRAS-CHAVE: teorias do crescimento econômico; termoeconomia; Georgescu-Roegen; recursos naturais; lei da entropia.

1 | INTRODUCTION

Criticism to the idea of endless economic

growth has been present at least since the beginning of the eighteenth century and in different shapes and forms. Malthus' population problem, Liebig's agricultural crisis due to finite guano reserves, Soddy's discount rate issue and mainly the question of availability of energy and non-renewable resources brought by Podolinsky, Neurath, Clausius, Jevons, Henry Adams and others seem to be different approaches to the acknowledgment of a definite upper limit to the scale of economic activity.

In the 1970s, a reinvigorated environmentalist movement, the oil crisis and the appearance of well-known academic books such as Club of Rome's *Limits to Growth* (MEADOWS *et al*., 1972) and Rachel Carson's *Silent Spring* (CARSON, 1968) have been accompanied by the works of economists arguing that economic processes are also natural processes, comprised ultimately of biological, physical and chemical transformations. Backed by recent developments in general systems theory and the laws of modern thermodynamics, they have tried to restore focus on biophysical constraints to economic growth on a finite planet and on the role of flows and stocks of energy and matter in the life-supporting metabolic processes on earth (AYRES; KNEESE, 1969; BOULDING, 1966; DALY, 1968; GEORGESCU-ROEGEN, 1971). These and other economists sharing the same ideas have later been associated with the term "thermoeconomics" (or also biophysical economics), coined in the beginning of the '60s by the American engineer and thermodynamicist Myron Tribus (EL-SAYED, 2003).

Among these works, Georgescu-Roegen's book *The Entropy Law and The Economic Process* (1971) constitutes the landmark of a theoretical criticism to growth *ad infinitum* that has ever since gained a certain momentum and influenced several schools of economic thought, although not enough to produce meaningful changes to the standard theories of growth adopted by mainstream economists. Georgescu-Roegen's main assertion was that the latter had been ignoring the basic pillars of modern thermodynamics. The entropy law – formulated by Sadi Carnot back in 1850 – was a key issue as, according to Georgescu-Roegen (1971, p. 3), "the entropy law itself emerges as the most economic in nature of all natural laws". The fact that energy always gets deteriorated during physical transformations in closed systems (and therefore entropy always rises in closed systems) would imply that economic activity is bound to degenerate to levels compatible with a "solar budget", as the only thing keeping earth from being a closed system is the sun. Other implications are the irreversibility of time – something that mainstream economists have hardly taken into account – and the theoretical limits to the efficiency of recycling and to other technological innovations, as well as the economy's dependence on finite resource reserves such as fossil fuels or heavy metals.

The entropic argument has added strength to former criticisms against endless growth. Nevertheless, it can be distinguished as a specific form of theoretical objection to continued growth based on the laws of modern thermodynamics, a different approach to the energy accounting and balance arguments relied upon since mid-nineteenth

century, or to more recent studies based on computable economic-ecological systems dynamic modelling similar to the Club of Rome's approach. None of these views has been able to draw much attention from mainstream growth theorists, whose scarce comments and replies have been persistently related to technological optimism in one way or another, e.g. the possibility of perfect substitution between natural resources and other production factors.

This article seeks to shed light on the controversy between thermoeconomists and standard growth theorists, largely based on Georgescu-Roegen's 1971 *magnum opus*. In order to do that, it is argued that such developments can be fairly represented by the papers published in a 1997 special issue of the *Ecological Economics Journal* dedicated to the memory of Nicholas Georgescu-Roegen (G-R henceforth). Having G-R's disciple Herman Daly as guest editor, the issue brings a subsection entitled *Forum: Georgescu-Roegen versus Solow/Stiglitz*. It begins with a paper by Daly challenging standard growth theorists Robert Solow and Joseph Stiglitz, whom are given the opportunity to reply. The contents of this debate are further explored in eleven other articles – written by invited scholars with a background in thermoeconomics –, including another piece by Daly (according to the editorial, Solow and Stiglitz's responses seemed to be directed toward Daly and not G-R, what would earn him an opportunity to comment on these).

The following section describes the main contents of the mentioned forum, especially those which can be historically related to the broader controversy between mainstream and thermoeconomists, ongoing since the '60s. Having shown the essential points that enlighten and contextualize this specific debate as a good approximation of the thermodynamic criticism to growth theory, a few concluding remarks summarize the arguments under scrutiny.

