Thermodynamics and the economics of absolute scarcity

Why and how thermodynamics is relevant for ecological, environmental and resource economics

Dr. Stefan Baumgärtner[1]

Energy and Resources Group, University of California, Berkeley, USA

Department of Economics, University of Heidelberg, Germany

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Abstract: The laws of thermodynamics are relevant for ecological, environmental and resource economics because they characterize one particular dimension of scarcity that nature imposes on human action. To lend plausibility to this claim, this paper builds on a distinction between relative and absolute scarcity. While neoclassical environmental and resource economics focuses more on relative scarcity, ecological economics is more concerned with absolute scarcity. Thermodynamics has direct implications for analyses of both absolute and relative scarcity. The paper also indicates areas of recent and potential future research where the relevance of thermodynamics becomes obvious.

Keywords: absolute and relative scarcity, human needs, economics, energy, entropy, substitutability, thermodynamics

Contact address: UC Berkeley, Energy and Resources Group, 310 Barrows Hall, MC #3050, Berkeley, CA 94720-3050, phone: (510) 642-1640, fax: (510) 642-1085, email: baumgart@socrates.berkeley.edu, http://www.stefan-baumgaertner.de

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1. The roles of economics and the natural sciences in the interdisciplinary study of economy-environment interactions

According to a classic definition, economics 'studies human behavior as a relationship between ends and scarce means which have alternative uses' (Robbins 1932). In that definition the notion of scarcity holds a crucial position, separating the economic dimension from other dimensions of purposeful human behavior involving the utilization of means to achieve ends. This leads to the understanding that economics is essentially about optimization under constraints, with constraints as an expression of scarcity.

The aspect of scarcity also allows to define the field of environmental and resource economics as a sub-discipline of general economics (Fisher 2001). For, environmental and resource economics studies those areas of optimizing human behavior subject to constraints where constraints are imposed by the natural world. Examples include the limited stock, concentration and spatial distribution of mineral resources; the natural growth of biological resources; the diffusion, transformation and decay of a pollutant in an environmental medium; and so on. In that view, the laws of nature captured by the physical, biological and environmental sciences are necessary for environmental and resource economics to gain an adequate representation of the relevant constraints.

This is a very simple picture of environmental and resource economics, and the interdisciplinary division of labor underlying the study of economy-environment interactions as an optimization under constraints. In this presentation I will add some complexity to the picture by taking a closer look at the notion of scarcity. Anyone who has ever taught an undergraduate economics class knows that the notion of scarcity is notoriously difficult to define and measure. One reason is that scarcity can only be meaningfully defined in relation to other terms and concepts. These include the notion of 'human needs', also contained in the definition of economics as 'human ends', and the idea of 'substitutability' among different means and ends.

I will argue here that taking such a more differentiated look at the notion of scarcity fundamentally alters the view on the roles of economics and the natural sciences in the interdisciplinary endeavor to study how humans interact with their natural environment.

2. What is scarcity? And how does economics deal with scarcity?

Let me start by discussing the question of what is scarcity. Here I will follow Faber and Manstetten (199?) and Faber et al. (1994).

2.1 The usual economic notion is one of relative scarcity

In common economic understanding, a means of production or a consumption good is said to be *scarce* if it carries opportunity costs. In order to obtain one additional unit of the good one needs to give up something else – some amount of another good, or an opportunity to do or not do something, or pay a monetary price. Thus, scarcity is defined in a relative way: a good is scarce in relation to other scarce goods. This definition is one of *relative scarcity*.

Such a relative notion of scarcity relies on one particular assumption about peoples' preferences. Saying that people are willing to give up something else in order to obtain one additional unit of a scarce good rests on the implicit assumption that people consider these two goods to be substitutes. Giving up one unit of good A and receiving in exchange a certain amount of good B will leave them equally well of in utility terms. Only then does it make sense to say that one is willing to pay for one good by giving up another good. The concept of relative scarcity thus rests on the implicit assumption of substitutability between goods.

