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Chapter 1

Biosphere Evolution, Ecology and Sustainability: Why Thermodynamics and System Theory Matter

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Abstract

This chapter explores the importance of thermodynamics and systems theory in terms of understanding the evolution, ecology and sustainability of the Biosphere. Firstly, the role of thermodynamics as both a driver and constraint upon the Biosphere is examined. The Biosphere is part of a complex system, the Earth system, which, like all complex systems, has a number of characteristics that are key to understanding its functioning, resilience and recovery from damage. These key characteristics of the Earth system are self-assembly and self-organization, emergence, nonlinearity, sub-optimality and real-time feedback. We examine the consequences of these for the Biosphere and for our own species. The relationship between how the Biosphere evolves and how it functions (its eco-physiology) is considered. Fundamental to this exploration are the concepts of Zusammenhang, as developed by Alexander von Humboldt, and of the Earth as a superorganism, as developed by James Hutton. The implications for environmental, social and economic sustainability are analysed, and suggestions as to how we should move forward are made. The chapter concludes by considering the consequences of thermodynamics and systems theory for any exobiosphere in the Cosmos, given the universality of these fundamental, underpinning concepts.

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Introduction

The Biosphere has had a long and turbulent history stretching across 3.8 billion years. Comet and meteor impacts, huge volcanic events and a runaway glaciation event in the Neoproterozoic era, known as snowball Earth, all have threatened its existence, and current human activity continues to perturb it. While it is unlikely to be the only biosphere in our universe, it is the only one that we know, from which we emerged and which, currently, provides the conditions that allow us to persist. In order to follow the journey of our own understanding of the Biosphere, and the Earth system within which it exists, we begin with Foucault's conceptualization of the history of ideas.

Foucault (1984) proposed that histories of ideas should be genealogical. Foucault's history relies on the telling of descent which traces the myriad events through which—thanks to which, against which—they were formed. The genealogy of ideas is extremely important in the case of the Biosphere. While the term 'Biosphere' is relatively recent, the conception of meaning has evolved across millennia. It has become what is referred to as a plastic word (Van der Laan, 2001), where meaning can be stretched and shaped within a myriad of different contexts, to the point where any rigorous definition disappears. Other similarly plastic words include sustainability, development, civilization, progress, sexuality, conservation, ecological and rewilding.

Philosophy, politics, geography, economic theory, science and the arts all play into what we consider the Biosphere to be, in terms of its meaning, value, importance, use, management and functionality. Weak sustainability theorists view natural capital as exchangeable with technological capital, while strong sustainability theorists view the Biosphere as irreplaceable (Skene and Murray, 2017). Passive rewilders consider nature as the best manager of its own recovery, whereas active rewilders advocate human intervention.

One of the most consistent, balanced ecological writers in ancient Greece was Theophrastus. He was the first to acknowledge that the rest of the Biosphere had a purpose independent of humans and emphasised the relationship between life and its environment. Yet his conception of an autonomous Nature, interacting with humanity, was overshadowed by the anthropocentric teleology of Aristotle.

Following a period of religious conceptualization of Nature either as a god in itself or representing the handiwork of a deity, to be reverenced and respected, in 1689, John Locke argued that, initially, God created the world and gave it to men in common to use for their sustenance. In other words, all the world was a commons. This was the beginning of the utilitarian conceptualization of the Biosphere, and represented a dramatic shift from the belief in Nature as the ‘primordial Mother’, where the Earth was regarded to be as equal and as necessary as God in the origins and process of creation (Merchant, 1980).

Locke stated that the Earth was *terra nullius*, or empty land, to be taken and used by civilized humans. For Bacon, to understand nature meant to disturb it and alter it (*natura vexata*) by means of human effort. This position would inform the Enlightenment philosophy of Condorcet (1955 [originally 1779]: p.173) who wrote that “Nature has fixed no limits on our hopes”. Nature was no longer to be worshipped, revered or treated with awe and wonder. Rather it would be used as a material source and sink for the progress of humanity.

Interpretations of the function, structure and evolution of the Biosphere and the Earth system as a whole vary widely. They truly have become plastic terms, from the superorganism of Hutton and the Gaia of Lovelock, to the slave of enlightenment thinking, a source and sink for humanity’s march of progress towards prosperity. From the utopian vision of the omega point encapsulated by Teilhard de Chardin, or of the Noosphere of Vernadsky, visions of metaphysical and physical origins and destinies pervade through history. Plato bestrode both with his shadows on the cave wall analogy, where the energetics of solar radiation led to the living world, whose physical structures inspired the shapes whose shadows danced and cavorted in front of the chained observers (Skene, 2009).

The selfish gene hypothesis, wherein the Biosphere is merely an extended phenotype (Dawkins, 1982), built from the genetic instructions of the cell, is the antithesis to Gaian thinking and the shadows of Plato, forming a reductionist, bottom-up model. The unit of organization has variously been ascribed to the gene or the planet, the individual or the species, forms or functions, the local or the global, spaceship Earth or the Cosmos. And these differing perspectives have significant repercussions for our understanding of the evolution, ecology and sustainability of the Biosphere itself and of our own roles within it.

Cause and effect have become ingrained in science. Plato emphasised that the sensual world was a mere shadow, and only through philosophy could the true meaning of existence be reached. Observations of shadows were seen as less informative than reasoning. As a result, for more than a thousand years after this, science became married to philosophy and became an exercise in logic, rather than observation.

It was Francis Bacon who challenged this marriage. In his Instauration Magna Part II: Novum Organum (1620), he wrote: “Men have sought to make a world from their own conception and to draw from their own minds all the material which they employed, but if, instead of doing so, they had consulted experience and observation, they would have the facts and not opinions to reason about, and might have ultimately arrived at the knowledge of the laws which govern the material world”.

Following the establishment of Descartes’ Mechanism, which separated the physical from the metaphysical (referred to as mind-body dualism), scientists and philosophers pursued the idea of a mechanized universe. This view states that the Universe can be explained based on cause and effect, allowing a reductionist linear chain of reasoning based on observation, and that every phenomenon can be adequately explained through the laws of motion.

From this point forward, two opposing philosophies emerged: rationalism and empiricism. In many ways the empirical view of science reached its apogee through Isaac Newton. Classical physics emphasised cause and effect. Newton’s laws allowed the prediction of everything from the fall of an apple to the trajectory of a spear or the orbit of a planet. Prediction provides power and underpins control and management. The Biosphere could be understood as a collection of species, and the number of such species representing biodiversity.

A pecking order was established, with those at the top lauded. Darwin (1994, p. 429) wrote: “Thus, from the war of nature, from famine and death, the most exalted object which we are capable of conceiving, namely the production of the higher animals, directly follows.” In this statement, two interesting points arise. Firstly, the Biosphere is considered as a field of conflict, within which the savage and bloodied battles of nature play out, and secondly, higher animals are viewed as exalted objects.

In a similar fashion, the classic food pyramid, ubiquitous in school textbooks, gives the impression of the apex predator, standing above all else, dominating everything. Yet nothing could be further from the truth. The apex predator is at the bottom of an energy food drain (not chain), wherein chemical energy, converted from solar energy, is produced by the primary producers, and is passed down the line of successive herbivores, omnivores and carnivores, like a bucket of water with a hole in it, until it is empty. The apex predators are reliant upon the successful passage of sufficient energy through the web of creatures between itself and the autotrophs in order to survive in an energetically demanding thermodynamic universe. Some ninety percent of consumed energy is lost at each link in the food web.

Plants and algae can survive without herbivores and carnivores, but the reverse is not true. The apex predator literally feeds off the crumbs from its master's photosynthetic table. Predator-prey populations curves tell the same story, wherein prey population size impacts on predator populations significantly. Thus, it could be argued that the apex producer and apex prey control the predator. Without our food we would be without hope. In many ways, the photosynthetic plants and algae can be viewed as the 'most exalted objects of which we are capable of conceiving' rather than the higher animals.

The emergence of empirical science, led by Bacon, would lead to a reductionist approach to the Biosphere, both physically (Newton) and biologically (Linnaeus and Darwin), the latter two of which broke the Biosphere down into a collection of species, both in terms of understanding diversity (Linnaeus) and evolution (Darwin). Species were then placed in two dimensional maps, called food webs, and keystone species were identified as significant, controlling agents. Reductionist thinking, first at the level of the species, and latterly at the level of the gene, stripped the Biosphere of its multi-dimensional complexity, both spatially and temporally, and left it as a purely mechanical entity that could be built upon or taken from with impunity.

