Taking the Gaia hypothesis at face value

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Abstract

The interest in understanding the climate-life system that has fostered the *Gaia hypothesis* (GH) has resulted in multiple explanatory theories, making its status unclear and controversial. This essay seeks to bring some clarity to the debates surrounding the GH with the aim to make it amenable to scientific scrutiny. We discuss what it means to take the GH at face value and its implications for a potential research programme we call 'functional climatology'.

Keywords: *NASA Viking mission, Schrodinger's What is life?, negative entropy, Gaia phenomenon, climate dynamics, Gaia hypothesis, autopoiesis.*

1. Introduction

The Gaia hypothesis (GH) has been fundamental in the development of what is now called Earth System Science (Lawton 2001; Turney 2003; Steffen et al. 2020), and key to the understanding of atmospheric carbon-based molecules as greenhouse gases that have a crucial effect on biosphere lifespan, long-term habitability and climate feedbacks (Lovelock and Watson 1982; Lovelock and Whitfield 1982). However, the GH remains much disputed and controversial (Schneider 1986; Gould 1988; Kirchner 1989; Margulis 1993, 2004; Kleidon 2002, 2004; Volk 2003a, b; Lenton and Wilkinson 2003; Lovelock 2003a, b). Some authors suggest that this is because it can be interpreted variously as a metaphor, an environmental philosophy, a worldview, or a research programme – or as all of these at the same time (Sagan 1990; Kineman 1991; Rawles 1996; Dutreuil 2016), and others consider that the hypothesis itself is merely pseudoscientific (Ruse 2020).

This proposal seeks to bring some clarity to the debates surrounding the GH by differentiating it from the Gaia phenomenon (GP) and the Gaia theory (GT). This dissection leads us to identify that GH involves Schrödinger's question "what is life?"[1] and that the debate and controversy around the idea of Gaia take place at the level of the current GT. The development of the current GT obliterates the Schrödinger's question, which still is greatly debated in biology (Cornish-Bowden and Cárdenas 2020), and therefore do not take the GH at face value. We discuss theoretical advances that can make the GH amenable to scientific scrutiny, and their implications for a research programme that we call 'functional climatology'.

2. Schrödinger's negative entropy motivated planetary scale life observations[2]

How might one detect life on another planet? NASA puts this question on Lovelock in the context of the Viking mission to Mars in the 1960s. This motivated Lovelock to explore what kind of physical system all living beings are, and hence to look at the Schrödinger's book 'What is Life?'; "*the book that most influenced my own thinking"* (Lovelock 1986, p. 646).

One of the tenets of this book is that a living system is an organized system because it *"feeds upon negative entropy"* (Schrödinger 1945, p. 73). Negative entropy is used as a shorthand for free energy[3]. Both classical

[1] We will refer to the term 'life' exclusively in reference to a concrete biological unity, organism or individual living system.

[2] "*Whether you can observe a thing or not depends on the theory which you use. It is theory which decides what can be observed*." Albert Einstein suggested this to Werner Heisenberg during his 1926 Berlin lecture (Brown and Rechenberg 1990).

[3] Schrodinger in the second edition of 'What is Life?' states; "*if I had been catering for them [physicists] alone I should have let the*

thermodynamics and statistical mechanics imply that entropy monotonically increases in closed systems. The notion that life, according to Schrödinger, maintains itself out of this tendency was the starting point in Lovelock's proposal to NASA (Lovelock 1965).

The Schrödinger-based approach[4] allowed Lovelock to decide which planetary-scale 'phenomenon' to observe, and decide key experiments for the potential detection of 'Martian life'. His reasoning was that as life as feeding upon negative entropy would maintain itself out chemical disequilibrium, the atmosphere of a planet with life would not be in equilibrium either. Arguably, this is the first Schrödinger-based prediction that Lovelock made: Mars's atmosphere is at thermodynamic equilibrium; therefore there is almost certainly no detectable planetary life on Mars.