As an illustration consider the following simple example. Bread is a scarce good. Nonetheless, all of us have enough bread to eat. Scarcity of bread only refers to the fact that obtaining bread carries opportunity costs. Obtaining one additional unit of bread implies that we have to give up something else. This is relative scarcity as defined above. Bread is scarce in relation to other goods, for instance other food, CDs, gasoline etc., which are relatively scarce as well. Furthermore, at the margin, and given the current average income level in developed countries, all these goods are substitutes for bread in satisfying preferences. Bread is relatively scarce in another respect too. For, it is assumed that with increasing demand for bread it is possible to just produce more bread.

2.2 Absolute scarcity as a stronger form of scarcity

If certain goods are not substitutable against others, and if they cannot just be produced, a relative notion of scarcity will not adequately capture the scarce nature of these goods.

As an illustration consider again the bread example. As argued above, at the margin and at sufficiently high income levels bread is scarce only in a relative sense. Now imagine a besieged town. There is only a limited amount of flour, bread and other basic foods available. This amount cannot be increased. What will happen? Bread and other basic food will become ever more scarce as the besiege continues, but the scarcity will be of a different kind than the relative scarcity discussed above. The scarcity of food will be of a fundamentally different kind than the also existing scarcity of CDs or gasoline because at some point it cannot be put into a meaningful relation to other, less essential goods any more. Bread, as other basic foods and water, is essential for survival, while gasoline and CDs are not. In such a case, when scarcity concerns a non-substitutable means for the satisfaction of an elementary need and cannot be levied by additional production, one may speak of *absolute scarcity*.

In the following, I will make recourse to preference theory to discuss why goods may or may not be substitutable against others, and how this leads to the distinction between relative and absolute scarcity.

2.3 Distinction between elementary and imaginary needs

In the history of economic thought a distinction has been made between two classes of human needs, which may be called ‘elementary needs’ and ‘imaginary needs’ following Schlosser (1784; cf. Binswanger 1991). This distinction goes back to the ancient Aristotelian distinction between the ‘natural economy’ and the ‘artificial economy’ (Roscher 1874: 529).[2] It shows up in various forms over time among various scholars preceding the neoclassical era in economics. For example, Thoreau ([1854]1998) employs a similar distinction based on whether the satisfaction of needs is ‘necessary of life’ or not, when discussing man’s relation to nature. And today, the United Nations’

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[2] Note that Schlosser has delivered the first German translation of Aristotle’s *Politics* and was obviously inspired by the economic ideas expressed therein (Riedel 1962).

Development Programme makes a distinction between basic needs and non-basic needs when assessing progress in worldwide poverty alleviation.

Elementary needs refer to obtaining all those means necessary to sustain human life and reproduction, for example eating, drinking, sleeping, shelter, heating, basic health care and basic education. They characterize the human existence as that of a biological animal. *Imaginary needs* extent to everything beyond that. If elementary needs are not satisfied at least to some minimum degree a human cannot live at all or not in a dignified manner. In other words, if elementary needs remain unsatisfied human life is either impossible at all or its is not so much a human life than just biological survival. In contrast, if imaginary needs remain unsatisfied an individual may feel very much unsatisfied but she will still live a dignified human life.

In modern economics it is presupposed that elementary needs can be satisfied and that they are, indeed, satisfied. This follows from the definition of economics as the study of choice among different alternatives. One may justly suppose that as far as the satisfaction of elementary needs is concerned there is no free choice. Someone at the verge of starving to death, when offered a choice between one slice of bread and a CD, is not free to make a choice. Such a person will take the slice of bread, and not even consider the value of a CD. This means, whether one satisfies basic needs are not, given the opportunity to do so or not, is not a matter of choice. Therefore, modern economics as a scientific discipline (and in contrast to all pre-neoclassical economics) has confined itself to the study of imaginary needs

((Also: discuss the role of substitutability and production for the distinction between basic and elementary needs.))

2.4 The distinction between elementary and imaginary needs allows to distinguish between absolute and relative scarcity

Corresponding to the distinction between elementary needs and imaginary needs one may distinguish absolute scarcity from relative scarcity. The two types of scarcity refer to the means for satisfying elementary and imaginary needs respectively. Since basic needs stem from the biological condition of human existence, absolute scarcity has sometimes been dubbed ‘objective scarcity’ and relative scarcity ‘subjective scarcity’ (e.g. Thoreau [1854]1998).

