Vol. 24: 61–75, 2024
https://doi.org/10.3354/esep00213

ETHICS IN SCIENCE AND ENVIRONMENTAL POLITICS
Ethics Sci Environ Polit

Published April 11

Beyond fatalism: Gaia, entropy, and the autonomy of anthropogenic life on Earth

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ABSTRACT: The current disruption of ecosystems and climate systems can be likened to an increase in entropy within our planet. This concept is often linked to the second law of thermodynamics, which predicts a necessary rise in entropy resulting from all material and energy-related processes, including the intricate organisation of living systems. Consequently, discussions surrounding the ongoing crisis commonly carry an underlying sense of fatalism when referencing thermodynamic principles. In this study, we explore how the understanding of life has been harmonized with thermodynamics to show that entropy production is a consequence of heightened complexity in life rather than its breakdown. Furthermore, it is crucial to perform a thermodynamic analysis of the Earth system as a whole to dispel fatalistic assumptions. The extremum principles linked to thermodynamics do not foretell the precise evolution of complex organisations but rather set the thermodynamic boundaries associated with their development. Ultimately, treating the Earth system as an integrated autonomous entity in which life and human societies play pivotal roles is essential for charting a sustainable path forward for humanity. Understanding how to contribute to thermodynamic states that are more conducive to life, rather than hastening the journey towards chaotic states, is paramount for human survival and well-being in the Anthropocene era.

KEY WORDS: Thermodynamics · Life system · Earth system science · Gaia · Maximum entropy production · Climate change

1. INTRODUCTION

The current ecological and climatic crisis poses many questions to humanity that relate to thermodynamic concepts. The problem of exiting from fossil fuel use and deploying renewable energies, the issue of waste and the limits of recycling, the collapse of ecosystems, mass extinction, and the increase in planetary disorder all appear to be related to fundamental concepts such as energy, entropy, irreversibility, and thermodynamic limits.

At the same time, the great chasm between the declared international agreements to reduce CO_2 emissions (UNFCCC 1997, 2015) and the fact that these emissions have continued to increase and appear to be at a maximum historical level (Friedlingstein et al. 2022) seems to bring a sense of fatality, as if human agency is powerless against some fundamental drive that forces us to continue to burn fossil fuels even when we are aware of the danger this brings to us.

Since its discovery, thermodynamic theory has been associated with a pessimistic outlook. When considered as a closed system, the universe's natural tendency would be one constant move towards death and decay and the ultimate heat death of the universe. This pessimism has also translated into a fatalist understanding of humanity's role in nature when considered under the viewpoint of the entropy law. For instance, Claude Lévi-Strauss commented that anthropology could be re-labeled as 'entropology', as 'Man has never — save only when he reproduces himself — done other than cheerfully dismantle million upon million of structures and reduce their elements to a state in which they can no longer be reintegrated' (Lévi-Strauss 1961, p. 397).

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Publisher: Inter-Research · www.int-res.com

We identify 2 common 'fatalistic' ideas that can derive from this understanding. First, 'decelerationist fatalism' is an accepted view that living activity (and human activity in particular) is, like any energy transformation process, inherently entropic. Given that entropy production is irreversible, we would have a limited (negative) entropy budget which we are depleting, more or less quickly. Therefore, the best we could aim at is to reduce our entropy production as much as possible (i.e. by diminishing energy consumption and improving efficiency), thereby winning time but knowing that by the mere act of existing we are inevitably depleting our conditions of existence. Georgescu-Roegens' analysis, which understands material resources as a finite stock of negative entropy in the Earth's crust, would be a classic presentation of this position: 'it is the meager stock of the Earth's resources that constitutes the crucial scarcity (...). If we stampede over details, we can say that every baby born now means one human life less in the future' (Georgescu-Roegen 1971, p. 304).

Second, 'accelerationist fatalism': an even more pessimistic view would consider that it is impossible even to reduce our disorder production rate. There appears to be an 'extremum principle' that pushes entropy production to the highest rates. According to Haff (2014a), such a principle would 'raise our skepticism about the likely long-term effectiveness on constraining fossil fuel use of instruments like policy statements, regulations, treaties, and political decisions, which, [...] would appear as rules made to be broken', as an 'increasing rate of energy use is not something humans can ultimately control' (Haff 2014a, p. 412).

This last view appears to coincide with the observation that throughout its evolution, life has increased its rate of energy consumption by finding increasingly powerful sources, starting with geochemical energy and then managing to use sunlight, oxygen, flesh, and finally fire, increasing in each step its complexity concomitantly with its capacity to use energy (Judson 2017).

In the same way, the whole history of human societies can be seen as a process in which humanity, as nature did on its own before it, learns to use more and more powerful sources of energy: from foraging to harvesting to using fossil fuels, ultimately exploiting and dissipating all available energy gradients (Deléage et al. 1991, Crosby 2007). The ultimate tendency of living and social organisations throughout their evolution would be towards increasingly intensive energy use, correlated with increased entropy production.

Added to the current failure to reduce greenhouse gas emissions linked to fossil fuel use, these accounts seem to provide a compelling case for a thermodynamic-based fatalism: the universe's inherent tendency to death and decay and the acceleration of this tendency by complex and energy-intensive organisations would all be necessary features of a world based on the laws of thermodynamics.

To critically assess the validity of these thermodynamic pessimist views, we will first, in Section 2, present the main ideas of classical thermodynamics, how they represent a conundrum for biological science, and how a thermodynamic understanding of living systems as open and self-organised thermodynamic systems make it possible to build a productive bridge between biology and thermodynamics. We then critically examine the claim that 'the purpose of life is to dissipate energy', which affirms that thermodynamics can provide a complete account of purposive phenomena in the living realm. We argue that in this aspect, living organisations are fundamentally different from simpler, self-organised structures in that they are able to determine their own goals.

In Section 3, we critically examine thermodynamic extremum principles as applied in climatology and ecological studies, and whose validity to apply generally to far-from-equilibrium systems is currently being discussed in science. We show how maximum entropy production and maximum power refer to an optimum state rather than an ever-increasing energy dissipation. Also, we present the idea that in far-from-equilibrium systems, maximisation principles have been shown to have an heuristic rather than a predictive value; that is to say, they help in the investigation of the particular structure and constraints that constitute a system at a given point, and which determine which is the optimum state rather than allowing for a prognosis of its development.