At the same time, the relationship between economics and the Biosphere had been shifting. Derived from the ancient Greek words οἶκος (household, the whole house) and νόμος (law, order or form), economics represents the study of the production, consumption and transfer of wealth. The etymology is significant in that ecology derives from similar roots, οἶκος and λογία (the study of). Robbins (1935) defined economics as the science which studies human behaviour as a relationship between ends and scarce means which have alternative uses, and neo-classical welfarism derives values from human preferences alone. This approach is in stark contrast to indigenous views of the Biosphere, wherein a close relationship between individuals, community and landscape shapes the entire culture and economy. Economics represents the most significant set of damaging interactions between humanity and the Biosphere, and, thus, must be an intrinsic and central focus for any path to a sustainable future for ourselves.

Ecological modernization theory emphasises that all efforts to achieve sustainability should centre around further modernization of existing institutions, such as governments, multinational organizations and laissez-faire economics, rather than seeking to replace them. Founded on weak sustainability theory, the free market, combined with technology and education, is trusted to deliver continued progress in the face of environmental perturbation. The 'Biosphere as machine' approach is fundamental to this thinking, meaning it can be fixed, re-constructed, replicated or re-invented. Mol and Spaargaren (2000; p. 23) assert that "all major, fundamental alternatives to the present economic order have proved infeasible according to various (economic, environmental, and social) criteria". Thus, we see a business-as-usual model, avoiding fundamental changes to the core economic model.

However, the absence of any valuation of the damage to ecological functionality has long been raised as a concern. Westman (1977) was one of the first to attempt to formulate a measure of the value of products, inclusive of damage or loss in value of ecosystem functionality, upon which we rely.

Costanza et al. (1997) developed the concept of marginal or incremental valuations of ecosystem services, which they defined as the estimated rate of change of value with changes in ecosystem services from their current levels. However, issues exist around this concept, because it is fundamentally anthropocentric, wherein valuation is based upon the usefulness of the Earth system to humans, and its functionality is distorted as merely a servant to our progress. As will be noted later, the Earth system is part of a much larger, complex thermodynamic system, whose functionality is not determined by our activities. Rather, its emergent outcomes will merely incorporate any disturbance we, as a species, create through our activities as part of the greater conversation.

However, any attempt to 'value' the Earth system very much misses the point in terms of how it actually works. In much the same way that the properties of a complex system belong to the system as a whole and not to any one component (such as humanity), so too any attempt to value the Earth system based on the currencies of modern financial markets, be they yuan, euros or dollars, is surely a futile exercise. Instead, much greater emphasis should surely be placed on the true functionality and drivers of the Earth system, encompassed in systems theory and thermodynamics.

While Costanza et al. (1997) admit that the true value of the Earth system is infinite, by persisting in calculating marginal value, the Earth system is still reduced to some manageable and colloquial expression, rather than the actuality of a great river of energy flowing through the planet and allowing order to be established, through the generation of disorder (in recognition of the second law of thermodynamics). By diminishing the Earth system to a fiscal value, we fail to grasp its true meaning.

Boulding's (1966) conceptualization of spaceship Earth did much the same thing, imprinting the idea of Biosphere as an isolated machine, cut off from the thermodynamics of the Universe, where we are the captains steering our ship, and somehow holding the fate of our world in our hands. Yet from the perspective of a complex system, the ship can be turned inside out at a moment's notice, transforming into a myriad of other forms, due to emergence, nonlinearity, tipping points and regime shifts.

If we could ask the dinosaurs what they thought of spaceship Earth, they could relate that their demise resulted from beyond the Earth in two forms. Firstly, the comet came from space and secondly the major driver of the mass extinction to which they succumbed was a thermodynamic one, wherein the energy from the Sun, upon which they relied in order to maintain order within an entropic universe, was drastically reduced due to dust filling the atmosphere, creating an impact winter and leading to collapse. It would not have mattered what economic model they used, how they recycled their goods or what fiscal plans they adopted. Nothing in the spacecraft could save them. Thus, our point of reference for understanding the Biosphere should not be as a spaceship, but as part of a much greater cosmic play, whose script is written in the laws of physics.

Life is often divided into different sets of organizational units, integrated and interdependent on each other. These can be labelled as the gene, the genotype, the phenotype, the individual organism, population, ecosystem, biome and Earth system. While reductionist thinking has focused on the gene as building block of everything, particularly within the evolutionary school of neo-Darwinian thinking, ecologists take a much more holistic view, seeing the properties of any given aspect as emergent from the system as a whole, rather than as a consequence of any given component or unit. Thus, when examining any particular unit of organization, this systems context must be borne in mind. In systems theory, as we shall discuss later, the properties of the Earth system belong to the system itself, rather than to any subsystem such as a community, a population or a gene.

The Biosphere and the Earth System

Although Vernadsky attributes the first use of the concept of a biosphere to Chevalier de Lamarck (1802) as the domain of life, it is, more commonly, Suess (1875, p.159) who is acknowledged as the first to use the term, 'eine selbständige Biosphäre' (an independent biosphere), defining it as the envelope on the planet that supports life. Seuss further wrote that: "The plant, whose deep roots plunge into the soil to feed, and which at the same time rises into the air to breathe, is a good illustration of organic life in the region of interaction between the upper sphere and the lithosphere, and on the surface of continents it is possible to single out an independent biosphere" (Seuss, 1875, p. 3). Seuss connects all four spheres or envelopes (lithosphere, atmosphere, hydrosphere and biosphere) as an interactive entity, with the Biosphere straddling the other three spheres. Some authors recognize a fifth sphere, the cryosphere (Steffen et al., 2005). Vernadsky (1945, p. 31) went further, recognizing the Biosphere as an emergent outcome of a complex system (what we now refer to as the Earth system), in accordance with the universal laws of physics, when he wrote: "It [the Biosphere] is emerging as a planetary phenomenon that is cosmic in nature".

The Amsterdam Declaration on Global Change (2001) defines the Earth System as a single, self-regulating system comprised of physical, chemical, biological and human components. The Earth system has come to represent the suite of bio-physico-chemical processes, combining to represent the physiology of the planet as a superorganism, much as was suggested by Hutton (1788). The emphasis is on a complex interacting set of functions rather than of forms, with myriad connections and the flow of information throughout.

As far as the Earth system is concerned, humans, like all else, are conduits of information and energy. The structures are relatively unimportant. The Earth system is a self-organising complex system, managed by the laws of physics, not humans. Vernadsky emphasised that the Biosphere was composed of the media in which life exists, a biogeochemical entity, rather than the life itself (Huggett, 1999). Vernadsky (1945, p. 1) understood the importance of energetics when he wrote: "The Biosphere is distinguished as the domain of life, but also, and more fundamentally, as the region where changes due to incoming radiation can occur."

A Change in Thinking

At the start of the twentieth century, physics underwent a revolutionary change, and with it, so did scientific thinking. The uncertainty principle, developed by Heisenberg (1927), states that the speed and position of a small sub-atomic particle cannot be known simultaneously. Furthermore, any attempt to measure these things will alter the object that we are observing. Thus, observation disturbs reality.

This uncertainty therefore breaks the sacred bond between observation and the material world. Albert Einstein, quoted by Gibbs Jr (2009, p. 75), stated that “Even space and time are forms of intuition, which can no more be divorced from consciousness than can our concept of colour or shape or size. Space has no objective reality except as an order or arrangement of objects we perceive in it and time has no independent existence apart from the order of events by which we measure it.”

New physics challenged to the core our understanding of the Universe, with the empirical cause-and-effect foundations of reductionist scientific thinking shaken to the core. Two other developments would combine, over the past century, to reshape our understanding the Biosphere in terms of its evolution, functionality and of our place within it: thermodynamics and systems theory.

Thermodynamics

The 19th Century saw the beginnings of a revolution in physical chemistry, particularly in terms of thermodynamics (Skene, 2015). Thermodynamics moved from a classical to a statistical phase. The classical phase represented a macroscopic theory of matter. In 1824, Carnot wrote Réflections sur la Puisance Motrice du Feu (Carnot, 1824), in which he concluded that heat could neither be created nor destroyed and that the total heat of the Universe was constant. When a temperature gradient exists, work can be done and there can be no such thing as perpetual motion.