But, obviously, the distinction between relative and absolute scarcity is not as clear-cut as it seems. First, both relative and absolute scarcity always refer to one particular point in space and time. Second, the distinction between elementary needs and imaginary needs is in part a subjective one. While there is little doubt about the amount of basic food necessary for survival, discussions are on about what the elementary level of education and health care is to allow a dignified human life. And should one think of a drug addict in terms of an elementary need for a narcotic, just because the person's subjective non-substitutable preference for the drug? Third, the question of substitutability needs to be addressed in a particular context and cannot be answered once and for all. Notwithstanding these problems, the two aspects of relative and absolute scarcity are well suited to describe the extremes on a continuum of different shades of scarcity.

2.5 Economics focuses on relative scarcity

Economics, by definition, deals with relative scarcity. As discussed above, factors of production, resources and consumption goods are always considered as being scarce in relation to other goods, and substitutability among them is one of the basic tenets of economics. Accordingly, economists have tended to subsume absolute scarcity under relative scarcity. Typically, in the example of scarcity of bread in a besieged town economists would recommend to increase the price of bread in order to achieve an efficient allocation of bread. As a consequence, demand for bread would drastically decline and everyone who could not afford bread anymore would have to look for substitutes for bread, existing and new ones. The possibility that all inhabitants of the town may starve to death is not a problem of economics, and it is not a problem amenable to the methods of economics. This is by definition of economics: the very definition of economics presupposes that scarce means have alternative ends, in other words, that there is a possibility of substitution and that there is room for choice. Choice, thus, is the true substance matter of economic analysis. For that reason, absolute scarcity, which implies that there is no choice, is in general beyond the horizon of economic analysis. Problems stemming from the possibility that there is no substitute for essential goods such as bread in a besieged town are not considered economic problems.

3. Relative and absolute scarcity of environmental goods and services

While neoclassical environmental and resource economics, just like economics at large, focuses on relative scarcity of environmental goods and services (Underwood and King 1989), ecological economics is concerned with addressing the relevant absolute scarcities as imposed by the biogeophysical environment. The belief held by ecological economists is that many environmental goods and services are not only scarce in a relative sense, but also in an absolute sense. This is part of the underlying 'vision' of ecological economics, where the term vision is used, following Schumpeter (1954, p. 41), to denote a 'preanalytic cognitive act'. Viewing environmental goods and services as absolutely or relatively scarce thus constitutes one of the basic differences in vision between neoclassical environmental and resource economics and ecological economics.

((also discuss: the role of the space and time scales. Many environmental goods and services are relatively scarce only in the short run or at one particular place, but become absolutely scarce in the long run and on a global scale. The concern of ecological economics with absolute scarcity is vindicated by a corresponding concern for the global long-term future as demanded by the ideal of a sustainable society.))

Environmental goods and services have long been considered to a free good. Only with the oil price crisis of the early 1970's, and realizing the dying of numerous surface waters and increasing air pollution in the 1970's, has a clean environment been regarded as a scarce good. Most economists consider this scarcity to be a relative one. The underlying belief is, that there is a large substitute ability between natural capital and human made capital, allowing for the possibility to make up losses in environmental quality of increases in producer consumption goods. In such a perspective environmental and resource economists argue that environmental problems can be solved by changing relative prices. For example an increase in the price of carbon dioxide emission is argued to reduce carbon dioxide emission. The efficient price is set such as to maximize welfare up based on the underlying believe that there is substitute ability between suffering from climate change and suffering from other welfare losses due to decrease in GDP.

The method of environmental and resource economics has been shaped by dealing with local and small scale environmental problems. Only recently have we become aware that some environmental problems, like for instance global climate change due to anthropogenic emissions of greenhouse gases or the global loss of biological diversity, are of a quite different kind. Not only are these new environmental problems global in scale. According to the view of many environmental scientists they also have the potential to threaten the conditions for human existence on this planet. In terms of the terminology introduced above, there is increasing evidence that the environmental problems we are currently facing are problems of absolute scarcity. Global climate change and loss of biological diversity may lead to losses of environmental goods and services that are essential for human survival and cannot be substituted for any more.