In Section 4, we illustrate the use that thermodynamics has been put to in the understanding of the Earth taken as a whole system as well as the role of maximum entropy principles in understanding earthly dynamics. Based on proposals by Lovelock (2004) and Kleidon (2016), we can thus define what an optimum state corresponds to on planet Earth as well as what role the industrialised and fossil fuel-reliant human society has within it.

On that basis, in Section 5, we discuss the issue of whether human society could, as a complex organised system, aim to reduce its own energy consumption to reduce greenhouse gas emissions. We argue that in thermodynamic terms, human society is better understood as a part of the Earth system. From this perspective, the continued depletion of fossil fuels and the rise of CO_2 in the atmosphere is seen as a malfunctioning of the Earth system that drives it away from an optimum state rather than a thermodynamic necessity. As we will defend, humanity can and must act to reorganise its use of energy and material goods in a way that helps to replenish rather than reduce Earth's potential for life.

2. THERMODYNAMICS AND THEIR APPLICATION TO THE UNDERSTANDING OF LIFE

The laws of thermodynamics provide a general and all-encompassing framework for the description of material reality, to the extent that Einstein (1979) thought they would never be overthrown. The first law allowed for the unification, or connection, of previously separated fields of physics. Energy can be transformed qualitatively but it cannot be created or destroyed. Thus, in an isolated system (to which no energy is added or subtracted), energy remains constant. The second law arises from the study of thermal machines and the realisation that in any energy-transformation process, it is impossible to fully convert energy into work. A part of the useful energy will irreversibly be lost in every step. This necessary loss is expressed in the increase of entropy, a property that relates to the lower quality of unusable energy. The law thus carries a time directionality within it, which distinguishes future states of the universe as always having less useful energy available than present and past states (Atkins 1984). Since its formulation in the field of thermodynamics, entropy has now found much broader applications through quantum physics.

In this section, we shall cover an explanation of how living organisation is possible given thermodynamic laws; secondly, the way in which thermodynamic laws have been used to give an account of what life is; thirdly, the limits of thermodynamic accounts to provide a full account of life and its teleological and finalistic nature. Finally, we critically examine the epistemic role of thermodynamics in relation to biology.

2.1. The living organism as an open thermodynamic system: Is the purpose of life to dissipate energy?

The relationship between thermodynamics and biology was classically construed as paradoxical. While physical reality tends necessarily to states of increased disorder and stillness, living phenomena exhibit an 'excess order' that seems to run counter to this tendency.

Early influential conceptions of life in relation to thermodynamics (Schrödinger 1944, Wiener 1965) conceived that the internal low entropy of the living organism is compensated by the export of entropy to the environment. Von Bertalanffy and others built upon this perspective, characterizing living systems as (thermodynamically) open systems (Bertalanffy 1968, Kauffman 2000, Moreno & Mossio 2015). Schematically, we can say that a living system always takes energy and matter from its environment to produce order within itself and exports waste and entropy back into the environment. In particular, all life forms we know need chemical energy to fuel their metabolism. That consumption of chemical energy then produces heat and waste materials. Adding heat to the environment increases the thermal entropy of the system. This general scheme can be applied to unicellular organisms, multicellular organisms, or more complex and integrated organisations such as complex societies.

Having guaranteed the compatibility of living organisation with the second law, Schrödinger (1944, p. 68) established that the understanding of biological complexity should move away from thermodynamic laws into 'other laws of physics, hitherto unknown'. However, the approach of Prigogine and his collaborators, years later, can be seen as reintroducing thermodynamics into the study of biological systems through the concept of dissipative structures (Prigogine & Nicolis 1967) as a form of self-organisation of matter within a system correlating to an increased efficiency in dissipation of an external energy gradient. These structures are characterized by breaks of temporal symmetry allowing for the appearance of non-linear, non-deterministic, self-organised, historical processes, which are all phenomenological features of biological complexity. Prigogine and his collaborators insist on the new vision of biological and human phenomena allowed by this advance in physical science; which would, by escaping the linearity and determinism of Newtonian science, call for a new alliance between natural and social science in which historicity and non-determinism would hold a strong place (Prigogine & Stengers 2005).

However, the apparent preference of matter for states of increased energy flow can also be taken as having a strong teleological explanatory value. Indeed, if dissipative structures increase the rate of energy dissipation of the system of which they are part, and thus the particularities of that system can be explained as serving this purpose, then this development of physical science would seem to allow for the reintroduction of finalistic principles in the investigation of nature, in a way putting physical science in a dominant position again within an unequal new alliance between natural and human sciences.[1]

This has led some authors (Schneider & Kay 1994, Swenson 1998, Sagan & Whiteside 2004, Schneider & Sagan 2006) to develop a general explanation of biological phenomena based on thermodynamic principles. In Sagan and Whiteside's words, 'teleology as found in purposeful organisms, including humans, derives from inanimate flow systems thermodynamically organised 'to' (this is their function, their prebiotic physiology and their materialistic purpose) reduce ambient gradients' (Sagan & Whiteside 2004, p. 173).

Swenson provides another version of this idea with his proposed law of maximum entropy production (hereafter LMEP), 'the system will select the path or assembly of paths out of otherwise available paths that minimize the potential or maximize the entropy at the fastest rate given the constraints' (Swenson 1998, p. 173). In that way, thermodynamics would predict not only that entropy tends to increase in every event, but that nature will always favour those events that create entropy at the fastest rate.

This preference would then have a strong explanatory value to account for a wide, overarching variety of events, from the origins of life to human psychology, etc: '[LMEP] provides the nomological basis for dissolving the postulates of incommensurability between physics and psychology and physics and biology — between thermodynamics and evolution' (Swenson 1998, p. 172) On a similar vein, Schneider & Kay (1994, p. 45) claim that through their reformulation of the second law of thermodynamics, they 'provide biology with a paradigm that not only describes the 'why' of life but also describes the directions in which living systems will develop and evolve'. It is the first claim that concerns us for now: the idea that the 'why' of life can be fully explained through thermodynamics. The second one, on the descriptive and predictive capacities of entropy principles, will be discussed in Section 3.