Statistical thermodynamics focused on the microscopic scale, involving probabilities of distribution. From this infinite number of microstates emerges the properties at the macroscale. Here, entropy represented the number of possible outcomes that a distribution could have. Boltzmann (Boltzmann, 1872) defined entropy in terms of molecular heterogeneity, where:

$$S = k \log W \tag{1}$$

(S = entropy, W = the number of energy levels available at a particular temperature and k = Boltzmann’s constant). Diffusion increases the entropy of a system, as seen in the Second Law of Thermodynamics. This equation formed the basis of all entropy concepts in modern science, playing an important role in terms of the development of quantum physics and can be found inscribed on the gravestone of Boltzmann in Zentralfriedhof, Vienna.

The Maximum Entropy Production Principle (MEPP)

Early in the development of thermodynamics, Berthelot (1879) stated that there was a directional element to thermodynamics in that any change in chemistry led to maximization of heat production. Onsager (1931) demonstrated that systems act to reduce barriers to increasing entropy. He mathematically demonstrated that:

$$dS/dt \,.\, I = \text{maximum} \tag{2}$$

(where dS/dt represents the rate of entropy change and I is the impediment to entropy increase). This became known as the Maximum Entropy Production Principle (MEPP). In its modern expression, the MEPP states that "non-equilibrium thermodynamic systems are organized in steady state such that the rate of entropy production is maximized" (Kleidon, Malhi and Cox, 2010).

The Earth system is one such system, and therefore the MEPP gives a directionality to it. This is most clearly demonstrated in the processes of diffusion and ecological succession (Skene, 2013), wherein a drop of ink disperses within a body of water until it is evenly distributed, and an ecosystem develops in such a way as to attain maximum entropy production (Figure 1). The MEPP adds to the second law of thermodynamics by not only including the direction of change, but the rate of change.

Serizawa, Amemiya and Itoh (2014) observe that when open systems, such as the Earth system, are in a state far from equilibrium, stabilization results from maximum entropy production. This is delivered by the emergence of dissipative structures. These structures can access free energy, reducing internal entropy (thus, increasing their complexity) and becoming more ordered, by dissipating entropy into their surroundings. Thus, complexity and dissipation are two sides of the one coin. The MEPP can be viewed as driving increasing complexity as a result of maximizing entropy production.

Recognizing that the laws of thermodynamics must govern the Biosphere as well as the rest of the Cosmos, Boltzmann was the first to suggest that the evolution of life was a thermodynamic process, writing: "The general struggle for existence of animate beings is therefore not a struggle for raw materials — these, for organisms, are air, water and soil, all abundantly available—nor for energy which exists in plenty in any body in the form of heat (albeit unfortunately not transformable), but a struggle for entropy, which becomes available through the transition of energy from the hot Sun to the cold Earth" (Boltzmann, 1974, p. 24).

Lotka (1922a; 1922b) proposed that an increase in total energy throughput and in energetic efficiency were outcomes of natural selection, while Odum (1995, p. 311) concluded that: "During self-organization, system designs develop and prevail that maximize power intake, energy transformation, and those uses that reinforce production and efficiency". This became known as the maximum power principle, and referenced neither natural selection nor competition.

Lovelock (1965, p. 568) stated that "Life is one member of the class of phenomena which are open or continuous reaction systems able to decrease their entropy at the expense of substances or energy taken in from the environment and subsequently rejected in a degraded form". He thus pointed to physics as the fundamental path in understanding life.

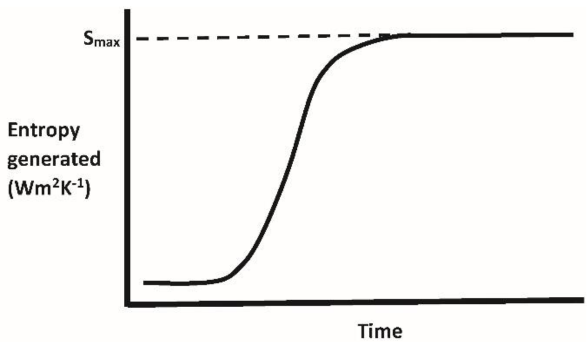

Figure 1. Entropy production during ecological succession follows a logistic curve, with maximum entropy production (S_{max}) reached for a particular ecosystem, representing a thermodynamic equilibrium through time. See Skene (2013) for more details.

Prigogine (1976) traced the evolution of life from far-from-equilibrium, non-living structures to living organisms as a process of increasing entropy production paralleled with increasing complexity. Ulanowicz (1997, p. 147) noted that "In any real process, it is impossible to dissipate a set amount of energy in finite time without creating any structures in the process". Swenson (1989) has suggested that much of the behaviour generally associated with either biological or cultural systems instead represents the physics of an expanding universe.

So, we now see that the dissipation of free energy, in line with the second law, leads, due to the incoming free energy from the Sun, to increasing entropy in the Universe, and increasing levels of complexity. Biological evolution, then, is a thermodynamic journey, leading to maximum entropy production and has a directionality. It is a diffusional process requiring opportunity, rather than a selective or contingent process, and the key energetic processes are functional and physiological, rather than form-based.

Through evolutionary times, forms are replaced by different forms, but the process of energy dissipation and its maximization continues unabated. Evolution works in the empty market places, not in the crowded back alleys (Skene, 2015).

Many studies have revealed that thermodynamics plays a core role in defining and determining key characteristics of the Earth system, both in space and time. Random mutations lead to information entropy within genetic material while correction mechanisms increase entropy production (i.e., correction processes are energy-expensive, dissipating free energy) (Salamon and Konopka, 1992; Tessera and Hoelzer, 2013; Skene, 2020a). Thermodynamics predicts which amino acids are formed most easily, with early prebiotic amino acids forming along a thermodynamic gradient, while later biogenic amino acids produced increased entropy of formation (Higgs and Pudritz, 2009).

Protein folding and function are thermodynamically determined (Lazaridis and Karplus, 2002). Metabolic networks have been demonstrated to evolve towards maximum entropy production (Unrean and Srienc, 2011) while the onset of cellular specialization, multicellularity, homeothermy and increasing organism size all lead to increased entropy production (Davies, Rieper and Tuszynski, 2013).

The MEPP has now been applied to a wide range of ecosystem-level characteristics (Harte, 2011; Harte and Newman, 2014; Chapman, Childers and Vallino, 2016), including spatial interactions (Volkov et al., 2009), spatial organization (Phillips, Anderson and Schapire, 2006; Harte et al., 2008; del Jesus et al., 2012), ecosystem biogeochemistry (Vallino, 2010; Vallino and Algar, 2016), zonation in the gradient of transformation of forests to peatbogs (Kuricheva et al., 2017), soil hydrology (Porada, Kleidon and Schymanski, 2011), semi-arid system heterogeneity (Schymanski et al., 2010), food web structure (Schneider and Kay, 1994a,b; Yen et al., 2016), hierarchical organization (Annila and Kuismanen, 2009), and ecological succession in tropical rainforest (Holdaway, Sparrow and Coomes, 2010; Lin, Cao and Zhang, 2011), lake (Aoki, 1987, 1989, 1990; 2006; Ludovisi, 2004), marine sediment (Meysman and Bruers, 2007) and Mediterranean (Celeste and Pignatti, 1988) ecosystems, where entropy production increases during earlier stages before reaching a maximum at maturity. As ecosystems transition into a mature state (or pseudo-steady state where Productivity: Respiration = 1), entropic output follows a logistic trajectory, levelling off at S_{max} (maximum entropic output), in accordance with the MEPP (Holdaway, Sparrow and Coomes, 2010; Skene, 2013).

At the global level, tectonic activity, global circulation patterns and climate change have all been shown to follow the MEPP (Paltridge, 1975; Dong, Bao and Shah, 1984; Lucarini and Pascale, 2014). Thus, the fingerprint of thermodynamics can be seen throughout the Earth system, from gene to ecosystem, shaping and driving the functional whole. But to understand how this driver expresses itself across so many levels of organization, we must turn to the Earth system itself.

Systems Theory

Origins

As we have seen, mechanistic, determinist, predictive science, dating back to Bacon and Descartes, has dominated our recent understanding of the Biosphere, particularly during the current Enlightenment era. With emphasis on forms, measuring ecosystem health by the number of visible species, and, more recently, with active rewilding, the Biosphere is seen as a construction project, built of a series of building blocks, and our approach to sustainability has involved interventionist processes. Evolutionary theory, originally focused on species, now heavily leans towards the gene as the unit of selection, with the rest of the Biosphere forming a type of extended phenotype (Dawkins, 1982). Complex problems are broken down into small steps or building blocks, which are then reassembled.