2 I THE GEORGESCU-ROEGEN VERSUS SOLOW/STIGLITZ FORUM

In a short introduction to the forum, Herman Daly states the purpose of the journal's special issue: to honor G-R with recent research drawing on this work. But Daly also doesn't refrain from uttering what may be an even greater goal when mentioning his own article: "…my contribution to this volume is an attempt to revive Georgescu-Roegen's unanswered criticisms of Solow/Stiglitz, made some twenty years ago..." (DALY, 1997b, p. 173). In his subsequent article, Daly states that "to my knowledge neither Solow nor Stiglitz has ever replied to Georgescu-Roegen's critique" (DALY, 1997, p. 262). Also Robert Costanza, then chief editor of the journal, has concluded the editorial of the issue stating that "the debate is far from over, but at least we are beginning to look for answers to G-R's many unanswered questions, or at least for better ways to ask the questions" (COSTANZA, 1997, p. 171), another demonstration of the frequent dissatisfaction of thermoeconomists with the lack of engagement from

their counterparts concerning criticisms to growth theory. Noteworthy exceptions such as Stiglitz (1979), Solow (1974) and Solow (1993), on the other hand, suggest that Solow and Stiglitz, though particularly accused of such omission, may have been the standard growth theorists who most responded to the thermodynamic criticisms after all.

2.1 Daly's Challenge

Daly (1997) begins his article in a somewhat harsh and sarcastic tone towards Solow's stance in favor of the substitutability between natural resources and other production factors, particularly capital. Instead of considering such possibility only as a logical exercise in the search for alternatives, Daly argues that Solow "retains it as a real possibility" (p. 261), and proof of that would be the absence of natural resources in the aggregate production function Solow has chosen for his growth model. Daly makes his point through a crude – though also illustrative – analogy: a production function without natural resources would be a recipe for making a cake with only a cook (labor) and a fully equipped kitchen (capital). Ingredients, running water and electricity would play no role whatsoever, and residues would be nonexistent (a clear hint at thermodynamic laws). Double the number of cooks or buy more equipment to the kitchen, and you'd have more cake. Even the later insertion of the flow of natural resources as a multiplying factor in the Cobb-Douglas production function (G-R called it the 'Solow-Stiglitz variant') would not help much in Daly's view: keeping labor constant, one could still reach a given output substituting capital for natural resources. G-R called it a "conjuring trick".

At this point, Daly mentions many of the counterarguments to G-R's critique that have been used by the mainstream since the '60s, such as (i) the misleading "free good" interpretation of natural resources, based on the assumption that they are not really scarce; (ii) the hypothesis of perfect substitutability between natural resources and reproducible capital (ingeniously questioning that, if this is so, then why not leave out capital and include natural resources?); (iii) the view in which natural resources are plentiful "building blocks" of matter/energy, which can be transformed by labor and capital into more valuable products (a view contrary to the entropy law, given that such transformations inexorably increase the entropy of closed systems); and (iv) technology's potential to decouple production and energy/matter inputs, which to Daly must nevertheless conform to the entropy law and whose veracity escapes the discussion at hand as the production function is intended to "represent actual production processes of today and the recent past – not unknown future possibilities" (p. 264).

For the rest of the article, Daly argues for a complementarity between natural resources and labor/capital, as well as for a zero marginal product of labor and capital in a production function with natural resources as a factor. That would be so because there can be no gain in capital or labor if the natural resource factor is held constant –

there wouldn't be any physical substance to add to labor or capital in the first place. The implications of such acknowledgment, for Daly, "would destroy neoclassical distribution theory – perhaps too heavy a price to pay for admission that the world, in effect, cannot get along without natural resources!" (p. 265). The alternative would be G-R's fund-flow model of the production process and its emphasis on interchangeable "transformation agents" or funds (labor and capital) and interchangeable "material agents" or flows (natural resources) with a relationship of complementarity among each other.

Daly's article entails some of the main thermodynamic critiques to standard growth theory based on G-R's best-selling book (and still today an open debate). The text ends with a footnote that is worth quoting in length, as it leaves no doubt about Daly's impatience towards his opponent's reticence and has also set the tone for Solow's reply:

> A perceptive reviewer suggested that the best way to get an answer to Georgescu-Roegen's critique is probably not to raise it again with the same people that have ignored it for twenty years, but rather to somehow get 10 000 students to ask their economics professors the following questions in class: (1) Do you believe that economic activities must satisfy mass balance? (2) Why is it that neoclassical production functions do not satisfy the condition of mass balance? (3) Do you believe that Georgescu-Roegen's interpretation of production as physical transformation is correct? (4) Do you agree that the economic system is embedded in the larger environmental system, and totally dependent on it as both source and sink for the matter/energy transformed by economic activity? (5) Do you believe that the matter/energy transformations required by economic activity are constrained by the entropy law? Ten thousand students, please take note! (p. 265).