[1]Although Prigogine's breakthrough always led him to insist on the acceptance by physical science of the specific role of biological and human sciences in the understanding of our complex world (Prigogine & Stengers 2005), some of his and his collaborators' work can be seen as a new reductionist effort, in which non-linear thermodynamics are applied in an overreaching way to the study of ecological and social phenomena, sometimes on the basis of dubious analogies (i.e. between a human being and a particle) (Bertrand 2017). The positions we discuss below correspond to a stronger and more explicit reductionism, based on a finalistic principle.

Swenson presents a mental experiment to help understand his law (Swenson 1998). A house in winter will slowly lose heat under the cracks of the door and windows, and, by conduction, through the walls. However, when a window is opened, heat will be quickly dissipated through it. While this process is going on, a small amount of conduction through the walls will also continue. This illustrates how the system as a whole will exploit all the available pathways in order to dissipate energy at the quickest rate. Nature will choose the available pathways that allow for the quickest dissipation. Given that, as the concept of dissipative structures indicates, 'ordered flow produces entropy faster than disordered flow', nature (by producing structures) is always 'in the order production business' (Swenson 1998, p. 180). This, according to Swenson, is the central drive that naturalizes finality.

The same example can be used to show the limitations and blind spots of such an attempt to give a general and all-encompassing thermodynamic explanation of biological phenomena: What led the window to be opened? If properly closed, it would not open itself no matter how big the potential is. For it to be opened, a force orthogonal to the window latch needs to be applied, and the thermodynamic potential itself does not produce this force. Going back to the terms of Swenson's formulation (Swenson 1998, p. 173), which are 'the available paths' is precisely the question that is begged. Nature and evolution have creatively and contingently produced new paths (such as biochemical ones) that did not previously exist. Although one can observe a tendency for the efficiency of many systems to increase, no general law can account for this creative force.

Moreover, what we observe in any house is that the design aims to maintain heat inside, not to dissipate it. Can the law of maximum entropy production, which claims to explain everything, also account for the existence of the actual design in reality? This fundamental question applies to many aspects of biological organisation where energy is stored (e.g. ATP) for later use rather than being immediately expended. While LMEP seems to correspond to intuitive features of natural reality, it is clearly insufficient to fully account for the vast complexity of biological systems. It is thus not surprising that proposals such as Swenson's have received criticism and been dismissed as purely speculative, given its lack of specificity (e.g. Mirazo 2001; Martyushev & Seleznev 2006).

It is not apparent that the way in which any particular organism is constructed acts to maximize the dissipation of energy. Quite the opposite; even if their overall result is exergonic, organisms generally concentrate and store energy, and seem to be interested in using it in purposeful ways rather than 'burning it' for the sake of the second law. Again, one can suppose that the energy will tend to dissipate at the highest possible rate given the constraints. However, then this just points to the constraints as what needs to be explained and tells us nothing about their particular configuration.

For an extremum principle to be relevant, it must have an explanatory value for the particular structure adopted by a system or be predictive about its future or most likely configurations. This cannot be assumed as a blanket principle about reality; the conditions, boundaries, and types of systems to which it might apply ought to be specified. It could be argued that the organismic scale is not the most relevant in exploring principles of entropy production maximisation in biology, but rather that it is at the social, ecological, or planetary scale that these are most likely to operate. In Section 4, we will explore this perspective in its most general scale, regarding the evolution of the Earth system as a whole.

The account of living organisation cannot simply be reduced to a physical self-organisation that would explain order. Organisation is more than order and cannot be reduced to a thermodynamic account (Mirazo 2001, Pross 2003, Fox Keller 2007, Juarrero 2014). The type of organisation that is characteristic of life emerges out of intricate evolutionary and developmental dynamics (Gould 1985, de la Rosa & Müller 2021), involving genetic, organismic, and environmental factors (Lewontin 2000), resulting in a multiscale historical (Jablonka & Lamb 2005) and agentive process (Walsh 2015) that bootstraps its own autonomy from generic physical or statistical laws.

A proper understanding of biological phenomena should account not only for their accordance with a preexisting natural law but also for their ability to set their own goals, which add a level of complexity to merely self-organised, teleomatic structures (Barandiaran & Moreno 2008, Moreno et al. 2011, Barandiaran & Egbert 2014, Moreno & Mossio 2015).

2.2. The thermodynamic framework as a prolegomenon to complexity and biological studies

The emerging consensus is that if a thermodynamic approach to far-from-equilibrium states can explain the possibility of the emergence of non-linear, complex phenomena, then the laws and explanations for these have to move away from thermodynamics and into other fields. Thermodynamics can thus be taken as a 'framework', rather than as a theory (Mirazo 2001) for the study of biological phenomena. In this way, the study of thermodynamic conditions for the existence of biological organisation acts as a sort of prolegomenon, whereby the far-from-equilibrium state is taken as a given pre-condition for the emergence of living organisation.

The discussion of thermodynamics occupies an introductory position, warning about what is possible and not possible for any complex system. The second law cannot be broken; thus, any endergonic process, which concentrates energy, must be coupled to an exergonic one, which dissipates it, with the dissipation being at least as large as the concentration. In this way, thermodynamic laws operate somehow like the parent warning their child that they should return home at a certain hour. If that condition is respected, the child, free from parental control, can do whatever he/she pleases during that time. Within the parents' normative framework, the child is autonomous to operate within constraints.

However, even if thermodynamics cannot give a comprehensive explanation of what life is or why it exists, the question remains whether thermodynamic extremum principles (for instance, the tendency to maximize the production of entropy) can effectively describe and predict the evolution of complex systems like those found in biology and society. As a result, the discussion shifts from a philosophical debate regarding the nature of life to a scientific inquiry regarding its predictability in terms of thermodynamic principles.

The next section aims to evaluate whether, according to current scientific knowledge, there are extremum principles in thermodynamics that might determine the evolution of ecological systems and human societies. To follow our example above; even if parental norms leave room for children to do as they wish provided they are back home on time, will children predictably try to maximise the time spent out before returning home? On the contrary, will they minimise the amount of time and try to return home as soon as they can? Are these extremum principles predictive and in some way determinant of their behaviour before coming home?