Experiments commonly bear little resemblance to the real world, because the complexity of the Biosphere is such that we are unable to explore it in its totality. This was clearly demonstrated in the failure of Biosphere II, a 3.15-acre artificial world of glass and metal, constructed in 1991, designed to recreate a truly self-sustaining environment, replete with ecosystem services

(Salzman, 2005). Time and time again, such models fail in the face of the emergent reality of a complex, open system, the Earth system. The Earth system requires system thinking in order to understand it and our place within it. Its characteristics are challenging for reductionist, empirical science, as we shall explore.

So, what is a system? A system is a network of mutually dependent and, thus, interconnected components comprising a unified whole (Trewavas, 2006). The properties of systems result from two key elements: systems have a hierarchical structure (Woodger, 1929) and that structure is held together by numerous linkages, producing very complex networks (von Bertallanfy, 1950; 1972). A complex system, such as the Earth system has five fundamental characteristics. These are essential to grasp if we are to understand the Biosphere.

Self-Organization and Self-Assembly

Complex systems develop and function as a result of the interactions that occur within them. They self-assemble and self-organize. Non-equilibrium self-assembly (NESA) can be observed throughout the Cosmos, from galaxies (Nozakura and Ikeuchi, 1984; Pakter and Levin, 2019) to flocking birds (Ramaswamy, 2010) and in microtubules assemblies (Papaseit, Pochin and Tabony, 2000; Desai and Mitchison, 1997).

Bishop (2012, p. 6) writes: “The interplay between parts and wholes in complex systems and their environments typically leads to the self-organization observed in such systems”. It is the possibility that the re-assembled outcome will be very different than that before the transition that creates huge interest and concern, as we shall explore when considering emergence and nonlinearity.

The assembly and organization of any component level of organization within a complex system is fundamentally energetically determined and directed by the context of the entire system. The lifeblood of this process is information feedback through the myriad interactions of the entire system. Thus, the system is neither reductionist nor holistic, but *transductionist*, meaning that the laws of thermodynamics and information radiate and resonate throughout every component and the outcomes are emergent.

Thus, we can envisage the Biosphere as a multi-armed seesaw (Figure 2). Here a balance is reached between the hierarchical levels, each undergoing non-equilibrium self-assembly (NESA), and each contributing to the whole.

Each component is constrained, and moves towards a maximum entropy production level that is possible within its context, while balanced by all of the other components, in order to result in a system-wide maximum. Here we see systems theory and thermodynamics together (Skene, 2020a).

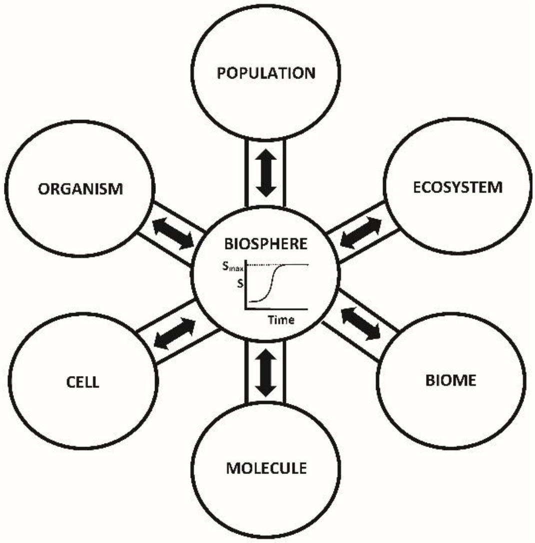

Figure 2. The Biosphere as a multi-armed seesaw. Each circle represents a level of organization of the Biosphere. Through real-time feedback, entropy production is maximised in each level, constrained by the requirement for the system as a whole, represented by the central circle, being able to maximize the overall entropy production across the system. The system self-organises in order to achieve this state. Each level adjusts its activities, as on a multi-armed seesaw, to achieve maximum entropic production (S_{max}) within the constraints of the overall system. Emergence, sub-optimality and non-linearity are outcomes of these constrained opportunities, found throughout the Biosphere. This is neither a top-down nor a bottom up arrangement, but rather a transductionist arrangement, where feedback flows throughout the system, leading to an emergent outcome. See Skene (2020a) for further details.

Steering the Earth system by deliberate human intervention is an impossible task, given the complexity. Thus, we cannot attain sustainability for ourselves by designed reconstruction of parts of the Biosphere, but, rather, we must reduce our perturbation, allowing self-healing from within the system. Self-assembly and self-organization will occur across the Earth system whatever we do, and so we must learn what impacts our actions have and adjust our behaviour with reference to these observations. Any sustainability programme must recognize this reality.

It is clear that Nature often undergoes resetting, such as when a fire burns through a forest, allowing new plants to germinate from seed and representing ecosystem regeneration at a local level. The power to regenerate is within the Earth system itself, either from recruitment of existing species, or the diffusion of life into newly available space through thermodynamic evolution (Skene, 2015; 2020a).

However, changes at the global level really only occur when the trigger is a huge event, such as an asteroid or comet striking the Earth, or from huge volcanic activity such as the Siberian traps or the Deccan Traps (Rampino, Caldeira and Prokoph, 2019; Keller et al., 2020). Here, a much more fundamental reorganization is required, with up to 95% of pre-extinction species lost.

Another example is the cyclical change over time in incoming solar radiation due to changes in the earth's tilt, precession and eccentricity, also known as the Milankovitch cycles (Spiegel et al., 2010). These changes impact on many different aspects of the Biosphere and, because the consequences are energetic, these changes are fundamental. Imbrie and Imbrie (1979, p. 101) wrote: "For all of the planets are constantly spinning, revolving, wobbling and tilting in a crazy celestial dance, every movement of which has some effect on the radiation they receive from the Sun."

Thus, the Milankovitch cycles control the pace of ice ages (Hays, Imbrie and Shackleton, 1976), with significant impacts on terrestrial and marine life, in terms of ecology and evolution (Bennett, 1990). They have also been linked to the periodicity of mass extinctions (Raup, 1987; Wu et al., 2013; Brookfield, Shellnut and Yui, 2022), suggesting the crossing of an energetic threshold (due the changes in incoming radiation) in terms of tipping points for planetary stability.

Anthropogenic changes may also eventually result in changes at a global level, stemming from rapid and dramatic alterations of atmospheric chemistry, eutrophication of the hydrosphere and habitat destruction, not only reducing species numbers, ecosystem resilience and integrity, but leaving the fundamental processes of diversification at risk.

In any understanding of the Biosphere, it is suggested that we must combine thermodynamics and systems theory, as they are inextricably linked. Of course, our own socio-economic behaviour, utilizing increasingly large amounts of energy (Fischer-Kowalski and Haberl, 1998), is in line with the laws of thermodynamics, as we build increasingly complex societies, since complexity increases entropic output. However, if this behaviour impacts on the Earth system (through climate destabilization, soil erosion, fertilizer run-off, habitat destruction and species extinction) then the natural economy of the Earth system will reset, re-organize and re-assemble, with no guarantee that our human economy will survive.

In other words, if we exceed the maximum entropy production permitted to us within the overall system, and, thus, reduce the maximum entropy production of the system as a whole, then the system will re-organize in order to maximize entropy production. This may involve tweaking various components, or a more significant rebuilding project that could involve existential risks to our species. Overshooting the maximum entropic production assigned to us by the system as a whole represents a dangerous and precarious path.

This is a much darker version of a circular economy, where the human economy impacts the natural economy, which in turn impacts the human economy. The natural economy will re-organize and this will determine the success or otherwise of the human economy. This is why we stress the importance of an embedded human economy, whose functioning must be contextualized within the Earth system as a whole in terms of decision-making, much as in Nature.

It is important to note that energy plays a central role here, both in terms of greenhouse gas emissions, raising the temperature on the surface of the planet, and in the energetic activities related to economic growth. More fundamental still are agricultural fertilizers, which drastically alter the energetic framework of the planet, both in the geosphere and hydrosphere.

It matters not whether this energy is green, blue or black in terms of its acquisition, but rather that increased energy from growth and maintenance of the human estate contributes to increasing entropy export into the surrounding environment, and risks exceeding the maximum entropic production for a stable system, thus potentially leading to a reboot of the system as a whole. Thus, energy reduction, not alternative methods of acquisition, is central here (Skene, 2021b).

Consider an analogy involving the growth of a cancerous tumour. A mutation may lead to a cell within a multicellular organism undergoing cell division with impunity, releasing itself from the constraints of being part of an organism. While this would doubtless produce much entropy as it passes through far more cycles of divisions and generates greater maintenance costs than neighbouring cells, it may also lead to the death of the organism, preventing further entropic production other than in the process of breakdown, post-death.