How can we find out whether such a claim is warranted? In other words, how, as ecological, environmental and resource economists, can we find out whether and where environmental goods and services and resources are not substitutable, and whether the needs they satisfies are elementary or imaginary? Finding answers to these questions requires to look beyond the limits of economics proper (Faber et al. 1994). Economists have to engage in a dialogue with natural and social scientists in order to find out. Social scientists, like psychologists and sociologists, can teach us about how needs emerge, how they are shaped, and how they evolve. The natural and engineering scientists can teach us what resources are available, how they may be transformed into intermediate or final products, and, thus, to what extent they may be substituted for each other and for other goods.

Such an interdisciplinary dialogue would allow economists to gain a lot of insight about the domain of validity and the limits of the economic approach, which is built around the notion of relative scarcity. The study of thermodynamics within ecological economics is just one example of such an interdisciplinary dialogue.

4. The use of thermodynamics in ecological economics

4.1 Thermodynamics allows to analyze the economic metabolism

Every process of change far from thermodynamic equilibrium requires low entropy energy. This is the case for natural ecosystems (e.g. a leaf growing on a tree) as well as for the human economy (e.g. the production of metal from metal ore).

The human economy, similarly to ecosystems, displays processes of change that require low entropy energy. Important insights into the nature of these processes can be gained by completely abstracting from the one feature that sets economic systems apart from natural ecosystem – human desires, wants and purposes – and focusing instead on the purely material aspect. When referring to this purely material and energetic dimension of the economic process, one may speak of 'industrial metabolism' (Ayres and Simonis, 1994). The term 'metabolism' is borrowed from physiology and denotes, in its original meaning, all of the internal processes of a living organism responsible for its maintenance, reproduction and growth. It comprises the extraction of energy and matter from the organism's environment and the disposal of dissipated energy and degraded matter into that environment. In a metaphorical sense industrial metabolism is then understood as the interconnected system of 'all materials/energy transformations that enable the economic system to function, i.e., to produce and consume' (Ayres and Simonis, 1994, p. xi).

Current economies severely interfere with their natural environment. To illustrate the macroeconomic dimension of material economy-environment-interaction, consider the waste produced by a typical modern industrial economy. The sheer amount of waste generated in is enormous. For example, in Germany (that is: former West Germany) in 1990 the amount of waste (measured in physical units, i.e. tons) exceeded the amount of useful economic output (also measured in physical units) by more than a factor of four: out of a total material output of 59,474.6 million tons generated by all sectors of the economy, only 3,602.6 million tons (6.1%) were contained in the different components of GDP, while 7,577.2 million tons (12.7%) were intermediate outputs for reuse within the economy (including recovered and recycled materials) and 48,294.8 million tons (81.2%) were final wastes (Statistisches Bundesamt 1997). This huge dimension of material waste generation is confirmed also for other industrialised countries, e.g. Denmark, Italy and the USA (Acosta 2001).

As this strong economy-environment interaction is, in the first place, an exchange of energy and matter, the laws of thermodynamics provide a useful analytical framework within which fundamental insights into society's metabolism may be rigorously deduced in energetic and material terms.

4.2 The Laws of Thermodynamics

Thermodynamics is the branch of physics that deals with macroscopic transformations of energy and matter. Briefly summarized, the fundamental concepts and laws of (phenomenological) thermodynamics can be stated as follows.[3]

((Here: one paragraph description of what is thermodynamics and what are its basic statements about the transformation of energy and matter.))

4.3 The application of thermodynamics in ecological, environmental and resource economics

Different approaches in the literature:

1. Isomorphism of formal structure
    - constrained optimization problems
    - Le Chatelier-principle / comparative statics
2. Analogy and metaphors
    - increase of "social entropy"
    - the economy as a "self-organizing dissipative structure far from equilibrium"

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[3] For a comprehensive introduction to (phenomenological) thermodynamics see Callen (1985), Kondepudi and Prigogine (1998) or Zemansky and Dittman (1997).

3. Thermodynamic constraints on economic action
    - resource extraction
    - production of goods and services
    - release of wastes and pollutants
    - recycling

    –> environmental, resource and ecological economics
4. Energy, entropy, exergy based theories of values

For a study of the different kinds of scarcities imposed on human economic action by nature, the approach identified under 3 is most promising. Various scholars have done research along these lines over almost half a century.