2.2 Solow's ReplY

Solow's (1997) very short reply (less than two full pages) gives the accurate impression that Daly will have to wait longer for an open, thorough debate on G-R's criticisms to growth theory. Solow seems to resent Daly's tone, and tries to explain (to readers of the journal and not Daly, as he clearly states) what he intended to do when working on macroeconomics of natural resources in the '70s. His answer is basically an attempt to place the same questions as Daly but transforming thermodynamic principles and boundary conditions into a question of degree, asking how important natural resources really are, to what extent renewable resources can substitute for nonrenewable resources or how much can technological progress help to minimize the role of natural resources. Drawing on his earlier works (SOLOW, 1974, 1993), he reinstates that human and natural capital are indeed substitutes – not perfectly, but sufficiently for more practical economic purposes. Therefore, as Solow claims in his article, "the substitution between renewable and nonrenewable resources is the essence of the matter" (p. 267). This vision is frequently associated with the concept of weak sustainability, addressed by GOWDY and O'HARA (1997) in the same issue but not within the forum subsection.

Solow thus shifts the discussion away from the limits imposed by the entropy law

– never openly acknowledging its inescapable influence on real economic activity – and into a pragmatic concern to find ways in which exhaustible resources can be replaced by renewable ones as the former's reserves decline toward zero. To Solow, the current scale of economic activity is still far short from existing environmental funds and flows, allowing economists to dismiss with the laws of thermodynamics until this state of affairs is no longer so. His answers to Daly's footnote questions are straightforward in this regard (particularly answers 2 and 5):

> 1. Yes.
>
> 2. Because up until now, and at the level of aggregation, geographic scope and temporal extent considered, mass balance has not been a controlling factor in the growth of industrial economies.
>
> 3. This is, no doubt, one aspect of production.
>
> 4. Certainly, and I welcome any attempts to model the dependence in a transparent way, so that it can be incorporated into aggregative economics.
>
> 5. No doubt everything is subject to the entropy law, but this is of no immediate practical importance for modeling what is, after all, a brief instant of time in a small corner of the universe (p. 268).

2.3 Stiglitz's Reply

Stiglitz's (1997) response is even shorter, however in more amicable terms (he nonetheless ends his article with the ironic remark that Daly has used more trees and other resources in his fairly lengthier paper). He pinpoints Daly's arguments as (i) the lack of adherence to the basic laws of physics and (ii) the erroneous idea of endless growth, oblivious to undisputable natural resource limitations. His main defense against these, as Solow's, finds shelter in the pragmatic claim that growth models are meant to deal with continuous growth only for the intermediate run – 50 or 60 years – and not for a timespan long enough so that the laws of thermodynamics become implacable. As if his growth theory would not be the ultimate growth theory accurately depicting physical reality, but instead a useful tool with practical economic purposes. In this intermediate run, it would be safe to say that capital and natural resources are in fact interchangeable, a matter of efficiency of the production process, unrestrained by the abundance of current resources and unaffected by the inevitable rise in entropy as a whole.

2.4 Daly's Reply To Solow And Stiglitz

In his final reply, Daly (1997a) did not seem surprised by Solow's and Stiglitz's answers. Criticizing how they have again not responded to G-R's thermodynamic critique (or even mentioning G-R at all), Daly dismissed Solow's arguments altogether, focusing instead on Solow's answers to his five footnote questions. Commenting on

Solow's answer to question 4, Daly adds that if Solow really agrees that the economic system is embedded in the larger (but finite) environmental system and is totally dependent on it, then Solow might consider an optimal scale to the macroeconomy in relation to the environment. Any growth beyond this point would be uneconomic.

As for Stiglitz's reply, Daly recalled G-R's assertions that in a 50-year timeframe fossil fuels would probably be depleted and a low-entropy solar society would be the only non-chaotic solution. To him, G-R would not only have a problem with growth models as incorrect representations of reality in the long run (in the thermodynamic sense), but also with their deceptive description of the production process and its negative effects during the necessary transition to the low-entropy solar society.

2.5 Contributions By Invited Thermoeconomists

The remaining ten articles by invited thermoeconomists contribute with significant insights and perceptions which fill the gaps and make it possible to claim that the forum is truly a good approximation of the whole controversy.