3. The Gaia phenomenon: observation of biological processes at the scale of planetary systems

The observation that Earth's atmosphere is distinct from Mars and Venus in being at chemical disequilibrium provided for the first time the recognition of planetary-scale biological processes, thereby suggesting that *"life has bulk properties and needs to be considered on a planetary scale"* (Lovelock 1986, p. 646). As Lovelock himself points out, biologists use phenomenological evidence to decide whether something is alive or not (Lovelock 1972, p. 579)[5] – and life also as "*a planetary phenomenon*" (Lovelock 1991, p. 3) has to be recognized as the phenomenon of life in itself[6]: the Gaia phenomenon (GP) (Margulis 1996), which is generally called simply as Gaia.

The GP is all or nothing, but it can be observed and therefore recognized in a multifaceted way, as living beings in general are. Several observations such as the often-referenced Lovelock's (2003) list support the existence of planetary-scale biological constraints and processes that constitute the way to recognize Gaia or the GP; Earth's atmospheric chemical disequilibrium, the long-term stability of marine pH and salinity, the maintenance of the hydrosphere, the rates of biogeochemical cycles, the biogenic methane of the Archaean atmosphere, the metabolic production and balanced levels of oxygen in the atmosphere, the impact of boreal forest and biodiversity on local and global climates, ocean-to-land transfer of elements by bioaerosols, the potential existence of a cloud albedo feedback to phytoplankton gas emission, the climate modulation by metabolic-enhanced rock weathering, and the biogeochemical redox states.

Although not all the points on this list are proven as evidence of planetary life, and are still under debate, the list provides a phenomenological background that has prompted a search for an overarching explanation. As Margulis wrote: "*having recognized the Gaia phenomenon I would like to explain…how long this Gaia phenomenon persisted…*" (Margulis 1996, p. 54). This involved mobilizing an ensemble of theoretical frameworks for explaining the many facets of the GP, giving rise, as we will see in the subsequent section, to the current GT.

4. The Gaia hypothesis includes Schrödinger's question 'What is Life?'

Moving from detecting the GP on Earth but not on Mars or Venus, to the GH's claim that 'Earth is alive', involves an assumption. This assumption is the GH, which is "*the hypothesis that supposed the Earth to be alive*…[the Earth] *as a living organism*" (Lovelock 1988b). This assumption inherently involves knowing the answer to Schrödinger's question 'What is Life? in the first place and therefore whether planets such as Mars belong to this class of systems. As Lovelock writes: "*it was by reading …*"*What is Life? [...] that I first realized*

discussion turn on free energy instead. It is the more familiar notion in this context. But this highly technical term seemed linguistically too near to energy for making the average reader alive to the contrast between the two things"

[4] Lovelock's Schrödinger-based approach is still of great use in planetary astrobiology exploration.

[5] "*At present most biologists can be convinced that a creature is alive by arguments drawn from phenomenological evidence*" (Lovelock 1972, p. 579).

[6] Phenomenon comes from the Greek verb *phainein*, that has the same root as the word *phenotype*, a uniquely biological concept. From this follows that phenomenon and phenotype can be regarded as synonymous: an experience that is apparent to perception or observed feature(s) of living systems.

that planetary life was revealed by the contrast between [...] a dead planet and [...] the Earth" (Lovelock 1986, p. 646). Consequently, the answer to Schrödinger's question is necessary, if not sufficient, for answering 'What is Gaia?' Margulis and Sagan follow up with their own attempt to answer it, in a book which they say: "*reproduces not only Schrödinger's title but also, we hope, his spirit*" (Margulis and Sagan 1995, p. 2).

