

1 **More than planetary-scale feedback self-regulation:**
2 **A Biological-centred approach to the Gaia Hypothesis**

3
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12 **Abstract**

13 **Recent appraisals of the Gaia theory tend to focus on the claim that planetary life is a cybernetic**
14 **regulator that would self-regulate Earth's chemistry composition and climate dynamics, following either**
15 **a weak (biotic and physical processes create feedback loops), or a strong (biological activity control and**
16 **regulates the physical processes) interpretation of the Gaia hypothesis. Here, we contrast with the**
17 **regulator interpretation and return to the initial motivation of the Gaia hypothesis: extending**
18 **Schrödinger's question about the nature of life at the planetary scale. To this end, we propose a relational**
19 **and systemic biological approach using autopoiesis as the realization of the living and the (M,R)-system as**
20 **the formal theory of biological systems. By applying a minimum of key categories to a set of interacting**
21 **causal processes operating on a wide range of spatial time scales through the atmosphere, lithosphere,**
22 **hydrosphere, and biosphere of the Earth system, we suggest a one-to-one realization map between the**
23 **Gaia phenomenon and (M,R)-Autopoiesis. We show that metabolic molecular *self-production* by *closure***
24 ***to efficient causation* on a planetary scale is plausible. This suggests that the Gaia phenomenon may be the**
25 **embodiment of *Life itself in the planetary domain*, a *sui-generis biological unity* and thus more**
26 **fundamental than self-regulation by feedback mechanisms. Formulating the Gaia theory in biological**
27 **terms provides a formal basis for the claim that planetary biology elsewhere in the universe must involve**
28 **and have a formal equivalence to a self-referential physical process which cannot be implemented by a**
29 **Turing machine and, therefore, has a non-computable character.**

30 **Keywords:** *Schrödinger's question, (M,R)-systems, Autopoiesis, Self-production, Closure to efficient causation.*

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34 1. Introduction

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37 Lovelock's hypothesis that Life is a planetary-scale phenomenon (Lovelock, 1979) followed attempts
38 to detect life on other planets by inspecting absorption spectra of their atmospheres (Lovelock, 1965). The
39 underlying idea was that chemical disequilibrium would be the signature of life on a planetary scale (Hitchcock
40 and Lovelock, 1967; Lovelock and Giffin, 1969, Lovelock, 1972), thereby extending Schrodinger's (1945)
41 characterization of life as maintaining '*negative entropy*'¹ at this planetary scale. The land-based measures of
42 Mars's atmosphere spectra then revealed that Mars's atmosphere is in chemical equilibrium, hence, lifeless
43 (Lovelock, 1975, 1980). In contrast, Earth's atmosphere is in chemical disequilibrium because of the continuous
44 biological production of a molecular mixture of highly reactive gases (Margulis and Lovelock, 1974). The
45 claim that life is a planetary phenomenon was later coined the *Gaia hypothesis* (Lovelock and Margulis, 1974).

46 The Gaia hypothesis has motivated a 'research programme' (Margulis and Sagan, 1997) on which
47 experimental evidence show how biological activity affects Earth's dynamics (Lovelock 2003a). Today, it is not
48 much disputed that Earth's climate, water, and trace elements dynamics involve biological activity on a wide
49 range of time and spatial scales. Examples include i) metabolic-enhanced rock weathering, ii) the existence of a
50 cloud albedo feedback to algal gas emission, iii) geological evidence that the Archaean atmospheric chemistry
51 dominated by methane, iv) the metabolic production and balanced levels of oxygen in the atmosphere, v) impact
52 of boreal forest and biodiversity on local and global climates, and vi) ocean to land transfer of elements by
53 biogenic gases. These empirical evidences have framed the present-day *Gaia theory* (Thompson, 1991, 1987;
54 Bunyard and Goldsmith, 1989; Barlow, 1992; Bunyard, 1996; Schneider and Boston, 1992; Schneider et al.,
55 2004; Crist et al., 2009).

56 However, as we argue in Section 2, much of the theoretical work associated with the Gaia hypothesis
57 addressed the question of whether life on Earth 'regulates' Earth's climate, and therefore appeals to the notion
58 of self-regulation by 'feedback mechanisms' which are a legacy of the development of cybernetic systems
59 (Wiener 1948; Von Foerster et al., 1951; Ashby 1956). Lovelock originally, and later with Margulis, advocates
60 the notion that Gaia is a "*a biological cybernetic system able to homeostat the planet for an optimum physical
61 and chemical state appropriate to its current biosphere*" such that "*life moderates the global environment to
62 make it more favorable for life*" (Lovelock, 1972, p. 579). That is, the physiological conditions of Earth were
63 regulated by and for the biosphere (Lovelock and Margulis, 1974). However, initially this conception has been
64 viewed as teleological and implausible to any neo-Darwinist mechanism of evolution (Doolittle 1981). Lovelock
65 and Margulis later used slightly different heuristic explanatory notions to represent and maintain the Gaia
66 hypothesis strictly in the scientific field, and to dissociate teleology from it. Over time, advocates and opponents
67 have used or proposed other multiple explanatory notions, and different catalogs and dictionaries to address the
68 Gaia hypothesis. It is therefore no wonder that the epistemological status of the Gaia hypothesis -as Life as

68 planetary scale phenomenon- grew unclear and controversial (Schneider 1986; Kirchner, 2002; Lenton and
69 Wilkinson, 2003; Lovelock, 2003b; Margulis, 1993; Kleidon, 2002, Volk, 2003, Margulis 2004, Lenton and
70 Latour, 2018). We argue therefore that a clear-cut mathematical formulation of the Gaia hypothesis is necessary.
71 It could focus, reinvigorate, and consolidate the Gaian research programme towards the recognition of central
72 features associated to biological phenomenon such as cognition and learning across scales of organization.