3. EXTREMUM THERMODYNAMIC PRINCIPLES IN SCIENCE

Extremum principles are pervasive not only in thermodynamics (Prigogine & Kondepudi 1999) but also in many branches of science such as physics, biology (Edwards 2007), psychology (Rachlin et al. 1981), and economics (Sen 1997). Such principles apply when a system, or agents within a system, can be predictively described as maximising or minimising some variable (e.g. energy, friction, biological fitness, economic benefit, or utility) or, more technically speaking, whether, given certain constraints, there is a stable or equilibrium state (competing with alternative states) that maximises or minimises a certain function. In this way, extremum principles help predict the evolution of such systems because they will tend to settle on the state in which the given function is maximised or minimised.

In the study of living beings, extremum thermodynamic principles have often appeared in studies of the development of ecosystems (rather than individual organisms). It has long been observed that ecosystems seem to evolve into states of increased energy capture and dissipation. Lotka formulated the maximum power principle (Lotka 1922), according to which there is an evolutionary pressure to increased energy use by living beings. More mature ecosystems would appear to be better at capturing and using sunlight, thereby increasing the entropy of the radiation that is re-emitted back to space. Odum & Barrett (2004), Margalef (1998), Ulanowicz et al. (1987), and Schneider & Kay (1994), among others, have elaborated on these ideas. Although they seem to correspond to observations on the general development of ecosystems, they have not been shown to be able to generate predictive measures (Virgo 2011).

Extremum principles are accepted as a basic tool for describing isolated systems and simple linear systems in near-steady states close to equilibrium (Section 3.1). They have been found to have empirical applicability in certain fields and under certain conditions in far-from-equilibrium states (Section 3.3). An overview of this discussion is provided in Table 1.

Table 1. Thermodynamic principles and their perceived fatalistic consequences

<table>
<tr><th colspan="4">Field of applicability</th><th>Law, theorem, principle or idea</th><th>Meaning</th><th>Perceived fatalist consequences</th><th>Rebuttal</th></tr>
<tr><td colspan="4">Natural Law</td><td>Second law of thermodynamics</td><td>It is impossible to build a perpetual motion machine</td><td>Any potential work or order will demand energy consumption and entropy release</td><td>The Earth is an open system with a constant supply of energy from the Sun</td></tr>
<tr><td rowspan="5">Different kinds of thermo-dynamic systems</td><td colspan="3">Closed systems</td><td>Maximum entropy principle</td><td>Every closed system eventually will reach a stable state of maximum entropy or thermodynamic equilibrium</td><td>Heat death of the universe</td><td>Does not apply to human timescale or planetary scale (the Earth is an open system)</td></tr>
<tr><td colspan="3">Open systems</td><td>The living organism maintains internal order by exporting entropy to its surroundings (Schrödinger 1944)</td><td>Life is not incompatible with the second law of thermodynamics.</td><td>- Every system exports entropy to its surroundings
- Life accelerates the race to disorder and death
- “Decelerationist fatalism”: the best we can aim to do is to “reduce” our negative impact on nature.</td><td>If a system, A, is part of a broader system, B, the consequences of A on B should be analysed not only in terms of the entropy A exports to B (which will always be a net positive according to the second law), but also of its functional integration within, which might overall increase B’s productivity.</td></tr>
<tr><td rowspan="3">Different kinds of regimes in open systems</td><td colspan="2">Close to equilibrium</td><td>Minimum entropy production principle</td><td>An open system may stabilise in a linear regime, close to equilibrium.</td><td>No consequence for far from equilibrium systems.</td><td>-</td></tr>
<tr><td rowspan="2">Far from equilibrium</td><td>“Dissipative structures”</td><td>Self-organisation can arise in inert matter subject to an energy gradient.</td><td>Energy dissipation or the production of entropy might actually explain order</td><td>All order can and should be understood as conducive to an increased dissipation of energy
(as in Swenson’s law of maximun entropy production)</td><td>The order of biological systems is of a higher level than physical self-organised systems. Even if dissipative structures can be useful to understand the origin of life, and indeed a living organism, as any other system, will always contribute a net dissipation of energy to its surroundings; not every aspect of biological organisation can be explained as part of a tendency to increase energy dissipation</td></tr>
<tr><td>Climatic systems, ecosystems, human society?</td><td>Maximum entropy production or maximum power</td><td>Systems tend to maximise their energy dissipation</td><td>“Accelerationist fatalism”: it would be pointless to attempt to reduce fossil fuel emissions, given the availability of technology and resources, we will always tend to burn the available fuels at the fastest rate possible.</td><td>-Same general rebuttal as for all open systems or decelerationism (it is the whole system, that is the Earth, that tends to maximise its power). The burning of fossil fuels rather reduces the productivity of the whole system.
- Maximum entropy production does not describe an infinite increase but rather a stable state, given the constraints.</td></tr>
</table>

3.1. Extremum principles in thermodynamic systems close to equilibrium

The second law of thermodynamics states that the entropy of an isolated system tends to increase until it reaches a maximum value, at which point the system is in thermodynamic equilibrium. This is the principle of maximum entropy, which sets a goal state for the isolated system. In that state, entropy production will naturally be zero.

By contrast, an open system kept away from equilibrium by external conditions may achieve a steady, linear state in which the production of entropy remains constant and is reduced to a minimum. This can be understood as an extension of the maximum entropy principle to open systems: in a similar way to how the closed system will achieve an equilibrium state in which entropy production is zero (as entropy is already at its maximum), the linear, close-to-equilibrium state of an open system is one in which internal dissipation is minimal. In such a state, the principle of minimum entropy production means that the system is configured to minimise internal dissipation (Prigogine & Kondepudi 1999).

Although there are local examples of this principle in nature, planetary-scale Earth dynamics and ecosystems in general are not found to be close to equilibrium. Therefore, extremum principles that are relevant to our goals must apply to far-from-equilibrium conditions.

3.2. Extremum principles in far-from-equilibrium systems

An open system which is maintained away from equilibrium by external constraints can also, given a small fluctuation, lose its steady state and become far from equilibrium, a state that is characterised by nonlinear relations (Prigogine & Kondepudi 1999). Complex organisations are considered to arise under such conditions (Wicken 1986, Collier & Hooker 1999, Prigogine & Kondepudi 1999). Furthermore, Prigogine and Kondepudi stated that no extremum principles can generally apply to far-from-thermodynamic equilibrium systems (Prigogine & Kondepudi 1999), with their unpredictability and irreducibility being one of their basic features.