Although how Schrödinger characterized the persistence of organization in biological systems as arising from negative entropy or minimization of free energy was a great insight in formulating the GH (Lovelock 1972), the persistence of various facets of the GP diverted attention mainly towards the use of theoretical frameworks such as self-regulation by feedback loops, irreversible self-organized non-equilibrium thermodynamics, and adaptive evolution. These have been critical in establishing the current GT. However, concentration on these theoretical frameworks has displaced, if not obliterated, Schrödinger's question and thus the essence of the GH formulation. Next, we discuss briefly why none of these explanatory frameworks are sufficient to fully address or to take the GH at face value.

5. The *status quo* of the current Gaia theory

Moving from the GH the 'Earth is alive' to *explain why* and *how* it may be alive, occur and persist (actual details) represents the Gaia theory. However, as we will see below, the GH has been modified to the 'planet is regulated' and much of the theoretical work, explanations and simulations have focused on this aspect, giving rise to the current GT (Thompson 1987, 1991; Bunyard et al. 1988; Schneider and Boston 1992; Bunyard 1996; Margulis and Sagan 1997; Turney 2003; Schneider et al. 2004; Crist et al. 2009; Tyrrell 2013). The current GT includes the theory of self-regulation by feedback loops, self-organized non-equilibrium thermodynamics, and neo-Darwinian adaptive evolution (Fig.1).

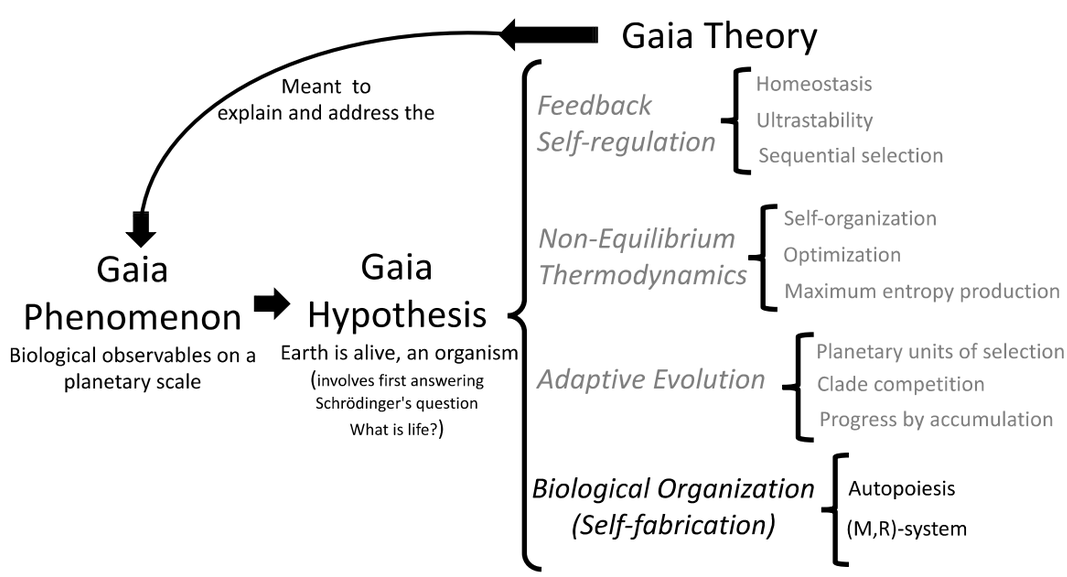

Figure 1. Dissection and explanatory genealogy of the current Gaia theory. The black arrows show the sequential loop among the Gaia phenomenon (GP), Gaia hypothesis (GH) and the explanatory genealogy of the current Gaia theory (GT) (grey font). Note that this loop departing from the GT is meant not only to explain the GP and address GH but depending on which of these theoretical explanations is used, it can potentially generate alternative observations of the GP, verifications of the GH, and therefore new research programmes and a renewed GT (black font).