73 The present article attempts to place some key biological formal theory and clear-cut characterizations
74 of living systems in the hope to identify a common and unified grounding to the Gaia hypothesis. We propose a
75 biological-centred formal framework of the Gaia hypothesis based on the language of relational and systemic
76 biology. In Section 2, we distinguish the Gaia phenomenon, the Gaia hypothesis and the Gaia theory. Section 3
77 outlines the steps leading towards a theoretical biology framework of the Gaia hypothesis with reference to
78 Autopoiesis and the (M,R)-system. Section 4 establishes the Gaian Autopoiesis through the modelling relation
79 between Autopoiesis and Gaia. In Section 5 we establish rigorously the theoretical ground of the Gaia
80 hypothesis in terms of the (M,R)-system. Section 6 outlines briefly some implications of biologizing Gaia
81 theory in Daisyworld mechanisms. Finally, section 7 summarizes the paper.

82 **2. Gaia hypothesis: Asking Schrödinger's question in the planetary scale**

83
84 The Gaia phenomenon is the perception, distinction and recognition of the phenomenon of life on a
85 planetary scale from the differential observables of planets like Earth, Mars or Venus. As Lovelock stated: "*At*
86 *present most biologists can be convinced that a creature is alive by arguments drawn from phenomenological*
87 *evidence*" (Lovelock, 1972, p. 579). The observation that Earth is qualitatively distinct from Mars and Venus,
88 therefore, provides the recognition of the Gaia phenomenon, and thus the expression of the Gaia hypothesis:
89 Life as planetary scale phenomenon (Lovelock and Margulis, 1974; Lovelock, 1979)(Fig. 1).

90 The formulation of the Gaia hypothesis was fundamentally influenced by the question of Schrödinger's
91 book 'What is life?' (Schrödinger, 1945). As Lovelock wrote: "*Erwin Schrödinger, whose small volume What is*
92 *life?[...] was, I would say, the book that most influenced my own thinking*" (Lovelock, 1986, p. 646). That is,
93 from a scientific standpoint, the most important challenge in the formulation of the Gaia hypothesis, from the
94 observation of Gaia phenomenon, was and still is to extend Schrödinger's question to the planetary scale: what
95 is planetary life? Is life a planetary phenomenon? As he wrote it: "*life has bulk properties and needs to be*
96 *considered on a planetary scale*" (Lovelock, 1986, p. 646).

97 The first prediction of the Gaia hypothesis as Schrödinger's question in the planetary scale was
98 confirmed: at the planetary scale, Mars is a lifeless planet. Yet, paradoxically, the present-day Gaia theory
99 sidesteps the Gaia hypothesis. Either their supporters or opponents implicitly assume that *Life* must be, on a

100 planetary scale, a stabilizing or a destabilizing *regulator*. The regulator thesis refers to cybernetic systems,
101 which are systems with a specific organization to self-regulate by feedback mechanisms (Wiener 1948; Von
102 Foerster et al., 1951; Ashby 1956). It has been stated that every good regulator of a system must be a model of
103 that system (Conant and Ashby, 1970). Following the cybernetic paradigm and around the notion of the
104 regulator, the Gaia hypothesis has been taxonomized, reinterpreted (weak and strong interpretation), and then
105 refuted (Kirchner, 1989, 1990). In the weak interpretation of the Gaia hypothesis, both the biotic and physical
106 processes create feedback loops and are coupled regulators (Kirchner, 1989). In the strong interpretation, the
107 biological activity is the regulator, and it controls the Earth chemistry and physical processes (Kirchner, 1989).
108 That is, the Gaia hypothesis, hence the phenomenon of life at the planetary scale, is reduced to an
109 epiphenomenon of chemical and climatic regulation by negative or positive feedback mechanisms in the Earth
110 system, as can be deduced from Kirchner's (1989, p. 225) own argument: "*Margulis and Lovelock (1974)*
111 *propose that 'a test for Gaia is to consider what would happen if life were now deleted from the Earth.'* *This is*
112 *of course, a test for life, not a test for Gaia*" (the underline is ours). Clearly, Gaia hypothesis is disentangled
113 from the Schrödinger's question. Therefore, the Gaia hypothesis is obliterated to become amenable to testing
114 and falsification (Kirchner, 1989, 1990).

115 In summary, the regulator thesis along with the neo-Darwinism confines the present-day Gaia theory to
116 the weak and strong interpretations of the Gaia hypothesis. Indeed, much of the present-day Gaia theory
117 addressed the question on what time-scale natural selection 'regulates' Earth's chemistry and climate. Whether
118 it is at local, regional or at the planetary scale. Under the weak interpretations, the *adaptationist programme*
119 (neo-Darwinism)(Gould and Lewontin, 1979; Nielsen, 2009) of natural selection (Darwin, 1859) provides the
120 evolutionary background for explaining whether self-regulation can be explained by mechanisms involving and
121 units of selection, competition, cheating and selfishness (Lenton, 1998, Lenton and Lovelock, 2000; Staley,
122 2002; Williams and Lenton, 2008, Doolittle, 2017). It also features explicative notions such as selection by
123 survival alone, and progress by accumulation (Doolittle, 2017; Lenton et al., 2018). On the other hand, under the
124 strong interpretations, homeostasis and optimization (Cannon, 1929) provide the explanative framework to
125 address the thesis of self-regulation at the planetary scale. Homeostasis is framed mathematically in terms of the
126 first-order cybernetics (Wiener, 1948), self-organization (Ashby, 1947; 1962a; Von Foerster, 1960) and
127 ultrastability (Ashby, 1956a, 1952). The possibility of self-regulation at the planetary scale is explored with
128 heuristic models such as Daisyworld (Watson and Lovelock, 1983), 'complex adaptive' systems (Lenton and
129 van Oijen, 2002; Levin, 2005, 1998; Schwartzman, 2002) and sequential selection (ultrastability) (Lenton et al.,
130 2018). When Gaia is seen as a system with many degrees of freedom, the possibility that it may optimize certain
131 quantities finds some justification in the theory of irreversible far-from thermodynamic equilibrium (Nicolis and
132 Prigogine, 1977) along with information theory (Shannon, 1948). Life would enhance and maximize entropy

133 production (Karnani and Annala, 2009; Kleidon, 2009, 2004; Kleidon and Lorenz, 2004; Toniazzo et al., 2005)
134 and reduce planetary scale gradients (Sagan and Whiteside, 2004).