In the late 1960s and early 1970s the laws of thermodynamics were found by economists to be concepts with considerable implications for environmental and resource economics (Spash, 1999, p. 418). The Materials Balance Principle was formulated based on the Law of Conservation of Mass as implied by the First Law of Thermodynamics (Boulding, 1966; Ayres and Kneese, 1969; Kneese et al., 1972). In view of the Materials Balance Principle all resource inputs that enter a production process eventually become waste.

At the same time Georgescu-Roegen (1971) developed an elaborate and extensive critique of economics based on the laws of thermodynamics, and in particular the Entropy Law, which he considered to be 'the most economic of all physical laws' (Georgescu-Roegen, 1971, p. 280).[4] His contribution initiated a heated debate on the question whether the Entropy Law is relevant to economics (see e.g. Burness et al., 1980; Daly, 1992; Kåberger and Månsson, 2001; Khalil, 1990; Lozada, 1991; 1995; Norgaard, 1986; Townsend, 1992; Williamson, 1993; Young, 1991; 1994).[5] While

[4] The works of Georgescu-Roegen are surveyed in a number of recent volumes (e.g. Beard and Lozada, 1999; Mayumi, 2001; Mayumi and Goody, 1999) and a special edition of the journal *Ecological Economics* (Vol. 22, No. 3, 1997).

[5] See Baumgärtner et al. (1996) for a summary of that discussion.

Georgescu-Roegen had, among many other points, formulated an essentially correct insight into the irreversible nature of transformations of energy and matter in economies, his analysis is to some extent flawed by wrongly positing what he calls a 'Fourth Law of Thermodynamics' (Ayres, 1999). It may be for this reason that the Second Law and the entropy concept have not yet acquired the same undisputed and foundational status for resource, environmental and ecological economics as have the First Law and the Materials Balance Principle.

But as Georgescu-Roegen's work and the many studies following his lead have shown, the Entropy Law, properly applied, yields insights into the irreversible nature of economy-environment interactions that are not available otherwise (Baumgärtner et al., 1996). In particular, it became obvious that the First and the Second Laws of Thermodynamics need to be combined in the study of how natural resources are extracted, used in production, and give rise to emissions and waste, thus leading to integrated models of ecological-economic systems (e.g. Faber et al., 1995; Perrings, 1987; Ruth, 1993; 1999).

5. Thermodynamics allows to draw a distinction between absolute and relative scarcity

In the analysis of economy-environment interactions, e.g. resource extraction, energy use, production, and generation of wastes, thermodynamics can tell the difference between relative scarcity (substitutability) and absolute scarcity (non-substitutability). The laws of thermodynamics allow to describe both types of scarcity, relative and absolute. Thermodynamic concepts can be applied to both microeconomic as well as macroeconomic production processes.

5.1 Thermodynamics and absolute scarcity

in general: absolute limits

This is the old discussion about the 'limits to growth'. Classic concern of ecological economics with absolute limits to human economy. View of the economy as an open subsystem of the larger, but finite and non-growing system of planet Earth (Daly). Leads to the idea of the optimal 'scale' of economic activity relative to the size of the biogeophysical system.

Examples:

- limits to substitution (materials, energy use for production and generation of waste)
- limits to recycling
- Inada condition does not hold for material resource inputs
- leading to: limits to growth

All this is old hat. But there are also some more recent and promising issues:

- irreversibility
- technical progress: thermodynamics tells what cannot happen (e.g. production of cement, resource extraction, learning curve with lower bound)

5.2 Thermodynamics and relative scarcity

The discussion about the relevance of thermodynamics for ecological, environmental and resource economics has moved beyond that and now turns out to be interesting also in terms of relative scarcity. Interdisciplinary cooperation between economists and engineers.

in general: trade-offs

examples:

- energy and materials use in production processes
- Energy/Entropy/Exergy analysis as an engineering tool
- inefficiency of waste
- energy use and time (finite-size-finite-time thermodynamics)
- efficient design of industrial processes and plants: Balancing different goals and constraints