Thus, constraints placed upon the cells within the context of the organism as a whole allow for the organism to continue as a complex system and to continue to maintain its complexity while exporting entropy to its surroundings. If, as a species, we exceed the entropy levels that contribute appropriately to the greater system as a whole, we may find ourselves surgically removed from the greater organism, or become lost in the regeneration and recycling of that organism, the Earth system.

A final point to add here is that a ‘successful’ cancerous cell, dividing as if there is no organismal context, may appear to be something that natural selection would encourage, as the genes are proving extremely fit. Yet the reverse is true, as the entire organism, and thus all the genes within it, are put at risk. And so, the context of the greater system is fundamental in order to understand any of the components. This is why sigmoid curves exist throughout Nature, with a levelling off at a maximum value, which thermodynamics informs us is the maximum entropy production for that particular component, be it cell respiration, photosynthetic rate, population size or ecosystem succession (Skene, 2020a). Exceeding this maximum level would lead to collapse and re-organization.

Thus, from ecosystem to molecule, from global circulation currents to precipitation patterns, there is a continuous process of self-assembly and self-organization across the Earth system, with thermodynamics in the form of the maximum entropy production principle lying at the heart of things. Arango-Rostrepo, Rubi and Barragán (2018) elegantly demonstrated that the hierarchical order of structures results from interactions and feedback at each stage of the assembly process.

Emergence

Because of the complexity of the Earth system, the properties of the system belong to the system itself, rather than to any given component, such as ourselves (Bedau and Humphreys, 2008). Emergent entities arise from the interactions of more fundamental entities, but cannot be reduced to those entities. Mill (1872, p. 371) wrote that “The chemical combination of two substances produces, as is well known, a third substance with properties different from those of either of the two substances separately, or of both of them taken together”. Lewes (1879, p. 413) noted: “The emergent is unlike its components in so far as these are incommensurable, and it cannot be reduced to their sum or their difference". Emergent characteristics are both consequent upon the underlying components and autonomous from them (Bedau, 1997). This is reminiscent of Theophrastus's autonomous Nature.

The complexity of interactions means that while we can measure the inputs and outputs of a system, there is a black box between these that is impossible to completely understand, given the multitude of communication channels and possible outcomes, akin to the uncertainty principle in physics, and the fact that we may not even know many of the players.

Take, for example, the microbial diversity in the soil. Although bacteria play essential roles in the crucial processes of nutrient cycling, pollutant degradation, waste decomposition, climate regulation and carbon metabolism, it is estimated that we have identified as few as 1% of them (Chaudhary, Khulan and Kim, 2019). DNA and RNA analysis picks up traces of some of the remaining 99%, also known as microbial dark matter (Zamkovaya et al., 2021), but, thus far, we have not been able to grow them in cultures, preventing any characterisation of their functions. It is also thought that many bacteria are in a state of dormancy at any given time. Thus, in terms of the soil, we really are dealing with a black box, making it impossible to accurately predict what impacts anthropogenic changes may yield.

An important emergent character is resilience. Hollnagel, Woods and Leveson (2006, p. 16) write: "Resilience cannot be created—and it does not have to be, as it is already present as an inherent, emerging property of all natural as well as engineered complex adaptive systems". Interestingly, Dai et al. (2012) reported that loss of resilience in ecosystems occurs just prior to catastrophic population collapse. Thus, the loss of resilience indicates an imminent collapse of the system, due to some unknown emergent property.

The complexity of the Earth system has been compared to non-symbolic artificial intelligence (Skene, 2020b). Non-symbolic AI learns rather than regurgitates. In other words, it doesn't follow a series of instructions, as is the case for symbolic AI. Consisting of a large series of processors which connect to each other, forming a neural network, a pattern emerges, and the machine elucidates its own mappings, rather than being instructed, in what is known as machine learning. The neural network is a black box, with inputs and outputs but we have no knowledge as to what occurs within the network itself. Such is the Earth system.

Thus, we cannot construct an ecological recovery, designing our way out of trouble, nor can we create resilience. Rather, the Earth system will deliver its future, and our own, dependent upon inputs and the laws of thermodynamics. Only an embedded economy, in resonance with the Earth system, can provide us with any hope of maintaining our place within the emergent Biosphere. Folke et al. (2016, p. 41) note "In essence, the social-ecological systems approach emphasizes that people, communities, economies, societies and cultures are embedded parts of the Biosphere and shape it, from local to global scales". Young et al. (2006) emphasise that cultural and economic globalization are leading to a decoupling of social and ecological systems, thus separating us from the Earth system, from the emergent whole and from any hope of resilience.

In order to reverse this decoupling, we need to focus on the outputs of our economic activity, particularly in terms of its environmental and social impacts. This can only be achieved through real-time feedback (see below). Recoupling means embedding our activities within the greater Earth system economy.

Nonlinearity

As a consequence of the complexity of the Earth system, and the importance of emergence, nonlinearity is another key characteristic. Nonlinearity represents the existence of multiple bifurcations, with switches between multiple unstable equilibria, appearing as chaotic behaviour (Wiman, 1991). Strogatz (2003, p. 182) noted that "every major unsolved problem in science—from consciousness to cancer to the collective craziness of the economy, is nonlinear". It emphasises the difficulties (as seen in physical chaos theory (Mason et al., 1986)) in predicting how a system will respond to changing feedback (Lövbrand, Stripple and Wiman, 2009). Dramatic, non-linear changes can and do occur when a complex system crosses a tipping point, leading to regime shifts (Rocha, Peterson and Biggs, 2015; Wernberg et al., 2016; Cooper et al., 2020; Meyer-Gutbrod et al., 2021). Not all regime shifts are negative for the species involved (Silva et al., 2021).

One example of a dramatic, complex shift is the edge effect in ecotones, at the border between two different ecotypes. Subtle changes in environmental edaphic conditions such as chemistry, energy, information, opportunity and zone can have vast impacts across just a few centimetres, transitioning from one ecotype to a completely different one. The complexity of these dramatic transitions is poorly understood. With anthropogenically driven alterations to many of the physico-chemical properties of our planet, both locally and globally, ecotones are likely to shift unpredictably and rapidly, leading to regime change (Smith and Goetz, 2021).

Such dramatic changes have occurred many times in Earth's history, but given the multiple, steep gradients of change across many key eco-physiological areas that we continue to alter, it is highly likely that these events will become much more common, and at scales ranging from micrometres through to biomes. Furthermore, there is no certainty of reversing them as we are heading into uncharted territory due to the large number of anthropogenic assaults upon the Earth system, with resilience hugely reduced as species redundancy collapses. This has important repercussions in terms of any sustainable economic approach. The uncertainty and risk of continuing to operate in isolation from the Earth system, while increasingly perturbing it, is likely to create the conditions for catastrophic change, but with little opportunity to predict it. Thus, it would be advisable to immediately take action *ex abundanti cautela* (out of an abundance of caution).

Sub-Optimality

Perhaps the most challenging characteristic of complex systems is sub-optimality. So often, we read of eco-efficiency, yet, as noted earlier, food pyramids tell a very different story, with 90% of the energy lost at each stage. All components must incorporate sub-optimality because it is impossible to optimise for each of the myriad of demands across the system (Farnsworth and Niklas, 1995; Grumbach and Hamant, 2020).

We see sub-optimality throughout the Biosphere (Parrish and Edelstein-Keshet 1999; Rodríguez et al. 2006; Shoval et al. 2012; Tendler, Mayo and Alon, 2015). For example, DNA correction mechanisms repair damage from mutations. If the repair process was completely optimized, there would be no generation of genetic diversity. If the repairs were too sub-optimal, the cell would cease to function. An intermediate level of sub-optimality delivers genetic diversity but also stable cell function. If squirrels remembered where they hid all of their nut stashes, forest regeneration would cease. Indeed, it can be argued that our pursuit of optimality has been our greatest flaw, leading to the collapse of ecological functioning through the use of fertilizers, pesticides, genetic modification and industrial productivity (Skene, 2020b). By optimizing for our own gain, we lose any semblance of system living.

Artificial intelligence algorithms involved in economics tend to seek optimal solutions, hence exacerbating the problems (Skene, 2020b). Failures related to the Sustainable Development Goals can also be traced to insufficient trade-offs across the seventeen goals and their targets (Skene, 2021a). The dangers of continuing to optimise for ourselves are significant. In any situation, we must inquire at the outset as to how much sub-optimality we need to introduce. Real-time feedback will inform us of what is appropriate.