5.1 Cybernetic control feedback self-regulation

Much of the theoretical work of current GT tends to focus on addressing to what extent the sum of living systems affects, regulates and controls the Earth's chemistry, climate dynamics and habitability by stabilizing or destabilizing feedback loops. The theory that systems, whether genetic, physiological or climatic, self-regulate through feedback loops can be considered as a legacy of cybernetics and control theory (von Foerster 1952; Ashby 1958; Wiener 1961) and the underlying theorem that "*every good regulator of a system must be a model of that system"* (Conant and Ashby 1970), developed as a mathematical framework for what Walter Cannon

(1929), in reference to Claude Bernard's *milieu intérieur* concept, named "*the error-correcting theory of regulation or homeostasis*".

Under the assumption that Gaia involves cybernetic feedback loops, Kirchner (1989) interpreted the GH as having a weak and a strong form. In the weak interpretation, biotic and physical processes are coupled regulators that operate through mutual feedback loops. In the latter, biotic activity is seen as the active regulator and controller of the Earth chemistry and physical climate process. That is, one deduces from Kirchner's own interpretation that the GH does not involve Schrödinger's question: "*Margulis and Lovelock (1974) propose that 'a test for Gaia is to consider what would happen if life were now deleted from the Earth.' This is of course, a test for life, not a test for Gaia*" (Kirchner 1989, p. 225).

Self-regulation by feedback loops is a reactive mechanism that is not confined to, nor is it a definitive feature of, living systems organization (Rosen 1985a, b), and therefore may not be sufficient for addressing the GH. For example, a thermostat is not a living system, but controls and regulates the room temperature through feedback loops. Mechanisms of feedback self-regulation have been described on so-far lifeless planets such as Mars (Chassefière 1991; Ng and Zuber 2006), and for the stabilisation of the surface temperature of a lifeless Earth (Walker et al. 1981).

5.2 Self-organization and nonequilibrium thermodynamics

Other theorists have proposed that Gaia displays self-organized criticality (Bak 1993), or that the system itself is a self-organized (Levin 1998; Lenton and van Oijen 2002; Schwartzman 2002), dissipative or planetary-gradient-reducer system (Sagan and Whiteside 2004). These concepts refer directly or indirectly to irreversible non-equilibrium thermodynamic systems and the statistical theory of dissipative systems, self-organisation, symmetry breaking and pattern generation (Nicolis and Prigogine 1977). When linked to syntactic (Shannon) information theory through the maximum entropy postulate (Jaynes 1957; Dewar 2005), Earth does appear to maximize entropy production (Kleidon 2007, 2009; Karnani and Annila 2009).

However, like cybernetic feedback loops, the phenomena of self-organized non-equilibrium thermodynamics are not specific to living systems. They are found in abiotic systems such as Bénard convection cells, the Belousov–Zhabotinsky reaction and so-called active matter (Sanchez et al. 2012; Fodor et al. 2016). Chemical disequilibrium based on Gibbs free energy has been calculated in lifeless planets (Krissansen-Totton et al. 2016). Indeed, the bulk of irreversible thermodynamics is an attempt to understand the dynamic properties of open systems (a class to which living systems belong) by preserving the mathematical apparatus developed to deal with equilibrium in closed, isolated systems, i.e., to preserve the thermodynamic entropy appropriate to adiabatic systems (to which living systems do not belong) (Von Bertalanffy 1950; Rosen 1979, 1988). Thus, although a necessary theoretical tool, the statistical theory of self-organized non-equilibrium thermodynamic systems appears to fall short of characterising living systems (Rosen 1978a, 1985c; Martyushev 2013).

5.3 Neo-Darwinian adaptive evolution

Several neo-Darwinists have rejected the GH, arguing that organisms cannot reach a 'common good' by natural selection and that natural selection cannot act on the whole planet (Doolittle 1981; Dawkins 1982). In response, Watson and Lovelock (1983) put forward a simulation they called Daisyworld, a hypothetical cybernetic planet which can regulate its temperature by feedback loops over a wide range of solar luminosities. These feedback loops are accomplished by ordinary physical processes rather than by natural selection. As Daisyworld refuted the objections, the critics have responded by developing Darwinian Daisyworlds that regulate their temperature simply through natural selection in terms of adaptation, competition, cheating and selfishness (Staley 2002). However, the more Darwinian characteristics were added, the less well planetary temperature self-regulation was attained (Saunders 1994; Roberston and Robinson 1998; de Castro Carranza 2013).