Clark (1997) raises the important issue of how supporters of the Cobb-Douglas production function may feel like there is no "empirical evidence that economic growth is being impeded by resource shortages" (p. 275), in spite of historical examples of economic collapses (e.g. Rome or Fascist Germany). Clark's point can be justified by Solow's fiercely criticized claim that "if it is very easy to substitute other factors for natural resources, then there is in principle no 'problem'. The world can, in effect, get along without natural resources, so exhaustion is just an event, not a catastrophe" (SOLOW, 1974, p. 11). Even in an "as if" context, such general assertions may be subject to this kind of contention, as was the case. Another keen argument by Clark counters Solow's exhaustible/renewable resource substitutability stance with particular strength: "exhaustible resources like minerals and oil do not appear to be in danger of running out soon, but renewable resources are in trouble worldwide" (p. 275). This is hard evidence that substituting renewable resources for exhaustible resources is not going to help much, even in the intermediate run.

Common (1997) tackles a different aspect of the debate. He stresses that mainstream economic science does not take into account the material basis of life, i.e. the role of natural resources and the natural laws they must abide, and therefore not only faces the risk of losing its scientific status, but also poses great danger to society at large. Common contends that economics curricula, textbooks and teachers share the same approach: they believe that natural laws are important, but not for practical economic purposes. This has been a recurrent complaint of G-R and maybe one of the reasons why he was often ignored by mainstream economists. Common's following remark represents precisely the opinion of thermoeconomists entangled in this dispute:

> It is very difficult to avoid the conclusion that economics, as opposed to some economists such as Solow and Stiglitz, does not take the material basis for economic activity, and the arising relevance of the laws of nature, seriously. Standard micro

> and macro courses and texts do not consider the interdependence of economic and environmental systems. This is the case at the undergraduate and postgraduate levels. Typically, students who will become accredited professional economists are not required to take courses in resource and/or environmental economics. Where such are offered, they are options, and frequently treated as disjoint (p. 277).

Opschoor (1997) underwrites Daly's position using fresh arguments against Solow's claims on substitutability and technological progress. According to him, "research on environmental Kuznets curves so far does not suggest that substitution and innovation have already solved the environmental issue for us" and "for all I know, in my part of the world (the OECD) the rate of increase in environmental and resource efficiency still lags behind the long-term expected growth rate for that part of the world" (p. 281). Also, Opschoor focuses on an old critique of thermoeconomists towards the mainstream: optimism would not be the best approach to manage the resources of the only planet we have at our disposal (this argument relates to the widespread 'precautionary principle' in the context of sustainability science). Referring to Solow (1993), he concludes that Solow's stance would be one based on "the hope that technological innovation will continue to reduce environmental claims per unit of product, faith in the ever present possibility of substitution, and love expressed as a plea to work with low discount rates in order to share equitably resources with future generations" (p. 282).

Opschoor proposes instead – countering the misplaced view that thermoeconomists have never come up with better models than the ones they criticize – that a complete description of the production process would involve not only the traditional production function, but also mathematical representations of quantitative and qualitative links between (i) labor, capital and natural resources and (ii) resource/waste regeneration processes and the economic process.

Ayres (1997) is the only author in the debate who disagrees with G-R's interpretation of the economic implications of the thermodynamic laws. However, he does it rather as a physicist, affirming that G-R "misunderstood a fundamental point of physics" (p. 286) (what doesn't mean Ayres cannot be called a thermoeconomist, given his background in physics and lifelong work advocating against the indifference of mainstream economics to natural laws and its perils to a continuously habitable planet Earth). Ayres recognizes G-R's role in the history of economic thought as the leader of the 'entropic school' of economics, nevertheless he challenges G-R's arguments by claiming that production is not inherently material-intensive. Ayres argues that there is not an upper limit to the 'service output' (in a human welfare sense) of a given material due to the possibilities of recycling, reusing, recovering such material or reducing its use. Even if materials can never be recycled with 100% efficiency, one could still use "free" solar energy to limit the amount of waste in relation to the amount of resources – a proportion which is a function of the efficiency of recycling.

The main question that sets G-R and Ayres apart is whether "matter matters", as cleverly put by G-R. If all we need is a sufficiently abundant source of energy (characterizing the sun as a 'sufficiently abundant source of energy' to support man's

recycling needs is another open issue) with which to transform waste into high quality materials – the alchemist's utopia –, then Ayres has a point. Only for the universe as a whole does Ayres agree that "matter matters", once there would be no external source of energy. His objections to G-R's thermoeconomics do not mean he supports standard growth theory, but they also do not help the case against endless growth, as they constitute a sort of technological optimism, even if based on an assumed physical possibility. Besides, the discussion at hand is void in terms of Solow's "intermediate run".