However, there are particular cases in which extremum thermodynamic principles have found application in these systems. For instance, in climatology, maximum entropy production principles have proven to have a useful predictive value (Lorenz 1955, Paltridge 1978). The atmosphere can indeed be modelled as a gas reservoir, whereby the different angle of solar radiation heats up the tropics and the poles at different rates. The atmospheric currents that move hot air toward the poles and cold air toward the tropics affect the temperature of these 2 extremes. Thus, the boundary temperatures of the system are not fixed but are rather affected by both the incoming and outgoing radiation and by the heat transfer process itself. The rate at which the heat is transferred actually reduces the temperature of the tropics and increases that of the poles.

The consequence is that while a strong temperature gradient drives an increased heat transfer process, a very high transfer process would deplete the temperature gradients, thus eliminating the push for the transfer. According to a principle of maximum entropy production, the interplay between these 2 negative feedback processes would predictably give rise to a state which corresponds to the one in which the entropy production is the largest (Kleidon & Lorenz 2006). In the climate model, it corresponds to a strong temperature gradient between the tropics and the poles, which allows for strong climatic currents.

The fact that the mixture of gases that comprises the atmosphere has a highly flexible character in which structures are easily made and unmade is a condition for the success of maximum entropy production principles in giving valid predictions (Virgo 2011). The success of maximum entropy production principles for predictive measures in climatology has led to speculation on whether a more general validity is possible for complex systems that are far from equilibrium — and in particular for ecosystems, where the tendency to maximise entropy production has been for long observed as a qualitative feature (Lotka 1922, Ulanowicz et al. 1987).

The observation of ecological succession has shown how, through their development, ecosystems tend to reach states in which solar energy is used in the most efficient way, resulting in a cooler surface temperature. Different principles have been formulated to describe this tendency: maximum entropy production (Dewar et al. 2014, Kleidon 2016), maximum rate of gradient degradation (Schneider & Kay 1994), maximum power (Lotka 1922, Kleidon 2023), increasing ascendency (Ulanowicz 1986), minimum specific energy dissipation (Margalef 1980), and others (see Yen et al. 2014). These different principles have been shown to be roughly consistent with each other (Bruers 2007, Yen et al. 2014)[2]. We will go into more detail — namely, regarding the relationship between the maximum power principle and maximum entropy production — in the specific discussion of Earth system dynamics.

3.3. The heuristic role of extremum principles

The way in which the ecosystem itself is organised in a way that maximises solar energy capture and use is, of course, the object of biological, evolutionary, and ecological study and cannot in itself be reduced to a simple thermodynamic analysis. The thermodynamic optimum state is always dependent on the particular and creative ways in which biological and ecological systems are able to organise to capture and use solar energy: ways which are structure-dependent, historic, and act as constraints on the system. Understood like this, thermodynamic optimality principles cannot be taken as physical laws but rather as descriptive tools that allow us to make predictions under certain conditions.

The discussion around the limits of photosynthesis can serve as an illustration of this point. Photosynthetic activity has long been a conundrum in this field because, despite being highly evolved, the rate at which it is able to extract energy from solar radiation and convert it into chemical energy in carbohydrates is below 1%, much less than what would be expected as a thermodynamic limit. Kleidon (2021) shows that in this case the thermodynamic limit might be given by the gas exchange rate of evapotranspiration and the ability of the atmosphere to transport it. The rate of gas exchange, which supplies CO_2 to the plant, would then be the constraint to energy transformation by photosynthesis.

In this way, the actual thermodynamic limit is only known once we have a proper description of the constraints that are at work. The predictive value of maximum entropy production is thus devalued to an heuristic tool that would allow us to identify the actual limits to the ongoing dissipation, which are given by the particular configuration of structures whose explanation, in turn, demands explanatory resources other than thermodynamic ones. This, in our view, corresponds to the heuristic role that Dewar (2009) attributes to maximum entropy production principles.

Many aspects of biological organisation, such as vascular networks and other kinds of distribution systems, do seem to follow principles of efficiency, which explains the fractal shapes that they adopt (West et al. 1997). However, that a particular part of the system takes a shape that is efficient (for instance, a vascular network distributes blood in a way that minimises energy heat losses) seems to correspond to the function of that part (to distribute blood), which is derived from the existence of the system as an organised entity.

Rather than providing all-encompassing fundamental laws that would allow us to predict the evolution of complex biological organisation, thermodynamics seems to allow for a general description of the development of a given biological entity at a given point.

3.4. A maximum entropy production principle for human societies?

Human societies can be described as complex systems which maintain their organisation by transforming matter and energy and exporting entropy to their surroundings (Harvey & Reed 1994, Court 2018). Through their evolution, we can observe how human systems have moved to increasingly intensive means of using available energy, with fossil fuels being the most productive of all (Deléage et al. 1991, Crosby 2007, Smil 2018). In the current conjuncture, fossil fuel use has been shown to increase CO_2 concentrations in the atmosphere, and thus drive climate change and global warming (IPCC 2014), to a point where it has become an existential risk for human societies (Huggel et al. 2022). Thus, politically driven efforts are being made to reduce CO_2 emissions (UNFCCC 1997, 2015).

However, some scientists consider that if the maximum entropy production principles were proven to be valid, any such effort would ultimately be futile (Haff 2014a): the tendency to use available energy, given the existence of the appropriate technological means, would be somehow inherent to our nature as a complex, dissipative system. The manner in which, despite the increasing awareness about global warming and the dangers of CO_2 emissions and political commitments to reduce fossil fuel usage, we have continued to move in the opposite direction, would seem to give reason to such fatalistic views.

This understanding is one in which human society is taken as a complex, organised system within a planet that acts as a stock and sink of material and energy resources. In such a view, the high complexity and activity of human society would inevitably tend to deplete the gradient and resources available on Earth. The maximum entropy production principle applied to human society would take us to a max entropy state on the planet as a whole.

[2]We are only considering maximisation principles related to thermodynamic magnitudes, and not 'the information-theoretic isomorphic' magnitude which is 'free energy' in Karl Friston's 'free energy principle' (Friston 2012).