135 In conclusion, the present-day Gaia theory is neo-Darwinized (it has been made compatible with the
136 adaptationist programme) and physicalized (Gaia can be simulated by dynamical systems using thermodynamics
137 and cybernetics) to fit the notion of *Life* as a planetary regulator (Fig. 1). They are important contributions
138 because they outline possible mechanisms of planetary self-regulation across scales. However, we argue that
139 they obliterate Schrödinger's question as the fundamental motivation of Gaia hypothesis. Indeed, certain abiotic
140 systems display a form of self-regulation. For example, the thermostat is an evolving ultrastable machine able to
141 regulate the temperature by feedback mechanisms (Ashby, 1952, 1956b). Mechanisms of regulation by feedback
142 loops have been described on lifeless planets such as Mars (Chassefière, 1991; Ng and Zuber, 2006). Abiotic
143 geochemical cycles, such as that of nitrogen, are plausible on a planetary scale (Laneuville et al., 2018). The
144 concept of negative entropy also appears to fall short for characterizing life. Irreversible, far-from equilibrium
145 states, symmetry breaking, and self-organization take place in abiotic systems such as Bénard convection cells
146 or dissipative systems (Fodor et al., 2016; Sanchez et al., 2012). Chemical disequilibrium and far-from-
147 thermodynamic equilibrium of exoplanets atmospheres have been identified in inhabitable planets (Krissansen-
148 Totton et al., 2016). Thus, self-regulation, self-organization, chemical disequilibrium, geochemical cycles and
149 even adaptive behaviour can and do appear in inanimate systems. Furthermore, from a strict thermodynamic
150 perspective, the entropy of living systems does not appear to be particularly low (Martyushev, 2013). With these
151 considerations at hand, we see that the Gaia hypothesis as the Schrödinger's question support the claim that the
152 Gaia phenomenon is the manifestation of something more than self-regulation and the postulations behind the
153 present-day Gaia theory. It involves more than organisms-environment coupled co-evolution, and more than the
154 Earth system viewed as a planetary system far from thermodynamic states with feedbacks and geochemical
155 cycles due to geochemistry and geophysics alone (Lovelock, 2009).

156 A parallel may be drawn with the cellular phenomenon. To fabricate a living cell, we need more than
157 the concatenation of biosynthetic cycles (Calvin cycle, tricarboxylic cycle, etc), gene regulation by feedback
158 circuits (such as operon Lac or ribosomal operon) and active matter (Fodor et al., 2016; Sanchez et al., 2012).
159 Likewise, bringing an inert planet far from thermodynamic equilibrium states with feedbacks and a selection of
160 geochemical cycles would arguably not yield the Gaia phenomenon. Therefore, the Schrödinger's question
161 remains the key to how best pose the Gaia hypothesis (Lovelock, 1986; Margulis and Sagan, 1995). The answer
162 to this question is the scope of the next section.

163 **3. Towards the theoretical biology of the Gaia phenomenon**

164

165 Biological analogies permeate the language around the Gaia hypothesis. Some renowned biologists like
166 Lewis Thomas state that ‘*the Earth [...] if not like an organism [...] is most like a single cell*’ (Thomas, 1974, p.
167 5). More recently, Harold Morowitz wrote “*the metabolic character of life is a planetary phenomenon, no less*
168 *than the atmosphere, hydrosphere, or geosphere*” (Morowitz et al., 2008, p. 8). These claims appear today
169 compatible with the Gaia hypothesis, if not defining it.

170 Since the beginning of physiology, the realization of the living of a biological system is characterized
171 by the maintenance of its internal physiological bounds, despite forcing fluctuations and dissipation. Claude
172 Bernard noted that “*All the vital processes, varied as they are, have only one object, to maintain the uniformity*
173 *of the conditions of life in the internal milieu*” (Bernard, 1878, p. 84). This asymmetry between external and
174 internal conditions is thus broadly recognized as important characterization of biological systems. Following the
175 notion of conservation of the *internal milieu*, Lovelock (1991) and Margulis (1990, 1997) considered that the
176 Gaia phenomenon can be characterized as a biological system: “*Different from a physicist, biochemist and neo-*
177 *Darwinist’s view...[Gaia is]... a bounded system that is open to a flux of energy and matter, and that is able to*
178 *keep its internal conditions constant, despite changing external conditions*” (Lovelock, 1991, p. 29 brackets are
179 ours). Or: “*Cells and Gaia display a general property...: as their surroundings change unpredictably, they*
180 *maintain their structural integrity and internal organization*” (Margulis, 1997, p. 267). Furthermore, they
181 recognized that instead of planetary homeostasis, “*Gaia’s history [ontogeny] is characterized by homeorhesis*
182 *with periods of constancy punctuated by shifts to new, different states of constancy*” (Lovelock, 1991, p. 141
183 brackets are ours), or “*Gaia...like the physiology of an embryo, is more homeorhetic, than homeostatic*”
184 (Margulis, 1990, p. 866). Homeorhesis indicates system dynamics with potential transitions to multistability and
185 stability of dynamics rather than stability of states. Waddington (1968, p. 12) indeed suggested that what “*is*
186 *being held constant is not a single parameter but is a time-extended course of change, that is to say, a*
187 *trajectory*”. In summary, a biological system responds to a perturbation (forcing fluctuations and dissipation),
188 thus maintains its internal physiological bounds, by returning to a homeorhetic trajectory, not to a homeostatic
189 state.