Despite the results of these artificial life experiments based on the feedback self-regulation theory, efforts have continued to be made to show that the 'modern evolutionary synthesis' must explain or at least be compatible with the GP. They appear to be based on manly two assumptions. The first one is that Gaia is not life, but i) an ensemble of planetary feedback loops, ii) an ensemble of biogeochemical cycles and/or iii) an adapted and differentially persisted *clade* or biosphere (excluding other components of the Earth system). All them are seen as 'units of selection' (Doolittle 2019). The second assumption is that the GP should be explained and consistent with how natural selection works. In essence, this requires a form of selection at a higher level than individuals, which may either be feedback, cycle or clade selection (hypothetically, different clades would have made several attempts, the surviving one is the one we belong to) (Doolittle 2019), or selection by survival - the hypothesis that biospheres can acquire persistence-enhancing adaptations by chance which strength or maintain Earth's climatic feedbacks (Lenton et al. 2018). This 'Darwinization' of Gaia (Doolittle 2017), carry the underlying notion that adaptive evolution and selection may operate at multiple time scales (Lenton et al. 2018) up to these self-perpetuating non-reproducing (Lenton et al. 2021) planetary units of selection (Doolittle 2019).

On the other hand, it is assumed that these ensembles of planetary units of selection can occur due to 'complex adaptability' (Levin 1998; Lenton and van Oijen 2002), 'progress by accumulation' (Doolittle 2017, 2019) and even, hypothetically, planetary reproduction (Gatti 2018). In all cases, the scientific objective appears to accommodate the 'modern evolutionary synthesis', i.e., how natural selection on Earth, inhabited by cells and multicellulars, is consistent with planetary feedbacks and self-regulation.

At present, the literature lacks a formal discussion of how such evolutionary formulations of the current GT can incorporate recent advances in evolutionary theory such as the extending evolutionary synthesis (Laland et al. 2015), or evolutionary theory beyond natural selection, and the adaptationist programme (Gould and Lewontin 1979; Nielsen 2009)[7] like the evolutionary natural drift (Maturana and Mpodozis 1991; Varela et al. 1991, chap. 9).

Despite the efforts of 'Darwinizing Gaia' to accommodate Gaia to cybernetics and neo-Darwinism, the evolutionary theory of natural selection, and indeed any evolutionary theory, appears to fall short of addressing Schrödinger's question, hence fundamentally sidesteps the GH. This does not imply that an evolutionary explanation is not useful; it merely indicates that evolution alone, although necessary to be consistent with the GP, is not sufficient to address the GH at face value.

6. Is the Gaia hypothesis a tractable hypothesis?

The GH suggests that the GP on Earth is the manifestation of something more than feedback self-regulation, irreversible self-organized non-equilibrium thermodynamics or adaptive evolution alone. A parallel may be drawn with synthetic biology. To fabricate a living cell, we need more than the concatenation of biosynthetic cycles (Calvin cycle, tricarboxylic cycle, etc), feedback gene regulation (e.g. operon Lac, ribosomal operon, etc) and active matter (Fodor et al., 2016; Sanchez et al., 2012). Likewise, bringing an inert non-equilibrium thermodynamic planet with feedbacks and a selection of geochemical cycles would arguably not yield the GP. Therefore, Schrödinger's question remains central for posing the GH (Lovelock, 1986; Margulis and Sagan, 1995). Yet, the current GT, by neo-Darwinizing and mechanizing the GH (treating Gaia as a unit of selection, or a thermodynamic or a cybernetic system) in order to fit the notion of Gaia as a planetary feedback regulator, obliterates Schrödinger's question, hence fundamentally the GH. The GP is reduced to an epiphenomenon, i.e., the instantiation of life does not occur on a planetary scale, but it is a simple *by-product effect* of cellular and multicellular activity occurring on a rocky planet. As Sagan, (1990, p. 188) quoting Harding, points out; *"we tend to think on this planet as a life-infested rock, which is as absurd as thinking of the body as a cell-infested skeleton"*.