Tisdell (1997) is a great asset to the forum, bringing yet more diversity to the collection of thermodynamic criticisms to continuous growth. His version comprises (i) the cumulative detrimental effects of Solow's "intermediate run" analysis, in which entropic phenomena are considered insignificant; (ii) the importance of renewable resources (and specially living ecosystems) to the economic process by counteracting entropy increases through their ability to self-organize into high quality structures – and therefore the not so great idea of freely substituting renewable for exhaustible resources; (iii) the fact that human capital, including scientific knowledge, "declines without continual investment in education and its preservation and transmission" (p. 290), which in turn depend on the use of natural resources – thus the conclusion that technological progress itself is subject to the entropy law; and (iv) the findings that technological innovation gains, although able to reduce material inputs for a given economic output, cannot avert a rise in total material use per capita (as personal consumption increases) or in total material throughput (as population and affluence increase).

Pearce (1997) details the natural/man-made capital substitutability discussion and claims for empirical evidence regarding substitution rates, elasticities and limits, as well as thresholds related to "critical capital" (i.e. capital subject to irreversible changes and normally associated with nonlinear behavior or "tipping points"). The lack of reliable information corroborates with the precautionary principle – doing otherwise would be reckless – and trying to substitute for ecosystem services (climate, biodiversity, water cycle etc.) is probably bound to less-than-unity elasticities with existing technology, a result that would imply that models based on standard growth theory are inherently unsustainable.

Perrings (1997) elaborates on thresholds and irreversibilities in a similar way to Pearce, adding that such interpretation is important to both neoclassical and thermoeconomists. He also reminds us of the existence of thermodynamic and bioeconomic models, the first general and evolutionary, the second partial and non-evolutionary and both presenting more ecological consistency than models based on production functions which do not account for the role of natural resources.

Other contributions to the forum have hardly added new elements that would promote the main thesis of this article. But they provide interesting perspectives worth mentioning: Peet (1997) criticizes the pursue of analytical answers to many

different sorts of questions, including the how to best describe the world (other than mathematically) or what would be the purpose of social and economic life (other than the "dehumanizing neoclassical perspective"); Turner (1997) underpins Pearce's main message and calls for plurality and transdisciplinarity in a quest for a "human-nature coevolutionary process" and, finally, Castle (1997) mentions the uncertainty associated with the efforts of gathering empirical evidence in favor or against natural/man-made capital substitution, as well as the need to find middle ground between "near perfect" and "highly limited" capital substitution arguments.

3 I CONCLUDING REMARKS

Daly, Solow and Stiglitz focused on the issue of substitutability between natural and man-made capital and the thermodynamic implications for practical economic purposes. Daly appears to be correct when pointing that Solow and Stiglitz don't really seem to think that the entropy law plays a role in current, day-to-day economic activity. Solow's assertion that we are dealing with "a brief instant of time in a small corner of the universe" and that therefore there are no practical implications of the entropy law implies in an understanding of the entropic argument only in the context of the ultimate energy death of the universe, when entropy is infinite, and all things are brought to a standstill. This is definitely not so for thermoeconomists, for whom Stiglitz's intermediate run is also subject to high quality materials scarcity, irreversible ecosystem services disruption and limitations to the prowess of technological progress, all very important claims with vast practical economic consequences.

The remaining articles have contributed significantly to the debate. The urge in favor of more empirical evidence in general; the moral question related to the precautionary principle in the absence of such hard evidence; the "matter matters" dispute stretching over to disagreements in theoretical physics; the pitfall of optimistic statements related to reducing material inputs for a given economic output as concurrently total material use per capita and total material throughput increase; all of these constitute crucial elements of an at least 30-year-old discussion. Mick Common's broader comments on the whole issue leave no doubt that the thermodynamic criticism is actually directed to the shortcomings of mainstream economics methodology, its inconsistencies with natural laws and an apparent political refusal of the mainstream economics establishment to give in to the economic importance of the entropy law. Oddly enough, this same establishment has proudly been accused of envying physics.

The G-R versus Solow/Stiglitz forum was a comprehensive exchange of ideas that summarized well a controversy which had started back in the '60s and that has still not been put to rest. The central arguments have varied along the years, even more so after recent developments in complexity science and nonlinear systems dynamics, as well as after the appearance of new empirical evidence. However, both physical and

epistemological bases of each side of the contention have not fundamentally altered. The 1997 special issue of *Ecological Economics* in memory of G-R can be seen, therefore, as the epitome of the thermodynamic criticism to growth theory and thus a reference in the subject for future studies, both in applied economics and in the history of economic thought.

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