This relates strongly to the intermediate disturbance hypothesis (He, Lamont and Pausas, 2019), where diversity and functionality are optimized at the system level through sub-optimality (disturbance) at the component level. The words of Condorcet, that Nature has fixed no limits to our hopes, represent a failure to recognize the fundamental truth that these limits are core characteristics of any functioning, complex system. This failure to embrace trade-offs is partly due to the silo effect of organizational structures, both in Academia and beyond, and the reductionist approach of Western thinking in general. It is also why the selfish gene hypothesis cannot offer anything in terms of understanding how the Biosphere functions and evolves, as it fails to recognize the significant of the Earth system and the other component sub-systems as anything more than an extension of the genes. Each element of the Earth system must have a modicum of selflessness if that particular element is to continue as part of the whole, and that level of selflessness dynamic in its scale.

From a thermodynamic perspective, increased complexity results in increased dissipation of energy (Fenchel 1974). Here we see systems theory and thermodynamics again being co-dependent. Thus, the more complex a system is, the greater the sub-optimality at any given level of organization. While Enlightenment thinking lauds optimization and efficiency as emblems of progress, in reality sub-optimality is not a sign of failure but is a symptom of a properly functioning system.

Real-Time Feedback

Complex systems are tightly linked across and between all levels of organization. The components are connected through feedback. Trophic relations play key roles, where populations of predators and prey are resonant through time. Pheromones also play a significant role. One example is the response of sagebrush to simulated herbivory. Neighbouring wild tobacco plants gained increased resistance to herbivores as a result. The tobacco plant was able to 'eavesdrop' on what was happening to the neighbouring sagebrush, alerting it to any impending threat of herbivores, and allowing it to switch on its defensive response ahead of time (Karban et al., 2003).

The communication channels between the components of the Earth system, both physical and biological, include energy (in many forms), mass, ions and other chemicals, which act as sources of information (Lucia, 2015). Arango-Rostrepo, Barragán and Rubi (2019) point to the development of feedback loops as the key factor in transitioning from self-assembly to self-organization.

Of course, as humans, we are unable to detect many of the signals within the Earth system. This is partly because we have lost much of the ecological intelligence possessed by our ancestors and, indeed, by current indigenous populations, due, fundamentally, to their embeddedness within the Earth system. Species limitations also exist. For example, we lack a tapetum lucidum in our eyes, preventing us from seeing in low light conditions. Our hearing range prevents the use of sonar and we are haplorhines (dry-nosed primates), with a much-lowered sense of smell than our cousins, the strepsirrhines (wet-nosed primates).

However, technology now offers us unprecedented access to feedback. Remote sensing from space, through to the billions of SMART devices linked together in the Internet of Things on the surface of the planet, offer unprecedented volumes of data. Skene (2020b) argues that artificial intelligence can analyse this data flow, informing us of the emergent outcomes of our interactions with the Earth system at scales from single leaves to entire biomes, thus allowing us to understand the impact of our activities. Such feedback provides us with the ability to monitor how any changes we make in our behaviour impacts upon the Earth system (Moriguchi, 2007; Rodrigues, Pigosso and McAloone, 2016).

Given that the Biosphere is an emergent system, any monitoring programme must act at every level of organization, from genetic diversity through to ecosystem functioning, in order to assess the true impact of our activities. Indicators at one level only, such as species diversity, will fail completely to represent the consequences of our actions. Thus, our economy needs to develop a very large pair of ears, listening for the signals that are central to the rest of Nature in terms of resource allocation, planning and productivity, with awareness across all levels.

Evolution

For many years, the living world was viewed as somehow separate from the inanimate world, and this was no more clearly evident than in theories relating to how the Biosphere functioned and evolved. It even pervaded early chemistry, leading to a division between organic (substances that changed irreversibly when heated) and inorganic (substances that reverted to their original form upon cooling) chemistry. Bergson (1907), in his influential book, *L'evolution Créatrice*, argued that an *élan vital*, or life force, was found in all living things, guiding the organic processes. Thermodynamics was not viewed as relevant.

Classical Darwinism envisaged individuals in any large replicating population differing in fecundity and mortality, allowing the fittest individuals to survive. However, the exact mechanism was not known. Mendel (1886) set out the basis of a mathematical science in terms of the inheritance of characteristics or traits with alleles. This would provide the basis of statistical Darwinism. Fisher's (1930) Genetical Theory of Natural Selection was the culmination of this work. Huxley (1942) laid out the modern evolutionary synthesis (MES) wherein genetic changes, acted upon by natural selection, lead to gradual evolution. Macroevolution can be explained by microevolution, a fundamentally reductionist position.

More recent evolutionary thinking, based around the concept of the selfish gene, goes so far as to argue that anything beyond the gene is merely the extended phenotype (Dawkins, 1982). This ultra-reductionist approach fails to take account of systems theory and thermodynamics, wherein properties are emergent and energetic in their essence.

There has been a move to extend the MES (in what is now known as the extended evolutionary synthesis (EES)) in order to include epigenetics and niche construction theory (Jablonka and Lamb, 1995; Jablonka and Lamb, 2008; Pigliucci and Müller, 2010). This has been in recognition of the complexity of the Biosphere and a partial rejection of reductionism and gene-centric thinking.

However, there remains an unwillingness among many biologists to recognize the roles of thermodynamics and system theory as central to any physico-chemical explanation of life. Demetrius (2000) commented that the science of thermodynamics only could be applied to inanimate matter. Such approaches continue to embrace vitalism, denying the basic facts of physics and chemistry, and, worse still, threatening our very existence as we deny the connectivity that lies at the heart of the Earth system, where energy and matter, be it animate or inanimate, combine together to provide the solution space needed if we have any hope of sustaining our species on the Earth.

Exobiospheres

In perhaps the first science fiction novel ever penned, *True History*, written by the Syrian author, Lucian, in the second century AD, he describes the crew of a ship, launched into space by a storm, as arriving at the planet Lychnopolis, apparently located in the constellation Taurus, between the Hyades and the Pleiades. Here, they encountered a series of highly intelligent lamps. He writes that they questioned one lamp and "spake unto it and questioned it of our affairs at home, and how all did there, which related everything unto us" (Hickes, 1994). This is the first imagining of intelligent life on an exoplanet beyond our own solar system. But what can systems theory and thermodynamic tell us about exobiospheres and the life therein?

As Huygens and Vernadsky had realized, the chemistry of life abides by the same laws as the rest of the Cosmos and the atoms that make up life are the same as those that make up the rest of the Universe. The entirety of the Biosphere on Earth also falls under these same laws. Therefore, the processes of emergence, evolution and functionality across the Biosphere must surely also obey these rules. Thus, in order to understand the Earth system, its evolution, function and future prospects, we must view it through the lenses of thermodynamics and systems theory.

Huygens (1698) established the scientific generalization that because the laws of physics were universal, it was feasible to conceptualize exobiospheres on distant planets and even how they might appear and function. Huygens argued that if we see the internal anatomy of a dissected dog, we can deduce how the internal organization of all dogs would appear. Thus, given that the same rules apply throughout the Universe, then the Earth and Sun allow us to deduce how other solar systems could appear.

Firstly, are there planets in the Universe that lie in the habitable zone (or goldilocks zone) having the potential for life? Cockell (2014) argues that there may be numerous uninhabited habitable planets, too young to have yet harboured life. The evolution of life could be rare, and, thus, more often than not, habitable planets may not be inhabited. One or more critical characteristics for life may be missing or the conditions for life may be too transient. For example, if our moon was closer to our planet, the Earth's crust is likely to be more unstable, leading to greater volcanic activity and earthquakes. These could be of such a scale as to threaten life.

However, given that there are estimated to be between twenty and sixty percent of stars similar to the Sun that will have Earth-like planets (Meyer et al., 2007), the chances of life existing elsewhere are likely. Of course, at the outset we need to define what we mean by life. We will use here Lovelock's (1965) earlier mentioned definition of life: "Life is one member of the class of phenomena which are open or continuous reaction systems able to decrease their entropy at the expense of substances or energy taken in from the environment and subsequently rejected in a degraded form".

This definition avoids any Earth-centric bias that would assume life would have to be identical to life on this planet in its chemistry, form and functioning. Furthermore, it avoids having to decide at what point an object becomes alive, a more difficult thing than judging when it becomes dead. Otherwise, at some point, a particular chemical bond or a particular reaction, added or subtracted, would separate the non-living from the living, if this were the case. Similar issues arise in a species. We would need to imaging a parent giving birth to a different species to trace back the moment that a new species arose. These are problematic issues both philosophically and practically (Skene, 2009).