However, far from a passive stock and sink externality, the Earth is itself a highly evolved and organised, far-from-equilibrium system (Jacobson et al. 2000, Anderson 2007, Lenton 2016, Steffen et al. 2020). Human societies have arisen as a part of it. Ignoring this means ignoring many (most) of the relevant constraints for the functioning of human societies, which depend on the earth's processes to sustain themselves. If we are to consider what an optimum state would be from a maximum entropy production standpoint, it is necessary to scale it up to the planetary scale beyond the false abstraction of an independent or isolated human system.

In the following section, we will discuss a thermodynamic approach to the understanding of the Earth system (Lovelock 1965, 1972, Kleidon & Lorenz 2006, Kleidon 2010, 2016) as an approach that models the Earth System from a thermodynamic perspective, including the use of maximum entropy principles and the position of the human species and society within it.

4. THERMODYNAMICS OF THE EARTH SYSTEM

The description of the Earth as a thermodynamic system has some precedents in the literature (Lotka 1922, Boltzmann 1974, Vernadsky 1998). In the context of the search for extraterrestrial life, James Lovelock came to the realisation that in the same way that the Earth's atmosphere exhibits an unstable mix of methane and oxygen due to continued biogenic processes, any planet bearing life would probably have a similar, measurable, chemical (and thermodynamic) disequilibrium in its atmosphere (Lovelock 1965). This led Lovelock and Margulis to their investigation of the Earth as a whole system whose distinct characteristic is the presence of life (Lovelock 1972, Lovelock & Margulis 1974). Their 'Gaia hypothesis' has since led to the creation of the field of Earth system science as a transdisciplinary research endeavour (Steffen et al. 2020, Rubin & Crucifix 2022).

Within this field, some works (Kleidon 2010, 2016) have focused on providing a characterisation of the Earth system in thermodynamic terms. Their analysis is particularly useful in order to clarify some of the topics in this paper, such as how thermodynamic laws shape the Earth; what an optimum state for the Earth is in thermodynamic terms; and what the role of human society is within the Earth and how it affects the thermodynamic state of the planet. We will provide a short summary of his work in order to approach these issues.

4.1. The Earth system dynamics

If we leave aside heat convection from the Earth's core and some initial chemical disequilibrium in the Earth's crust, all material processes within the Earth, including human societies, ultimately extract their energy from solar radiation. We can thus picture a series of concentric processes, the outermost of which is the atmosphere, that contain a temperature gradient because of the different rates of absorption of solar energy between the tropics and the poles. This gradient drives atmospheric motion (Kleidon 2016).

Atmospheric motion transports water vapor, transferring part of its power to the hydrological cycle. This cycle, in turn, contributes to the erosion of the continental crust and the transport of sediments, which means transferring part of its power to geochemical cycling. Hydrological and geochemical cycling are the basis for the development of photosynthetic life on the surface of the Earth. However, photosynthetic life not only receives its energy from these cycles but is also able to capture energy directly from solar radiation, transforming it into chemical energy and performing different kinds of work, increasing the total amount of energy that is directly available to life forms in the Earth's crust. The chemical—physical gradients that are created by these photosynthetic processes also contribute to the potentiation of upper-level processes, such as, importantly, the hydrological cycle, which in its current configuration is highly dependent on evapotranspiration by plants.

The increased free energy availability allowed by the transformation of solar radiation into chemical energy by photosynthesis has drastically transformed the dynamics and shape of the Earth's crust. From the emergence of granitical continents (Rosing et al. 2006) to animal life and the current development of a 'technosphere' based on fossil fuel usage (Dukes 2003), all these processes are ultimately dependent on photosynthesis.

4.2. Thermodynamic limits to Earth system processes and the application of the thermodynamic extremum principles

If the Earth can be described as an open thermodynamic system, and ultimately all of its processes can be described in thermodynamic terms, then what about the application of maximum entropy principles to describe its dynamics?

According to Kleidon's model (Kleidon 2016), the gradients that drive every energy transfer in the Earth are ultimately dependent on work processes done in the previous steps, given that the Sun's energy was captured, either as a temperature gradient or as chemical energy, through photosynthesis. For instance, the energy made available for geochemical cycling by the hydrological cycle depends on the rate at which the hydrological cycle is able to perform work. Overall, the ability to transport mass marks the general limit of activity within the Earth system.

The second law of thermodynamics establishes the theoretical upper limit for work processes in a system, given certain boundary conditions (i.e. the Carnot limit). However, in the systems considered, a lower limit needs to be established: given that the flux that depletes a gradient is driven by the gradient itself, a maximally efficient flux would eliminate its own drive. The maximum power of such a system is thus lower than the one that would be derived without taking into account the effect on the boundary conditions (Kleidon 2016). This also means that the energy that is available for work for each energy process (such as atmospheric motion, geochemical cycling, etc.) is necessarily reduced in every step, not only in the infinitesimal quantity that the second law would, in principle, require.

Thermodynamic optimality principles establish that each system will move, if able to develop the necessary structures, to states close to this upper thermodynamic limit. For instance, atmospheric motion appears to move at a rate that maximises the work done to dissipate the gradient (Paltridge 1978, Kleidon 2016). From this perspective, the most important descriptor becomes the work that is made by planetary processes, as it is the usefulness of these processes that is most significant for living activity. Whereas energy captured in the planetary surface will always be ultimately dissipated as heat, it is what happens in between, whether work has been done with it or not, which becomes more relevant (Volk & Pauluis 2010, Kleidon 2023).

From the point of view of the system as a whole, a state of maximum power is one in which biotic processes have increased gradients which allow for the most work and where this work is effectively realized. According to Kleidon, 'we could expect a maximum rate of mass exchange on a planet with a cool temperature that is above freezing, but not too warm. This state likely represents a state with the greatest absorption of solar radiation at the surface, the greatest rate of conversion into other forms of energy, and the strongest biogeochemical cycling. It would thus seem that this state of the Earth system is a state that is thermodynamically optimal with a maximum rate of dissipative activity at the planetary scale' (Kleidon 2016, p. 339).