[7] The *adaptationist programme* inherits from the early 20th century modern synthesis school of evolution by natural selection the assumption that all or most traits of organisms are evolved optimal adaptations. The prominent alternative to the adaptationist programme is structuralism (Thompson 1917; Gould 1971; Rosen 1978b; Arthur 2006).

We argue, however, that the controversy over the GH does not imply its intractability or down on a cryptic vitalism. Similar to other authors (Mikulecky 2000; Gare 2008; Korthof 2014; Kineman 2019), we think that the best route to a successful approach to the GH and hence a renovated GT is through a clear-cut delineation of what life is and what that implies (Margulis 1997). Gaia should be considered primarily as *metabiotic* (Clarke 2020) and not simply as the biosphere or a global ecosystem as Lovelock insisted, although focusing on regulation; *"[i]t is not the biosphere alone but the whole Earth system that does the regulating"* (Lovelock 2009, p. 166).

However, all major theories accounting for 'Schrödinger's what is life?' are focused on the cellular scale (Cornish-Bowden and Cárdenas 2020), and this focus neglects precisely what the formulation of the GH has changed, by arguing that Schrödinger's question could be answered by also looking at the planets. Then, GT as a theory of living planets can also be a theory for cellular life (Lovelock 1987), suggesting that Earth system science is properly studied as a biological science and that biological organization models can be applied meaningfully at the scale of the entire Earth (Lerdau 2014). Therefore, there should be some attempt to show how the theories that account for Schrödinger's question at one level also apply at the other, and to what extent understanding Gaia could illuminate the nature of life itself.

Current evaluations of 'what is life?' follow a diversity of approaches (Cornish-Bowden and Cárdenas 2020). Most of them are associated with cybernetic systems and feedback loops. In contrast, others reject these approaches and instead explicitly recognize cognition, autonomy and anticipation as central and distinctive features of biological systems organization (Varela 1979; Maturana and Varela 1980; Rosen 1985d; Friston 2013). Specifically, given the limitations of characterizing life as a mere cybernetic regulator, autopoiesis (self-production/self-fabrication), a clear-cut characterization of living systems organization, was suggested before any criticism as a way of addressing the GH (von Foerster 1975). According to Margulis, '*[w]hereas the smallest recognizable autopoietic entity… is a tiny bacterial cell the largest is Gaia*' (Margulis, 1990, p. 861); "*planetary physiology… is the autopoiesis of the cell write large*" (Margulis and Sagan 1995, chap. 54), while Lovelock argued that: "*[t]he tightly coupled evolution of the physical environment and the autopoietic entities …led to a new order of stability: the state associated with Gaia*" (Lovelock 1988a, chaps. 219–220). Addressing the question of what life is – and specifically the idea that it involves autopoiesis – suggests that explaining Gaia as an autopoietic system could be a promising way forward (Fig.1).

Several authors consider that autopoiesis is a plausible scenario for the instantiation of life organization on a planetary scale (Capra, 1996; Capra and Luisi, 2014; Clarke, 2012; Jantsch, 1980; Kazansky, 2004; Levchenko et al., 2012; Margulis, 1990, 1997; Margulis and Sagan, 1995, 1986; Onori and Visconti, 2012; Sahtouris, 1996). Recent work showed that this is plausible using a proof-of-concept based on the chemical organization theory and the zero deficiency theorem applied on a simple but representative Earth molecular reaction network (Rubin et al. 2021b).