6. Conclusion

All taken together, thermodynamics is relevant for ecological economics in various ways and on different levels of abstraction. First, as all processes of change are, at bottom, processes of energy and material transformation the laws of thermodynamics apply to all of them. Taking a thermodynamic perspective thus creates a unifying perspective on ecology, the physical environment, and the economy. It allows to ask questions that would not have been asked from the perspective of one scientific discipline alone. For instance, taking a thermodynamic perspective allows to gain a broader view on the notion of scarcity and on how economics deals with scarcity. Second, on a more specific level thermodynamic concepts allow to incorporate physical driving forces and constraints in models of economy-environment interactions, both microeconomic and macroeconomic. This is essential for understanding to what extent and in exactly what way resource and energy scarcity, nature’s capacity to assimilate human wastes and pollutants, as well as the irreversibility of transformation processes, constrain economic action. Thermodynamic concepts thus allow economics to relate to its biophysical basis, and yield insights about that relation which are not available otherwise. Third, on an even more applied level thermodynamic concepts provide a tool of quantitative analysis of energetic and material transformations for engineers and managers. They may be used to design industrial production plants or individual components of those such as to maximize their material and energetic efficiency, and to minimize their environmental impact.

References

Acosta, J.J. (2001). *Physische Input-Output-Rechnung: Ansätze, Möglichkeiten und Probleme einer aktivitätsbezogenen Stofflussrechnung auf nationaler und regionaler Ebene*. Institut für Regionalwissenschaft der Universität Karlsruhe,

Ayres, R.U. (1999), ‘The second law, the fourth law, recycling, and limits to growth’, *Ecological Economics*, **29**, 473-483.

Ayres, R.U. and A.V. Kneese (1969), ‘Production, consumption, and externalities’, *American Economic Review*, **59**, 282-297.

Ayres, R.U. and U. Simonis (1994), *Industrial Metabolism: Restructuring for Sustainable Development*, Tokyo: United Nations University Press.

Baumgärtner, S., M. Faber and J.L.R. Proops (1996), ‘The use of the entropy concept in ecological economics’, in Faber et al. (1996: Chap. 7).

Beard, T.R. and G.A. Lozada (1999), *Economics, Entropy and the Environment. The Extraordinary Economics of Nicholas Georgescu-Roegen*, Cheltenham: Edward Elgar.

Binswanger, H.C. (1991), Wachstum durch Imagination: J.G. Schlossers Theorie der imaginären Bedürfnisse, in: *Geld und Natur. Das wirtschaftliche Wachstum im Spannungsfeld zwischen Ökonomie und Ökologie*, Stuttgart and Vienna, pp. 195-238.

Boulding, K.E. (1966), 'The economics of the coming spaceship Earth', in Jarrett (ed.), *Environmental Quality in a Growing Economy*, Baltimore: Johns Hopkins University Press.

Burness, H.S., R.G. Cummings, G. Morris and I. Paik (1980), 'Thermodynamic and economic concepts as related to resource-use policies', *Land Economics*, **56**, 1-9.

Callen, H.B. (1985), *Thermodynamics and an Introduction to Thermostatics*, 2nd ed., New York: Wiley.

Daly, H.E. (1992), 'Is the entropy law relevant to the economics of natural resources? Yes, of course it is!', *Journal of Environmental Economics and Management*, **23**, 91-95.

Faber, M. and R. Manstetten (199?), *Philosophische Grundlagen von Ökonomie und Ökologie (The Philosophical Foundations of Ecology and Economy)*, Lecture Notes, Department of Economics, University of Heidelberg.

Faber, M., R. Manstetten and G. Müller (1994), Interdisziplinäre Umweltforschung aus ökonomischer Sicht (Interdisciplinary environmental analysis from an economic perspective), Naturwissenschaften **81**: 193-199.

Faber, M., R. Manstetten and J.L.R. Proops (1996), *Ecological Economics – Concepts and Methods,* Cheltenham: Edward Elgar.

Faber, M., H. Niemes and G. Stephan (1995), *Entropy, Environment and Resources: An Essay in Physico-Economics,* 2nd ed., Heidelberg: Springer.

Fisher, A.C. (2000), Introduction to special issue on irreversibility, *Resource and Energy Economics* **22**, 189-196.

Georgescu-Roegen, N. (1971), *The Entropy Law and the Economic Process*, Cambridge/MA: Harvard University Press.