This cool state of the Earth is partly achieved by a reduction in greenhouse gases in the atmosphere, such as CO_2. But most importantly, an oxygenated atmosphere with low CO_2, together with the reduced carbon compounds generated by life on the Earth's surface, represents a strong chemical disequilibrium. This is in line with Lovelock's observation that planets endowed with life would exhibit a thermodynamic disequilibrium in their atmosphere (Lovelock 1972)[3].

Current measurements and estimations of temperature and CO_2 throughout the Earth's history seem to indicate that, indeed, there is a long-term trend towards a cooler temperature and low CO_2 concentrations, both coherent with a thermodynamic optimum thermodynamic state for the whole Earth system. In particular, during the Cenozoic period, starting with the great Cretaceous–Paleogene dinosaur extinction, the planet became gradually fresher, culminating in the Quaternary period. The particular mechanisms that have caused this process are an open question in climatic science (Retallack 2001, Mudelsee et al. 2014, Lu 2015). Some will put more emphasis on tectonic and geological processes, whilst others insist on the evolutionary and ecological developments of life which have allowed for a more productive biosphere. Both aspects are undeniably linked. The maximum entropy production perspective does not in itself provide an explanation but rather allows us to describe this recent period as an evolved state in which the productivity of the whole system has moved towards a maximum.

4.3. Human activity in the Earth system

The human species has evolved during the Quaternary period, which we have described in the previous section as a relatively optimum state of the Earth system. What is the thermodynamic characterisation of human societies within this context? As with any other process on Earth, human activity is sustained by free energy, made available by processes happening

[3]We must note that Lovelock's original observation referred to the disequilibrium between methane and oxygen within the atmosphere, whereas here we are referring to the disequilibrium between the atmospheric composition and the organic compounds in the crust. In fact, as Kleidon points out (Kleidon 2016, p. 250), the presence of methane in the atmosphere can rather be seen as an inefficient 'energy leak' in the decomposition of organic compounds in the crust.

within the geosphere. In the first place, there is the energy needed to sustain metabolic activity (functions within our bodies). This is primarily supported by food, obtained from photosynthetic and biotic life, which provides the necessary free energy for the functioning of our bodies. It is worth noting that the magnitude of this physiochemical transformation is estimated, given the current population of 7×10^9 people, at around 0.7–4.9×10^{12} W (Kleidon 2016), which is already at the scale of planetary processes such as oceanic circulation, whose power can be estimated at around 2–7×10^{12} W.

On top of this, there is the energy needed to sustain the externalised activity of human society; i.e. the whole technosphere (Haff 2014b). The sources of this energy are mostly free energy stocked in fossil fuels along with nuclear fission and renewables. The total amount of energy used is estimated at around 17×10^{12} W (Kleidon 2016).

To the extent that human activity is sustained by free energy that is made available by external processes (photosynthetic activity and fossil fuel production by bio-geospheric processes), it can be seen as dissipating existing gradients. In particular, the rate at which gradients from fossil fuels are depleted is much higher than the rate at which they are generated (Dukes 2003), which clearly makes it an unsustainable source. The human species is consuming, each year, the equivalent of 400 yr of all the currently existing life on Earth converted into fossil energy. Furthermore, the increase of atmospheric CO_2, the main driver of current anthropogenic climate change, can be described as a reduction in the thermodynamic disequilibrium of the Earth's atmosphere, which potentially decreases its overall productivity.

Regarding alternative renewable energy sources, there is an important distinction to be made between different kinds. Eolic activity transforms kinetic energy from the atmosphere into electric energy for human use. In this sense, it depletes an existing gradient and takes away energy from essential geospheric processes. The amount of energy in wind is limited and is necessary for the hydrological cycle. Eolic energy can thus be seen as an extractive source of energy (Kleidon 2016).

On the other hand, the development of direct concentrated solar technology and photovoltaics allows humanity to generate free energy out of solar radiation in a way analogous to photosynthetic activity, and in a more efficient way (Kleidon 2016). Solar energy can thus be seen as a way for humans to increase, rather than deplete, the total free energy available for biotic processes on Earth. Reforestation of deserted areas is another way in which total free energy available for biotic activity could be increased due to human action. In this way, according to Kleidon, we can imagine 2 kinds of futures (Kleidon 2016): one in which the demand for energy by human activity increases more quickly than the generation of free energy available to human processes, which would result in a depletion of gradients and an overall decrease of free energy available for biotic processes on the Earth. On the other hand, we can imagine that human activity manages to generate free energy from solar radiation at a higher rate than it increases its demand. The thermodynamic limits for these processes lie, at least theoretically, very much above the current rates. Overall, this would increase the total free energy available for biotic processes on the Earth. We will come back to this scenario in Section 5.2.

This general scheme, in terms of free energy production and expenditure, does not, of course, account for many other effects of the anthropogenic technologies on planetary processes. For instance, while a solar panel might be able to capture solar energy in a more efficient way than a tree, the process of production of the panel (from mining to manufacture and transport) is far more disruptive to planetary processes than the growth of a tree. We will delve further into this in the following section.

5. DISCUSSION AND CONCLUSIONS

5.1. Theoretical consequences for the understanding of life and thermodynamics

From the type of empirically sound application of thermodynamic principles to Earth systems science proposed by Kleidon, life does not appear to be reducible to thermodynamic principles, and neither is thermodynamics simply a prolegomenon for the study of the complex organisation of life. Rather than looking to thermodynamics for an explanation of life, we should look to the biosphere to explain the far-from-equilibrium thermodynamic configuration that is characteristic of our planet. This thermodynamic disequilibrium cannot simply be taken as a prerequisite for life. Even if it is likely that early Hadean Earth had strong disequilibrium and reactions that allowed for the emergence of self-organisation in an abiotic context (García-Ruiz et al. 2020), the fact that Earth still has a strong thermodynamic disequilibrium today and has not yet reached a steady state close to equilibrium is the result of the continued existence and development of life.

The fact that the Earth is exposed to solar radiation and thus can be considered as an open system away from equilibrium because of this constraint is not sufficient to explain the far-from-equilibrium context in which living organisms develop. Living organisms feed from external gradients that are already highly organised and specifically configured as a result of the processes of life. Thus, an organisational description of life always needs to take into account the planetary scale at which these processes function. This bears important consequences on the way we understand the relationship between living processes and entropy production (including human activity).