The autopoietic characterization of biological systems as self-produced (fabricated) through operational closure is organizational (Maturana and Varela 1980). This operational closure organization refers to how biological systems are materially the result of their own operations, such that a molecular metabolic network produces a boundary that enables it to continue producing itself, in dynamical and thermodynamically open conditions. Further formal treatments of autopoiesis has been shown to have an equivalence to the formal theory of the "Metabolism-Repair" (M,R)-system (Nomura 1997; Zaretzky and Letelier 2002; Letelier et al. 2003) developed as a mathematical model of biological self-fabrication (Rosen 1958, 1972a). Rosen (1985e) considers that the closure effected by an (M,R)-system is 'closure to efficient causation' – a form of closure which is distinct from thermodynamic closeness (material closure), and it does not in itself involve feedback loops or biogeochemical cycles.

To exemplify this point, consider a closed glass bottle, half full of water but open to solar radiation. The radiation

evaporates the water that is condensed in the walls of the bottle. Condensed water falls as liquid, to be again subject to evaporation. The evaporation-condensation cycle is analogous to a geochemical cycle, with the glass bottle and sun acting as efficient cause and boundary condition in the sense that they constrain the internal flow of water. But this is not a biological system, as the glass bottle is not self-produced: an external agent produces it. If the glass bottle were itself produced by the evaporation-condensation cycle fuelled by solar energy, then one would say that the glass bottle self-produces, achieves closure to efficient causation organization and hence is a living system (Hofmeyr 2007).

As the self-fabricating organization occurs at different scales (Maturana 1980), Mikulecky (2000) previously suggested that the theory of the (M,R)-system may provide the formal basis for mathematically proving the GH. Lane (2018) and Kineman and Wessman (2021) expanded the (M,R)-system theory to ecosystems level, and we have shown that the (M,R)-system attributes can affect deeply our understanding and modelling of the Earth's climate-system complexity (Rubin and Crucifix 2021). This implies that as long as the components of a system satisfy the conditions of self-fabricating organization, they may accomplish a set of relations of self-production, which can be distinguished, heuristically, as structures having 'functions' (Rosen 1972b; Varela and Maturana 1972). For example, the heart has a certain form (structure) that is adequate to 'pump blood'. Although this may not be the only constitutive relation with the body, this has an effect on the whole organism that at the same time maintains the heart pumping blood. At the cellular level, to take another example, the folded enzyme affects its cytoplasmic environment by catalysing components, which also maintains the conditions for the right folding to occurs and hence its catalytic function. Similarly, we also consider that the Earth's climate-system and its biosphere may accomplish a same sort of self-referential set of relations (Rubin and Crucifix 2021).

A crucial point is that the organization of self-fabrication by closure to efficient causation allows living systems develop anticipative models of themselves and their environment to self-repair and persist (Rosen 1985a; Louie 2012). In dynamic terms this has been framed as free energy minimization and active inference (Friston 2013). Framing the Earth as an autopoietic system could indeed allow the system to persist over a nontrivial time-scale through active inference (Rubin et al. 2020, 2021a), allowing the possibility of cognition and anticipation at the planetary scale. In fact, we consider that from these advances in biological theory, the GH can be theoretically tractable, as initially oriented, in a non-mystical formal manner, opening the possibility to study the Earth's climate from an organizational 'functional' standpoint.