Kåberger, T. and Månsson, B. (2001), 'Entropy and economic processes – physics perspectives', *Ecological Economics*, **36**, 165-179.

Khalil, E.L. (1990), 'Entropy law and exhaustion of natural resources: Is Nicholas Georgescu-Roegen's paradigm defensible?', *Ecological Economics*, **2**, 163-178.

Kneese, A.V., R.U. Ayres and R.C. d'Arge (1972), *Economics and the Environment: A Materials Balance Approach*, Washington: Resources for the Future.

Kondepudi, D. and I. Prigogine (1998), *Modern Thermodynamics. From Heat Engines to Dissipative Structures*, New York: John Wiley & Sons.

Lozada, G.A. (1991), 'A defense of Nicholas Georgescu-Roegens's paradigm', *Ecological Economics*, **3**, 157- 160.

Lozada, G.A. (1995), 'Georgescu-Roegens's defence of classical thermodynamics revisited', *Ecological Economics*, **14**, 31-44.

Mayumi, K. (2001), *The Origins of Ecological Economics. The Bioeconomics of Georgescu-Roegen*, London: Routledge.

Mayumi, K. and J.M. Gowdy (eds) (1999), *Bioeconomics and Sustainability. Essays in Honor of Nicholas Georgescu-Roegen*, Cheltenham: Edward Elgar.

Norgaard, R.B. (1986), 'Thermodynamic and economic concepts as related to resource-use policies: synthesis', *Land Economics*, **62**, 325-328.

Perrings, C. (1987), *Economy and Environment: A Theoretical Essay on the Interdependence of Economic and Environmental Systems*, Cambridge: Cambridge University Press.

Riedel, M. (1962), Aristoteles Tradition am Ausgang des 18. Jahrhunderts. Zur ersten deutschen Übersetung der "Politik" durch Johann Georg Schlosser, in: *Alteuropa und die moderne Gesellschaft. Festschrift für Otto Brunner*, Göttingen, pp. 278-315.

Robbins, L. (1932), *An Essay on the Nature and Significance of Economic Science*. Macmillan, London.

Roscher, W. (1874), *Geschichte der National-Ökonomik in Deutschland*, München.

Ruth, M. (1993), Integrating Economics, Ecology and Thermodynamics, Dordrecht: Kluwer.

Ruth, M. (1999), 'Physical principles in environmental economic analysis', in J.C.J.M. van den Bergh (ed.), Handbook of Environmental and Resource Economics, Cheltenham: Edward Elgar, pp. 855-866.

Schlosser, J.G. (1784), *Xenocrates oder Ueber die Abgaben. An Göthe,* Basel.

Schumpeter, J.A. (1954), *History of Economic Analysis*, Oxford University Press, New York.

Spash, C. (1999), 'The development of environmental thinking in economics', *Environmental Values*, **8**, 413-435.

Statistisches Bundesamt (1997). *Beiträge zu den Umweltökonomischen Gesamtrechnungen, Band 1: Physische Input-Output-Tabellen 1990*, Statistisches Bundesamt, Wiesbaden.

Townsend, K.N. (1992), 'Is the entropy law relevant to the economics of natural resource scarcity?', *Journal of Environmental Economics and Management*, **23**, 96-100.

Thoreau, H.D. ([1854]1998), *Walden, or Life in the Woods*, first published 1854, reprinted in: N. Baym et al. (eds), *The Norton Anthology of American Literature*, Vol. 1, 5th ed., W.W. Norton & Co., New York, pp. 1768-1942.

Underwood, D.A. and P.G. King (1989), On the ideological foundations of environmental policy, *Ecological Economics* **1**: 315-334.

Williamson, A.G. (1993), 'The second law of thermodynamics and the economic process', *Ecological Economics*, **7**, 69-71.

Young, J.T. (1991), 'Is the entropy law relevant to the economics of natural resource scarcity?', *Journal of Environmental Economics and Management*, **21**, 169-179.

Young, J.T. (1994), 'Entropy and natural resource scarcity: a reply to the critics', *Journal of Environmental Economics and Management*, **26**, 210-213.

Zemansky, M.W. and R.H. Dittman (1997), *Heat and Thermodynamics: An Intermediate Textbook*, 7th ed., New York: McGraw-Hill.