190 Since the development of cybernetic systems, the response to perturbances appealed to the notion of
191 self-regulation by feedback mechanisms. There is, however, an alternative explanation why biological systems
192 maintain their homeorhetic trajectories within physiological bounds. It relies on *self-fabrication* by *closure to*
193 *efficient causation* in the (M,R)-system (M=metabolism, R=repair) (Rosen, 1991a, 1972, 1958) and *self-*
194 *production* by *operational closure* in autopoiesis (auto=self, poiesis=production) (Maturana and Varela, 1980)
195 characterization (Fig. 2). These explanations have become important, because for a process to be regulated, it
196 must first be produced. That is to say, the material production precedes the regulation (Rosen, 1991a, Maturana
197 and Varela, 1980). Therefore, it is logical to pay attention first to how the systems are constituted materially, to
198 later study how this material production may or may not be regulated. This reflects ‘what life *does*’ as to best

199 represent ‘what life is’, thus a way to answer Schrödinger's question (Cornish-Bowden and Cárdenas, 2017;
200 Friston, 2013; Letelier et al., 2011; Maturana, 1980; Piaget, 1967; Ramstead et al., 2018; Rosen 1985, 1991a;
201 von Foerster, 1974).

202 The (M,R)-system outlines the inferential aspects of a formal system, hence the theoretical
203 characterization of biological systems in mathematical language (Fig. 2A). Based on the (M, R) formal system,
204 Rosen states: “*a material system is an organism if, and only if, it is closed to efficient causation*” (Rosen, 1991a,
205 p. 244). Rosen (1972, 1985a, 1994b) identified an efficient cause with the enzymatic ‘active site’ which is the
206 operator that induces or constrains the material flow of unlikely chemical reactions, and thus, it is the generator
207 of forcing (Jee et al., 2018). The active site is only found in the tertiary structure and three-dimensional form of
208 an enzyme. It determines the catalytic activity of the enzyme, and is configured in the protein folding
209 (phenotype at very basic molecular level). Protein folding is not predetermined in the DNA/RNA sequence,
210 hence the ‘active site’ is not coded in the genomic sequence. It is non-isolable and non-fractionable from the
211 folded enzyme which is produced, specified and determined only in the realization of the living of biological
212 systems (Rosen, 1991a).

213 Self-fabrication by closure to efficient causation take place when the (M,R)-system models a biological
214 system selecting a set of elements A (matter and energy) of its environment and effectively transforms them in
215 B by its catalytic function F . The function F represents the efficient cause of this transformation. This reads F :
216 $A \rightarrow B$ (Fig. 2A). However, the efficient cause F is subject to dissipation, and therefore needs to be repaired,
217 fabricated, produced and replaced. A new efficient cause is introduced, the repair function ϕ which takes B as
218 material cause to produce F . This reads ϕ : $B \rightarrow F$. But the efficient cause ϕ is also subject to dissipation, and
219 therefore needs to be fabricated and produced as well. It requires another efficient cause, and then yet another
220 efficient cause for the production of this efficient cause, and so on infinitely. The (M,R)-system could, of
221 course, be simply augmented with another mapping that would do it, but this would lead to an incipient *infinite*
222 *regress*². Instead of invoking efficient causes ad infinitum, the nontrivial key point in the (M,R)-system formal
223 representation of biological systems is that the efficient cause (repair function) ϕ is fabricated from inside,
224 rather than from the outside the system. This is done by proving, ‘*under stringent but not prohibitively strong*
225 *conditions*’, the existence of a map β that replicates ϕ . The condition is related to the existence of a function
226 that assigns a map β to an least one $b \in \beta$ such that, for those $b \in \beta$, $\beta_b(B)$ satisfies the relation $\beta_b(B): F \rightarrow \phi$.
227 The satisfaction of this condition generates closure to efficient causation, thus a clear-cut formal characterization
228 of a biological system. In this case, each efficient cause in the system is materially produced within the system
229 itself by metabolism (F), repair (ϕ) and replication (β). They are mutually dependent on each other, or, in the
230 terms of formal logic, they are mutually ‘*entailed*’ (Rosen, 1972). The fabrication of *every* efficient cause is

231 caused (*internally entailed*) by another efficient cause produced within the biological system. The organization
232 of the fabrication of all catalytic elements is embedded in a metabolically closed loop — a circularity of
233 efficient causes — implying that biological systems do not require any catalyst from their environment
234 (Cornish-Bowden, 2015). When the product of a self-fabricated catalyst (efficient cause) is used as a necessary
235 component for the fabrication of another catalyst, which participates in the fabrication of the catalyst that gives
236 rise to it. In the words of Rosen: “*the (M,R)-system itself describes a situation in which fabrication process itself*
237 *has been pulled inside the very system in which what is fabricated is operating [...] (M,R)-system is thus, in*
238 *itself, a theory of fabrication [...] whenever we pull a fabricator inside a system by putting it together with what*
239 *it fabricates, the results is essentially an (M,R)-system”* (Rosen, 1991a, p. 252)... “*(M,R)-system...involves an*
240 *iteration of the very process that generates it [...] with enough entailment to close the realization process up on*
241 *itself”* (Rosen, 1999, p. 265). As the (M,R)-system refers to itself in its operations: “*...an (M,R)-system in which*
242 *the operator ϕ is itself entailed from within the system is an (M,R)-system”* (Rosen, 1989, p. 28), the (M,R)-
243 system theory is also a theory of self-referential systems (also known as impredicative systems). This suggests,
244 on formal grounds, the existence and physical realization of self-referential causal systems (Rosen, 1985a).