Since energy flow is essential, we need a source, possibly a hydrothermal vent on our exoplanet or a neighbouring star. It is believed that life on Earth started deep under water, evading powerful radiation from the Sun prior to the formation of an ozone layer (Baross and Hoffman, 1985). This early biosphere on Earth was chemoautotrophic, meaning that its energy was derived from inorganic material. The simplest life forms on other planets could be of this form, and may involve no other trophodynamic levels. They would live by acquiring energy from material and energy on their planet, reproducing and dying.

This is the simplest food chain imaginable – a single type of organism. Certainly, using hydrogen sulphide to make sugars, as some chemoautotrophs do, requires less energy than using water, as photosynthetic organisms do (Felbeck, 1981). Thus, it would be initially more energetically likely to occur. However, it is also very plausible that our exobiosphere could be driven by energy from a neighbouring star.

As mentioned above, early life on Earth was thought to be limited to within the oceans, deep enough to avoid extreme mutations from ultraviolet radiation, prior to the ozone layer developing. Of course, the issue of UV radiation would not be a problem if the particular types of early life on our exoplanet were not susceptible to mutation by radiation. But a ready supply of free energy is required, wherever you exist, in order to maintain order in an entropic universe. We have seen that increasing complexity results in increasing energy dissipation, in line with the second law of thermodynamics, and that all open, far from equilibrium systems such as our exobiosphere will adhere to the maximum entropy production principle.

And so, if energy supplies were sufficient and relatively consistent, we would expect life to diversify and occupy whatever niches are available. It is quite likely that comets and asteroids would exist and, thus, mass extinctions could occur. Comets may also have supplied significant volumes of water to our exoplanet (Delsemme, 2000). Milankovitch cycles may well play a role too, as may perturbations of the exoplanet itself. Provided that conditions did not change irreversibly, we could see life re-organizing and the diffusion of diversity continuing up to the point where all available niche space was filled.

There may be two trophic levels, with decomposers recycling dead autotrophs. An energy source is an energy source, and so using one lifeform to short circuit the whole photosynthetic or chemoautotrophic phases, or possible trapping them in the forms of chloroplasts, as eukaryotic photosynthetic organisms do, could work on other planets too. Disease organisms could be present, feeding off other organisms as parasites or using them to replicate within.

Could our life forms be cellular? This relies largely on whether or not water is present. Cells primarily control chemical reactions by setting up specific chemical concentrations, often different from the surrounding environment. Water has probably played a huge role in determining the structure of cells on Earth, given that it is the major solvent on our planet. The cell membrane consists of a phospholipid bilayer. The phosphate and glycerol head is hydrophilic, and two fatty acid tails are hydrophobic. Thus, the membrane is designed around water. The second law of thermodynamics sets rules for what is energetically feasible in terms of reactants. Membranes, with carrier proteins as part of them, allow the concentrations of reactants and products to be controlled by active and passive transport in order to control reaction dynamics. The cell membrane therefore provides a semi-permeable barrier, which, in combination with reaction thermodynamics, controls metabolism (Toussaint and Schneider, 1998).

Will there be herbivores and predators in our exobiosphere? Any large terrestrial organism will likely exist as a multicellular structure due to limitations of cell size on many aspects of functionality. Cell size of phytoplankton in our planet's oceans, for example, affects physiological rates and ecological function, including metabolic rate (growth, photosynthesis, respiration), light absorption, nutrient diffusion and uptake, sinking rate, maximum numeric abundance and grazing rates (Finkel et al., 2010). Multicellularity reduces transport limitations, provided that a transport system is available (such as xylem, phloem or blood vessels), with many small cells as compared to one giant cell.

More importantly, multicellularity allows for cellular specialization. Having more than one cell type would allow for division of labour, offering potentially more targeted functionality (Ispolatov, Ackermann and Doebeli, 2012). On Earth, even single-celled organisms mostly live in multicellular, multispecies consortia, such as biofilms.

Trophic levels do allow for increased complexity, which leads to increased energetic degradation in line with the second law (Meysman and Bruers, 2007). Thus, where possible, we could expect increasingly sophisticated food webs, up to the limit of maximum entropy production. The upper limit will be determined by the basal area of the food pyramid – i.e., how large the photosynthetic base is. This can be limited by a wide range of things including nutrient supply, energy capture efficiency and other population constraints.

Herbivorous and carnivorous constraints also come into play, as do recycling (detritivore) capacity and rates. If nitrogen is in short supply, there may be photosynthetic organisms that also hunt, akin to carnivorous plants on Earth. How steep the sides of any food pyramid are may depend on a number of factors. Steeper sides mean less loss between each link in the chain. On Earth, 90% of energy is lost with each link. Perhaps on a different planet, this could be greater or less. The higher the value of loss, the shorter the overall chain, as insufficient energy exists to have many links.

Of course, much of life on Earth relies on endosymbiosis (Martin, Garg and Zimorski, 2015), resulting from a form of delayed carnivory or delayed parasitism, in that eukaryotic cells at some point swallowed, or, this chapter suggests, were infected by, Proteobacteria (mitochondria), and in certain cases, Cyanobacteria (chloroplasts), but failure to digest them led to their incorporation and ongoing replication, before their genetic control was mostly moved to the eukaryotic nucleus. If only Proteobacteria were present in an endosymbiotic state, then any eukaryotic organism would require to eat in order to obtain sugar, just like all non-photosynthetic eukaryotes here on Earth. On Earth those Protista with only the remnants of Proteobacteria within them (or having lost the Cyanobacteria over time) formed the basal organisms of the kingdoms Fungi and Animalia, whereas those that swallowed and kept both Proteobacteria and Cyanobacteria, led to the Kingdom Plantae. So, the acquisition of key organelles by infection or phagocytosis has shaped the phylogeny of life on Earth.

How likely is this to unfold in our exobiosphere? The emergence of eukaryotic organisms without the ability to photosynthesise has played a significant role in how our biosphere has evolved. Of course, there could be another reason for animal-like creatures to exist. Perhaps the switch to absorbing photosynthetic organisms occurred because of a shortage of space or other resources, meaning that enough energy or essential nutrients could not be acquired for survival. Possibly being starved led to the emergence of this survival mechanism, a form of predation. Plants can develop traps and enzymes to capture and digest animals here on Earth. Perhaps carnivorous photosynthetic Protista, evolving in such conditions, eventually lost their ability to photosynthesise, becoming obligate predators (either herbivores, parasites or carnivores). Many obligate holoparasitic plants on Earth, such as *Rafflesia lagascae*, no longer photosynthesise.

Hence, we could have species who started out as photosynthetic organisms, but now eat other organisms instead, or a halfway house, interspersing predation or parasitism with photosynthesis.

There could easily be a planet with only autotrophs present (though requiring detritivores where nutrients were in short supply). If energy capture did not utilize water, but water was present, then an ozone layer would not form and life would remain in sufficiently deep water bodies, protected against ultraviolet radiation, unless a biochemistry developed that was insensitive to UV damage.

Indeed, maybe the organisms on our exoplanet could actually utilize UV as an energy source. This would also provide a better basis for panspermia (the dispersal and seeding of life throughout the universe), since high levels of radiation are viewed as barriers to intergalactic if not interstellar travel of the 'seeds' of life (McKay, 2014). Given these advantages, it may well be that somewhere in the Universe such a UV-insensitive chemistry exists, populating a wide volume of space due to its dispersal ability. Indeed, if panspermia lies at the base of life on Earth, possibly the UV-insensitive chemistry was lost early on, forcing life to move deeper in our oceans for protection until the build-up of an ozone layer.

Thus, in our exobiosphere we can postulate that organisms will need to absorb energy. A food web will only develop if there are organisms who cannot absorb energy from a non-living source (a star or hydrothermal vent, for example) or from the recently dead. Of course, decomposers will be essential for the continuance of life if fundamental resources are significantly limiting. Otherwise, resources will gradually become locked up in the dead.

Since the laws of thermodynamics are likely to hold universally, the elaborate games of biology will play out, dependent upon available chemistry. Available energy will be the determining factor throughout the exobiosphere, at every level of organization, forming the basis of the exoplanetary system. There will likely be food webs, associated senses related to resource acquisition and defence and reproduction. Given that the periodic table of chemical elements is also likely to be universal, then molecules formed will also be predictable, depending on the geological history of the planet. The structure of molecules and their interactions are fundamentally energetic in nature.