If we consider the whole Earth as a complex, multilayered dissipative system, the net entropy production of this system results in radiative entropy sent to outer space. As a consequence, this entropy has little or nothing to do with increasing decay and death: the entropy sent back to space is the result of the biosphere maintaining a highly rich and powerful living system.

Within the Earth system, the state of maximum power corresponds not to a depletion of existing gradients but, in fact, the opposite: the generation of powerful gradients, particularly chemical ones, that have increased thermodynamic disequilibrium over time, allowing the system to better use solar energy. A relevant example of this creation of gradients by life is the capture of carbon by biotic organic compounds and the oxygenation of the atmosphere. This chemical configuration is a far-from-equilibrium state which is highly reactive and allows for the complex life forms we know. This disequilibrium has increased rather than decreased over Earth's history (Inglis et al. 2015), until recently.

5.2. Practical implications

From this standpoint, the recent great acceleration of human societies (Steffen et al. 2015) which has resulted in, among other things, rapidly increasing levels of CO_2 in the atmosphere is not the natural continuation of the process of increasing entropy production by the Earth system, but rather an increase in entropy within the Earth system, which indeed deteriorates the conditions for life. This is consistent with other interpretations that characterise the current moment as that of a drastic increase in entropy within the Earth (Stiegler 2018, Valero et al. 2021, Montévil 2023). Going back to the fatalist accelerationism position presented in Section 1, we stress that the consequences of the increased energy consumption through fossil fuel use by human societies have to be seen not in continuity with the development of life, but rather as a disruption of this process.

However, is this disruption something inherent to the human species? As with other heterotrophic organisms, humans depend on the chemical energy that has been captured by autotrophic ones (like plants, algae, or bacteria that are able to produce organic compounds out of inorganic ones and in combination with energy extracted from light or from inorganic reactions). Thermodynamically, it could seem that these organisms simply live on others' work. However, an ecological perspective shows that they can also perform ecological functions that contribute to the increase in biotic thermodynamic power. For instance, herbivores grazing plants puts them back in a state of high growth rate while also contributing through their waste generation to accelerate the cycling of nutrients (Pastor et al. 2006). Their presence might thus contribute to the increase of total autotrophic activity. Of course, an excessive population of herbivores will tend to deplete vegetated mass quicker than it can recover, so carnivores and apex predators function as population controllers in natural ecosystems (Ritchie & Johnson 2009), together moving the system towards a state of increased productivity.

Humans are primarily heterotrophic beings. Thus, to understand our role within the global ecosystem, it is not enough to consider the rate at which we appropriate energy provided by photosynthetic life, but also how our activity interacts with life in ways that degrade it or enhance it. On the one hand, it is clear that in recent times, the activity of human societies has led to a decrease in biomass (Bar-On et al. 2018). On the other hand, this cannot be seen as inherent to the human presence within an ecosystem. For instance, it is now understood and recognised that the presence of indigenous peoples has contributed to the development and conservation of increasingly productive ecosystems (Garnett et al. 2018, Lombardo et al. 2022).

Currently, experiences in rewilding (Perino et al. 2019) and in regenerative agriculture (Sherwood & Uphoff 2000) show that an intelligent intervention by humans can serve to boost biotic activity and carbon capture with very low (or negative) inputs in terms of energy and nutrients. For instance, a practice in regenerative agriculture is to use cover crops that protect the soil from degradation caused by exposure to direct sunlight while continuing to produce organic material from sunlight that can be used as fertiliser (Dabney et al. 2001). The overall result is an increase in total biotic activity, which can serve to sustain human life through food while at the same time maintaining biodiversity, increasing carbon capture, water retention by soil, etc.

Therefore, if we are to describe human society as a dissipative structure exporting entropy to its surroundings, then we have to acknowledge that either this is an abstraction that does not take into account other interactions with the surroundings that might help replenish energy gradients, or that the total dissipating effect is not justified by a necessary physical principle but only by the current particular socio-economic configuration. In other words, there is nothing in the nature of thermodynamic principles that either compels our social system to consume more free energy than what we can help produce, or to reduce the biotic activity that surrounds us and degrade our environment. We are not necessarily, by bio-physical imperative, driven by extremum principles to maximize energy dissipation but instead are politically obliged to dissipate better, with a sense of better that can only surface beyond thermodynamic principles when we attend to the organisation of life at the planetary scale.

From a thermodynamic point of view, the essential question is not only how we reduce the entropic disruption of our environment linked to human activity, as in the fatalist decelerationist perspective (which of course we should do if this entropy results in the breakdown of the Earth system as an evolved thermodynamic object), but more fundamentally, how can human activity contribute to the regeneration of biotic activity, ecosystems, and biodiversity. This is far from a thermodynamic impossibility but something that we might be well equipped to do as an intelligent species capable of understanding ourselves as interdependent within our Gaian context.

The main difference between humankind and other living species is our capacity to coordinate our collective action by means of shared virtual scenarios; that is, to be reflexively, narratively oriented. This can be a peril if we use it to imagine ourselves as all-powerful Prometheans able to indefinitely transform and consume the resources around us or as all-powerless Epimetheans carried out by fictional extremum principles. However, if used to take care of living systems, it can serve to accelerate the regeneration of ecosystems. The condition is that we place at the center of our concern not human society as such, but the whole life system of which we are part, which would appear as a very intelligent thing to do. Doing so demands that we create, rather than destroy, the thermodynamic gradients that we live by.

Acknowledgements. A.M. and X.E.B. carried out this work in the context of the Outonomy Research Project, grant PID2019-104576GB-I00 funded by MCIN/AEI/10.13039/50 1100011033. Both authors have also benefited from being members of the IAS-Research group, funded by the Basque Government (grant IT16668-22, Principal Investigator Jon Umerez). Special thanks go to Kepa Ruiz-Mirazo, Miguel Aguilera, and Sergio Rubin for their careful revisions of the early versions of the manuscript. Open Access funding was provided by the University of Basque Country.

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Editorial responsibility: Konstantinos Stergiou, Thessaloniki, Greece
Reviewed by: S. Rubin, A. W. Stahel, A. Kleidon

Submitted: October 11, 2023
Accepted: May 6, 2024
Proofs received from author(s): July 27, 2024