245 Autopoiesis rather outlines and characterize the physical realization of the living of biological systems,
246 thus the *causal* aspects of natural systems. That is, autopoiesis “*describes the molecular processes...taking place*
247 *in the realization of the living of living systems... not a philosophical proposition of a formalization of the*
248 *phenomenon of life...the molecular autopoiesis of a cell is its living in the continuous realization of their self-*
249 *production without the participation of any organizing principle”* (Maturana, 2011, p. 144). An autopoietic
250 unity is characterized as “*a network of processes of production (transformation and destruction) of components*
251 *which: (i) through their interactions [openness to flux of matter and energy] and transformations continuously*
252 *regenerate and realize the network of processes (relations) that produced them; and (ii) constitute it (the*
253 *system) as a concrete unity in space in which they (the components) exist by specifying the topological domain*
254 *of its realization as such a network”* (Maturana and Varela, 1980, p. 78, brackets are ours)(Fig. 2B). There is no
255 separation between the product and the producer: Their operational closure results in the same continuous self-
256 referential process from which it is produced: “*a closed domain of operational relations specified only with*
257 *respect to the system organization that these relations constitute, and thus it defines a space whose dimensions*
258 *are the relations of production of the components that realize it as a concrete biological unity”* (Maturana and
259 Varela, 1980, p. 97).

260 Because the closure of both systems is explicitly related (Nomura, 2001, 1997; Zaretsky and Letelier,
261 2002; Letelier et al., 2003) in the notion of *metabolic closure* (Letelier et al., 2011, 2006; Soto-Andrade et al.,
262 2011), Autopoiesis and the (M,R)-system satisfy the *modelling relation*, in the way Rosen (1985, p.15) defined
263 it: “*a process of bringing into relation two entailment structures, a material one governed by causality, and a*
264 *mathematical governed by inferential rules”*. A biological system is then characterized by the autopoiesis as the

265 physical realization of an (M,R)-system, and the (M,R)-system as the theoretical model of autopoiesis (Fig. 2C).
266 Following this, here, we shall distinguish a biological system as an *(M,R)-autopoietic unity*, (Fig. 2D), thereby
267 bringing about an equivalence between closure to efficient causation and operational closure.

268 The operational closure to efficient causation can be contrasted with a chemical reaction, where the
269 catalysts (the ‘efficient cause’) that transform the reactant into products are not a product of the reaction, nor the
270 material of the reactants: the catalysts are external to the chemical reaction. Therefore, the chemical reaction is
271 ‘open to efficient cause’ which makes its *causal entailments* unrelated, and thus fundamentally different from
272 biological systems. Operational closure to efficient causation can also be contrasted with cybernetic systems
273 (Maturana, 2011; Rosen, 1985b) and artificial intelligence (AI) in general (Maturana 1980; Rosen, 1985a). The
274 latter have an organization determined (designed, fabricated, programmed and controlled) from outside by input
275 / output control feedback mechanisms, while the (M,R)-autopoietic unity have an organization defined from
276 within, which is not always amenable to input / output control parameters (Casti 1988). However, the latter is
277 distinct from self-organized systems (Rosen, 1959, 1994a; Maturana, 1987, 2002; Maturana and Varela, 1980;
278 McMullin, 2001, 2000), far-from thermodynamic equilibrium systems (Maturana 1980; Rosen 1978a) or the
279 chemoton (Cornish-Bowden, 2015). That is, the chemoton (Gánti, 2003), dissipative structures (Nicolis and
280 Prigogine, 1977), hypercycles (Eigen et al., 1977) and autocatalytic sets (Kauffman, 1986), either at molecular
281 (Hordijk et al., 2019; Jain and Krishna, 2001) or ecological level (Cazzolla Gatti et al., 2018), do not attain
282 operational closure to efficient causation (Chemero and Turvey, 2006; Letelier et al., 2011). Moreover, they can
283 be surrogated to a dynamical system (Jain and Krishna, 2001), and implementable in computer simulations in
284 contrast to the (M,R)-autopoiesis (Letelier et al., 2006; Louie, 2007; Luz Cárdenas et al., 2010; Maturana, 1980;
285 2011; Rosen, 1985a, 1988b, 1991a)(see section 6). In summary, the (M,R)-Autopoiesis explains how, despite
286 forcing fluctuations and dissipation, biological systems maintain their homeorhetic trajectories within
287 physiological bounds and why they are distinct from chemical, self-organized, thermodynamic and cybernetic
288 systems. We conclude, therefore, that the (M,R)-Autopoiesis represents a *necessary* and *sufficient* rigorous and
289 formal clear-cut criterion to answer the Schrodinger’ question.

290 Although (M,R)-Autopoiesis’ scope is for cellular and multicellular phenomena rather than for
291 planetary systems, it is nonetheless *necessary* to formally express the Gaia hypothesis, and it would make sense,
292 at first glance, to consider it as the most generic and less restrictive definition to characterize whether the Gaia
293 phenomenon is (or not) a biological phenomenon. If so (M,R)-Autopoiesis may be common to large classes of
294 systems, if not universal throughout a range between different discrete scales, from planets to cells and vice
295 versa, as suggested before (Lovelock 1987; Margulis 1997). Mikulecky (2000) previously suggested that the
296 categorical expression of the (M,R)-system may provide the theoretical biology for approaching formally the
297 Gaia hypothesis. To this end, our main question here is whether operational closure to efficient causation takes
298 place on a planetary scale, i.e. whether the Earth operation implements causal and inferential relations of

299 processes of production and fabrication that are embedded in metabolic closure (Fig. 3A). To our knowledge,
300 this has never been seriously examined. In the next section we materialize this proposal.