On Earth, the presence of many metals is thought to be due to the traumatic birth of the moon, resulting from the impact of a large planetoid, named Theia, with the Earth. Initially the heavier elements sank towards the core, leaving silicates dominating the mantle and crust. The impact of a planetoid led to the silicates leaving the planet and eventually forming the moon, while the majority of the metals in Theia now coalesced nearer the surface of the planet. These metals may have formed a ring (the late veneer hypothesis) near the surface of the Earth (Sleep, 2016; Li, 2022), within easy access to surface-dwelling humans, and have allowed the industrial revolution and the birth of technology in human civilization. More fundamentally, metals such as iron, manganese and magnesium have central roles in metabolism, particularly in energy transformation. If these metals had not been as readily available, due to Theia missing the Earth, how different may our story have been as a species?

Context of Species

If species do exist (and, remember, the species concept in Archeobacteria and Eubacteria is fairly meaningless due to horizontal gene transfer (Hanage, Fraser and Spratt, 2005)), they would be part of a food web as here on Earth, with ecological succession and zonation both occurring. Communities evolve within both temporal and spatial contexts. We would therefore expect our exobiosphere to be organized in various ways. As organisms interact with their environment, the feedback will most likely lead to changes in the environment, allowing other species to fill new niches.

The flow of energy within a particular trophic level will impact on that level and those above and below it, leading to changes in geology, atmosphere and hydrosphere (if present). Changes will lead to new opportunities and constraints on our distant planet. Regime shifts may occur as tipping points are crossed, and so there is no guarantee of a Gaian homeostasis, as neither is there here on Earth. Systems theory and thermodynamics are in charge, not the Earth. There may be extinction events driven by the geology of the exo-planet (Burgess, Muirhead and Bowring, 2017), drastic changes in cosmic radiation from γ-radiation from an exploding neutron star (Melott et al., 2004) or from an extra-exoterrestrial impact.

All of these events would likely have a dramatic impact upon our exobiosphere. Of course, it will all depend at what stage of its evolutionary, thermodynamic journey we encounter our exobiosphere. If we had visited Earth 3.8 billion years ago, or just after the Permian mass extinction event, our biosphere would look very different than it does today.

Exobiomes

It is worth mentioning that our distant planet will no doubt have exobiomes, driven by both the curvature of the surface relative to the local star, and to circulatory currents. Winds have been observed on neighbouring planets within our own solar system. On Mars, polar regions are visible that change throughout the Martian year, representing seasonality. Our distant planet may also have one or more moons, impacting on the exobiosphere directly or indirectly and possibly protecting against extra-exoterrestrial bolides. Mountain ranges may well form, influencing climate and providing physical gradients and barriers to migration, while Milankovitch cycles may lead to some form of glacial cycling in terms of incoming radiation levels.

The energetic and systems theory architects of Earth's biosphere, discussed in this paper, are based on universal concepts, indicating that, evolution, chemistry, biology and ecology will most likely be recognizable. The exobiosphere will have evolved under constrained diffusive opportunism, and the key constraints and opportunities will be energetic. Given that molecules, organisms, populations and communities all dance to the same energetic and systems tune, and that this tune is likely to be universal, then the rhythms of life are likely similar.

Differences will be contingent on things such as the presence or absence of water, the chemistry of any replicative molecules, the location and type of the nearest star, the availability of particular chemical elements, whether life is carbon-based or not and the frequencies and types of mass extinction events. However, the dance will not be led by these, but by the multifaceted interactions of physics and chemistry and of systems theory. Taking this approach allows us to predict much more than a gene-centric approach, since we are not limited by the gene in our imagining, a Gaian approach, precluding planetary regime shifts, or a carbon/water approach, limiting our imagination to an Earth-centric vision. Instead, we can be certain that the architects of life here on Earth, thermodynamics and systems theory, will apply throughout the Cosmos.

Conclusion

We see that theoretical and experimental evidence demonstrate that at every level of organization of the Biosphere, thermodynamics plays a central role, acting as the architect of change, structure and functionality, in conjunction with system theory. The Biosphere and all of its levels of organization move towards a state of maximum entropy production. Thus, systems theory and thermodynamics are intimately intertwined, and together allow us to understand the Earth system.

The totality of the Earth system ultimately moves towards maximum sustainable entropy production as the feedback leads to a transition from self-assembly to self-organization (Arango-Rostrepo, Barragán and Rubi, 2019), all the while building in complexity and in entropy export. Whatever the conditions, the system itself is an emergent entity, and the component parts, be they cells, populations or ecosystems, continuously adjust as a result of the feedback flowing through the system, a process we term transduction.

Thus, the Biosphere is not something to underestimate, as the events occurring and responses generated are fundamentally cosmic in their essence and dependent upon a huge river of free energy flowing from our nearest star. We are not destroying the planet, but ourselves. The Earth system is a responsive, complex system, emergent in character, non-linear and self-organizing. Our so-called destruction of the Biosphere merely represents feedback to this system, and will produce an emergent response.

As merely a component within the much more complex whole, we risk provoking it into a re-alignment based on the impact of our actions. Planetary regime shifts can occur and fundamentally over-rule any Gaian homeostasis. Any idea of species protection or continuance is not on the radar of the Earth system. It is a physical entity with no recognition for its components other than in terms of entropy production, feedback and the maximization of this property at the system level.

The Biosphere does not exist to serve us. The idea of the Earth system existing as a set of ecosystem services, pandering to the needs of the human race, and as something that we can somehow put a fiscal value upon, does more than a disservice. It potentially leads us closer to the existential cliff. The Earth system does not recognize any of the components, or species. It sheds not one tear for a species lost to extinction. Rather, it is a complex thermodynamic entity, with chemistry as its lifeblood, continually pulsing through the veins of feedback, with systems theory governing the behaviour of this complex system. Bearing this in mind, we ought to tread carefully, less we provoke re-organization, re-assembly and re-alignment. This is no spaceship, where we can tweak the controls and polish the dashboard, guided on its path of progress chosen by ourselves. Rather, it is a part of the Cosmos, with forces and laws that form a colossus that bestrides the narrow world and all that live upon it.

As we have drifted further from our place within the Earth system, we have lost the awe that transcends any imaging of Nature as somehow our possession. Philosophical and scientific thinking, encapsulated by the Enlightenment, have led us on a path away from the Biosphere. We exist in a bubble world wherein we celebrate ourselves and plot a path of progress to some imaged utopian condition. This is far from the physical reality of our planet, and we risk everything with such a vision.

Humboldt referred to the living breath of nature (lebendiger hauch der Natur). He considered the natural world as an organic whole emerging from the harmonious interrelationship between all abiotic and biotic objects. He wrote: "In considering the study of physical phenomena, not merely in its bearings on the material wants of life, but in its general influence on the intellectual advancement of mankind; we find its noblest and most important result to be a knowledge of the chain of connection, by which all natural forces are linked together, and made mutually dependent upon each other; and it is the perception of these relations that exalts our views and ennobles our enjoyments" (Humboldt, 1997, p. 23). He further emphasised this integrity by highlighting connectivity using the term 'Zusammenhang' (literally 'hanging together') which points to the need for embeddedness within the Earth system.

This passage is extremely relevant, particularly in terms of his reference to the 'knowledge of the chain of connection by which all natural forces are linked together'. We now recognise the thermodynamic forces that permeate the entire material world as this connectivity. If we include our resource supply chains as part of this, then we can elucidate how these man-made chains can fit together with the larger chains within the Earth system, and manage them in an ecologically intelligent way.

By connecting our 'ways of being' with that of the Earth system, we then come into resonance with it and, most importantly, act in ways that enable it to heal and diversify, simultaneously providing us with the essential basis for our ongoing existence. In order to understand what this means, we need to understand how the Earth system works, and the implications for our decision-making and our activities within the thermodynamic economy of the Earth system, rather than our own man-made sordid economies of profit, power and inequality.

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Research and Professional Experience:

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1997-2010: Principle Investigator, School of Life Sciences, University of Dundee

Professional Appointments:

Register of Scientific Experts for the Ministero dell' Istruxione, dell' Universita e della Ricerca (REPRISE)

Member of the Scientific Editorial Board of the journal Circular Economy and Sustainability

Visiting Research Fellow at both the University of Winchester Business School and the University of Leeds Business School and has been a consultant at the Centre for Low Carbon Futures, University of York.

Honors:

Australian Association of Rhodes Scholars Scholarship 1996/7
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Winner of the American Libraries Association CHOICE Outstanding Academic Title Award 2020.

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