7. Towards a 'functional climatology' research programme

The GH as initially oriented, i.e., that Earth system's homeorhetic trajectories are determined *by* and *for* the system itself (Lovelock and Margulis 1974; Margulis and Lovelock 1975), involves some form of organization where the system's components instantiate a set of relations that preserves the organization of the system and determines its trajectory. As the heart is 'blood for the body', we have to ask if it is legitimate to consider whether, for example, the Amazon forest is 'pumping water for the climate'. So far, current research has provided some intriguing observations about the Amazon not just seeding but making its own rain (Loomis 2017): the trees of the Amazon, in addition to producing seven more times moisture and clouds than the Atlantic and absorbing 1 billion tons of CO_2 annually (Brienen et al. 2015), are capable of generating trade winds and bringing atmospheric rivers inland from the Atlantic through the anticipation of dry periods (Wright et al. 2017). These atmospheric rivers in turn are retained by the Andes (acting as a topographic barrier) and distributed with mountain nutrients downwards through the Amazon towards the Atlantic heavily affecting the salinity, pH, light penetration, and sedimentation of a wide area of the tropical North Atlantic (Moura et al. 2016). This flow can be connected with part of the nutrients that are transported by wind (Amazon drived?) from the Sahara desert to the Amazon (Nogueira et al. 2021) across the Atlantic, affecting the growth of algae (Walsh and Steidinger 2001) and microorganisms which produce annually more than 60% of biogenic cloud-forming aerosols (McCoy et al. 2015). This 'functional connectivity' of the Atlantic and the Andes through the Amazon structure thus may

impact the climate system through modulating the water and nutrient cycle, and global energy balance.

In other words, taking the GH at face value will suggest that the idea of spatial and temporal climate dynamics is not anecdotal and that the Earth instantiate metabolic closure on a planetary scale. For instance, the rates of biogeochemical cycles that affect climatic and geomorphological changes (e.g. great oxidation event (Rosing et al. 2006)), are effectively constrained, at the planetary scale, by a small number of key enzymes (Williams 1996) scattered mainly in the Earth's microbiome (Falkowski et al. 2008; Stolz 2016) and mostly produced in anticipative manner (Siegal 2015). These geo-climatic changes established by the activity of key enzymes acting as boundary conditions (Kauffman 2020) at the same time expanded the genomic repertoire and hence the enzymatic capacities of the system (Chen 2021), suggesting the encoding of both short- and long-term memory, autonomous changes in boundary conditions (control parameters) and metabolic closure on a planetary scale.

Can we move from these observations and appealing descriptions to a formal criterion that would help us to draw a line between wishful thinking and a characterisation of the organization of Earth's components that sees it as satisfying the set of autopoietic relations of self-fabrication? Have the Earth system components the same rate of fabrication? What is the causal relation, for example, between the fabrication of Greenland and the fabrication of the Amazon? How and where does the Anthropocene affect Gaian self-fabricating? Could there be effective geoengineering or 'Earth stewardship' without side effects on a planetary system that autonomously self-repairs?[8] This could be the core of a research programme we call "functional climatology", upon which we could lay the groundwork for an understanding of the Earth system as a living unity from an organizational standpoint.

In practice, this programme will take self-fabricating organization models (Rosen 1972a; Louie 2006) as surrogates of the Earth system to map geo-climatic processes and identify feedforward signalling pathways that satisfy planetary-scale relations of autopoietic (M,R) organization. The biospheric component of the Earth system should be considered not as a passive and reactive subsystem, but fundamentally as an active and arguably together with the whole Earth as an autonomous and anticipatory system (Rubin et al. 2020). This means that one of the main objectives of this programme will be to identify how the organization and homeorhetic dynamics is determined by the *anticipatory models* that the Earth may have of its environment (the Sun and space radiation) and of itself (its own geomorphological dynamics, including the Anthropocene).

The implementation of this programme will extend the conventional input/output and state-variable frameworks upon which climate and feedback control theory is based, to explicitly mobilize the mathematical biology apparatus (Thom 1986; Casti 2002) towards Earth-system functioning. In other words, this programme will require a clear delineation among the Gaia phenomenon, the Gaia hypothesis, and the Gaia theory and will demand taking a step beyond the current consensus that GT is mostly about control feedback regulation, irreversible self-organized non-equilibrium thermodynamics or neo-Darwinian adaptive evolution.

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[8] Perhaps this is why in Margulis' opinion: " 'Stewardship of the Land' seems repulsively anthropocentric to me, even though [such] intentions are laudable" [footnote 33 of (Clarke 2020, p. 14)].

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