301 **4. Mathematical biology of Geophysiology: A formal expression of the Gaia hypothesis**

302 We begin by denoting all the Gaia's fluxes of matter and energy and its efficient causes of
303 transformation (Fig. 3B)(cf. Volk, 1998) as a *single* mapping in which a planetary abiotic (Cornish-Bowden and
304 Cárdenas, 2017; Goldford and Segrè, 2018; Hordijk and Steel, 2018; Luisi, 2014) or inorganic catalytic network
305 I reacts and transforms matter and energy (M) into ongoing geochemical cycles (C) (Fig. 3B):

$$306 \quad I: M \rightarrow C \quad (1),$$

307 that is, for any $m \in M$, we have:

$$308 \quad m \rightarrow c = I(m).$$

309 The efficient cause I (hence, a mapping or function) is thus identified with a multi-scale pre-metabolism (non-
310 enzymatic autocatalytic network) which, in a given environment, transforms M into C . M is the collection of all
311 sets of energy and matter m ($m \in M$) of the atmosphere, lithosphere and hydrosphere which can be transformed.
312 C includes everything that is being produced by I : the numerous geophysical and geochemical processes that
313 generate the collection of all sets of geochemical cycles $c \in C$ (Fig. 3B). As I , the abiotic pre-metabolic-like
314 chemical network, is a physical entity subject to decline, dissipation and disruption, it needs to be effectively
315 repaired and/or replaced. Likewise in an (M,R)-system *every* efficient cause F must have an associate ϕ that
316 maintains the concentration of F . On the Earth system, the *metabolic enzymatic* activity of the biosphere O
317 (from organic) mainly linked to origin and activity of microbes (Cavicchioli et al., 2019; Magnabosco et al.,
318 2018; Margulis and Sagan, 1986; McGenity, 2018; Falkowski et al., 2008; Raoult, 2010; Stolz, 2016) may
319 correspond to ϕ . The efficient cause O acts as a selector of C , which becomes the material reserve to produce I .

$$320 \quad O: C \rightarrow I, \quad (2)$$

321 O is therefore a second efficient cause (mapping) which, in a given environment or boundary condition,
322 metabolizes selectively, catalyses and transforms C into I through multi-scale enzymatic metabolism (Caetano-
323 Anollés et al., 2007; Medini et al., 2005; Sun et al., 2017) allowing continuous operation of I from existing C
324 (Fig. 3C). As the metabolic transformation of C into I by O removes, geologically transforms and relocalizes
325 compounds (Atekwana and Slater, 2009; Falkowski et al., 2008; McGenity, 2018; Tornos et al., 2018), it
326 effectively constrains Earth's material dynamics, thermodynamics, electromagnetism and geomorphological
327 structural changes such as the configuration of the continents, tectonic and volcanic activity, ocean salinity, pH,

328 redox potential, ocean circulation, distribution of ice sheets, etc (Hinkle, 1996; Kleidon, 2002; Kump, 2004;
 329 Lowman and Lowman, 2002). This can be written as:

$$330 \quad M \xrightarrow{I} C \xrightarrow{O} H(M, C) \quad (3)$$

331 where $H(M, C)$ is a set of mappings from M to C , and O is the efficient cause that acts as a metabolic selector of
 332 existing C that converts its products into new I (Fig. 3C). However, O is subject to ageing, senescence, decline
 333 and thus potential disruption. It therefore requires another efficient cause to be produced and remain operating.
 334 Like in the (M,R)-system we can avoid efficient causes ad infinitum if, in the formal expression of the Gaia
 335 hypothesis, we can identify an efficient cause γ (a *replication* function) using the content of the set C , in which
 336 case γ will be entailed inside the Earth system and act on I to ensure the continuous operation of the efficient
 337 cause O , the metabolic enzymatic activity of the biosphere. This systemic and relational replication may
 338 generate closure to efficient causation at the planetary scale (Fig. 3C).

339 Rosen's approach (Rosen 1972) (see Mossio et al., 2009 for an computable attempt using Lambda
 340 calculus), to formalize it, and thus to prove the existence of effective self-referential functions in general, and
 341 the existence of an efficient cause γ within the set C in our formal definition of Gaia hypothesis in particular, is
 342 by having an *inverse evaluation map* as follows. Let X and Y be sets, and $H(X, Y)$ is a set of mappings from X
 343 to Y . In general, we always regard the elements $x \in X$ as operators \hat{x} on $H(X, Y)$, by defining

$$344 \quad \hat{x}(f) = f(x)$$

345 \hat{x} is in this case called the evaluation map associated with $x \rightarrow X$. Then,

$$346 \quad \hat{x}: H(X, Y) \rightarrow Y.$$

347 One such evaluation map has an inverse \hat{x}^{-1} then we can define this inverse as

$$348 \quad \hat{x}^{-1}: Y \rightarrow H(X, Y).$$

349 The inverse exists *if and only if*

$$350 \quad \hat{x}(f_1) = \hat{x}(f_2) \text{ implies } f_1 = f_2, \text{ or}$$

$$351 \quad f_1(x) = f_2(x) \text{ implies } f_1 = f_2.$$

352 that is, once x is known, $f(x)$ contains enough information to determine f within the set $H(X, Y)$

353 So, to formally identify γ we can identify:

$$X = C$$

$$Y = H(M, C),$$

354 where M and C are the sets A and B in the (M, R)-system respectively (see Fig. 2A). This shows that if an
355 evaluation map in this case is invertible, it is precisely a map into the set

$$H[C, H(M, C)]$$

356 to which B belongs.

357 The map can be parameterized as a function of $c \in C$, where c is a particular product produced by the system
358 for which the inversion condition is satisfied:

$$359 \quad \gamma_c: H(M, C) \rightarrow H[C, H(M, C)](4)$$

360 such that $\gamma_c(I) = O$

361 That is, once the inversion condition is satisfied for a given c , it is possible to define γ_c which will ensure the
362 replacement of O using information provided by the product of $O(c)$ (Fig. 3C).

363

364 Under these terms, the Gaia hypothesis is expressed as the existence of the closure to efficient
365 causation: $I \rightarrow \gamma_c \rightarrow O \rightarrow I$. The existence of an inverse evaluation map would therefore imply that the
366 operation of the Earth system is encoded in the entire system, but not in a specific component of it. Indeed, γ_c is
367 an efficient cause of O , thus, an efficient cause of the efficient cause of C , which contains c , and which
368 determines γ_c . This closed entailment loop implies that a subset of C (c , in this case) needs to contain
369 information about C itself. C is, however, multifaceted. It involves multiple time scales, and contains the
370 numerous geophysical and geochemical structures generate by Earth's metabolism, including orography,
371 topography, heat and chemical gradients. Similar to enzymes in a cell, some of these structures play the role of
372 an efficient cause necessary for producing the metabolism. The subset $\gamma(c)$ represents this efficient cause. It is
373 on this basis that one can say, formally, that the process of fabrication of the Earth system produces O based on
374 what the Earth system recognizes of itself, like a biological unity. Finally, equation (5) formalizes a one-to-one
375 map between the Gaia phenomenon and the (M,R)-system (Fig. 3A, D). The Earth processes of production
376 would satisfy the (M,R)-system formal model, in which the efficient causes are uniquely determined by their
377 products, requiring no external efficient cause (Fig. 3D). The efficient causes of Earth's operation need not be
378 added from the outside. They exist inside the Earth system. The (M,R)-system is the formal expression of the
379 Gaia hypothesis and essentially the theoretical model of Gaia phenomenon. The latter is the realization of the
380 former. Having suggested this, in the following section, we will provide a plausible, empirically supported
381 account of autopoiesis as the realization of the living of Gaia phenomenon.

382

383 **5. The Metabolism and Repair of Gaian Autopoiesis implies conservation of organization under**
384 **structural change**

385
386 Vernadsky (1945) suggested that Life is not *a* form of energy and is not merely *a* geological force,
387 rather it is *the* geological force. So, the natural question he asked was: ‘*How on Earth can it (Life) change*
388 *material processes?*’. Given the limitations of characterizing life phenomenon as a mere regulator, autopoiesis
389 was suggested as the realization of the living of Gaia phenomenon (von Foerster, 1975): the relations of
390 production on Earth system may correspond to an autopoietic system. Several authors consider that the
391 production of the atmosphere (mainly troposphere and stratosphere), in the same domain in which the planetary-
392 scale metabolism continuously, generates the very same relations of production offers evidence for autopoiesis
393 in the planetary scale (Capra, 1996; Capra and Luisi, 2014; Clarke, 2012; Jantsch, 1980; Kazansky, 2004;
394 Levchenko et al., 2012; Margulis, 1990, 1997; Margulis and Sagan, 1995, 1986; Onori and Visconti, 2012;
395 Sahtouris, 1996). Margulis wrote: ‘*Whereas the smallest recognizable autopoietic entity... is a tiny bacterial*
396 *cell the largest is Gaia*’ (Margulis, 1990, p. 861). Or that ‘*planetary physiology...is the autopoiesis of the cell*
397 *write large*’ (Margulis and Sagan, 1995, p. 54).

398
399 Is it, however, possible to identify on the Earth system an organization of processes of self-production?
400 “*Since it is a defining feature of an autopoietic system that it should specify its own boundaries, a proper*
401 *recognition on an autopoietic system as a unity requires a proper recognition [...] that defines the limits of the*
402 *system in the same domain in which it specifies them through [...] relations of production of components that*
403 *generate these relations and define it as a unity in a given space*’ (Maturana and Varela, 1980, pp. 108–109).
404 Accordingly, a proper recognition of Gaian Autopoiesis should offer evidence of the continuous processes of
405 self-production by closure to efficient causation on the planetary scale. We consider here that to recognize the
406 autopoiesis as the realization of the living of Gaia phenomenon, both natural systems, Gaia and an autopoietic
407 system should satisfy, through empirical evidence, the modelling relation as indicated in the figure (4A).

408
409 Today, it is generally accepted that the productions of troposphere: aerosols (Dani and Loreto, 2017;
410 Fröhlich-Nowoisky et al., 2016; Gantt and Meskhidze, 2013; Lana et al., 2011), methane greenhouse gas
411 (Conrad, 2009; Izon et al., 2017), some clouds (Charlson et al., 1987; Hughes et al., 2014), and even
412 stratospheric ozone (Falkowski, 2006) are immediately related to multi scale planetary metabolic activity
413 (Goldford and Segrè, 2018). The Earth’s metabolism takes place in the subsurface and surface of the lithosphere
414 and ocean, the atmosphere, the rhizosphere, the gut microbiomes, in the dark, rare and deep biosphere
415 (Cavicchioli et al., 2019; Magnabosco et al., 2018). It is carried out mainly by prokaryotes (Margulis and Sagan,
416 1986; McGenity, 2018; Falkowski et al., 2008), the so-called ‘Gaia microbiome’ (Stolz, 2016) and its pan-
417 genome (Medini et al., 2005), which comprises autotrophic, heterotrophic, anoxic and oxide activity. It has been

418 suggested that the Earth's prokaryotes constitute along with eukaryotes an interconnected single *rhizome* of life
419 (Raoult, 2010). Morowitz states that “*all organisms interact (are connected) through the gas-phase components*
420 *that they take up from and give off to the atmosphere...life...persists over long geological periods only because*
421 *of integrated processes of the atmosphere, the hydrosphere, the lithosphere, and the biosphere*” (Morowitz,
422 1993, pp. 5–6). That is, the atmosphere is not only the product of the planetary-scale metabolism, but allows its
423 continuous operation through the hydrosphere and lithosphere suggesting a plausible scenario operational
424 closure at planetary-scale. Indeed, one of the main motivations of proposing the Gaia hypothesis was that the
425 planetary-scale metabolism does not merely affect the chemical composition of the atmosphere and vice versa;
426 they self-produce in a single mutual continuous process (Margulis and Lovelock, 1975).

427

428 Recent additional empirical evidence somehow may support this possibility. The different values of the
429 water deuterium-to-hydrogen ratio (D/H) observed recently on various bodies in the Solar system, suggest a
430 non-asteroid origin of Earth's cycled water (Altwegg et al., 2014)(Deep mantle Earth's water is not found, so
431 far, to be cycled water (Hallis et al., 2015)). In biological systems, a significant amount of water is produced
432 metabolically (endogenously) (Li et al., 2016). In addition, the conservation of the core signatures of the early
433 Earth metabolism in contemporary cellular biogeochemistry (Morowitz, 1993) suggests that most prokaryotes
434 notably, methanogens ($\text{CO}_2 + 4\text{H}_2 \rightarrow \text{CH}_4 + 2\text{H}_2\text{O}$) (Bardgett et al., 2008), sulphate-reducing bacteria ($\text{CO}_2 +$
435 $2\text{H}_2\text{S} \rightarrow \text{CH}_2\text{O} + \text{H}_2\text{O} + 2\text{S}$) (Barton and Fauque, 2009) and subsurface cyanobacteria (Puente-Sánchez et al.,
436 2018) contributed greatly to the metabolic origin and ongoing of the troposphere, stratosphere and hydrosphere
437 (Harding and Margulis, 2009). Moreover, through the hydrological cycle, nutrients are geologically modified
438 (Atekwana and Slater, 2009), mobilized (McGenity, 2018), localized (Tornos et al., 2018) and integrated in
439 biogeochemical cycles (Falkowski et al., 2008) (Fig. 4B)

440

441 The evidence accumulated so far offers thus a plausible account of *continuous processes of molecular*
442 *self-production* of the terrestrial environment. Furthermore, the fact that Earth's metabolism defines molecularly
443 the boundary (hydrosphere, troposphere and stratosphere) in the same domain in which it is specified indicates
444 molecular metabolic closure in the planetary scale, and henceforth, an “*Autopoietic Gaia*” (Margulis, 1990)
445 (Fig. 4C). In fact, the explanatory scope of autopoiesis covers the phenomenological basis of broader domains of
446 biological realization than the cellular and multicellular scales. Maturana refers to such larger-scale domain of
447 biological realization as ‘higher order autopoietic unity’. Crucially, he indicates that such realization must be
448 molecular: “*There are autopoietic systems of higher order, integrated by (populated by) lower order autopoietic*
449 *unities that may not be the components realizing them as autopoietic systems... there are higher order*
450 *autopoietic systems whose components are molecular entities produced through the autopoiesis of lower*

451 *autopoietic unities*” (Maturana, 1980, p. 53, parenthesis and subline are ours). This implies that Gaia
452 phenomenon is the molecular constitution of planetary scale metabolic closure.

453

454 Some proposals such as the ‘molecular biology of Gaia’ (Williams, 1996), a ‘wasteworld of by-
455 products’ (Volk, 2004) and the biogeochemical cycles as the unit of natural ‘selection’ bypassing taxonomic
456 individual species (Doolittle, 2017, 2014) support somehow that Gaia phenomenon is molecular. However,
457 operational closure to efficient causation at the planetary scale is more than these proposals. For example,
458 biogeochemical cycles, like cellular biochemical cycles, are loops of *material* causes, but not loops of *efficient*
459 causes (Louie and Poli, 2011). Loops of *material* causes take place because there are efficient causes that make
460 the material elements be cycled. In other words, the biogeochemical cycles or by-products ($c \in C$ in the (M,R)-
461 system) are necessary for enabling Gaian autopoiesis, but they are only partially constitutive of it.

462

463 The metabolism and repair of Gaian autopoiesis implies that the Earth is an *organized* system as a
464 biological system, i.e. the present terrestrial environment is itself the result of its own fabrication processes. That
465 is, at geological scales, there is no separation between product and producer, between biotic and abiotic
466 elements. As such, Gaia represents a *sui generis* scale of (M,R)-autopoietic organization in the planetary scale,
467 and thus a proper biological *domain* of realization of the living (Fig. 4C, 3D). With domain we refer to a
468 biological *unity*, such as the cellular or multicellular organism, which is distinct from self-organized emergent
469 systems, i.e., Gaia is different to a colony-like stigmergic assemblages of agents that can form a ‘global’
470 superorganism that emerges out of their interactions. This description fails to capture molecular operational
471 closure to efficient causation. The (M,R) of Gaian Autopoiesis suggests that the continuous process of terrestrial
472 self-production is a biological realization of its own at the planetary domain.

473

474 In the formulation of autopoiesis, biological systems are distinguished by their organization and
475 structure (Maturana and Varela, 1980; Nomura, 2006). While the former is preserved, i.e. self-production by the
476 closure to efficient causation must persist, the latter may change through the flows, cycling and continuous
477 transformation of materials (Letelier et al., 2006; Maturana and Varela, 1980). This explains why life
478 phenomenon persists despite structural changes during ontogeny and phylogeny (Maturana, 1980; Maturana and
479 Mpodozis, 2000). For example, despite large structural changes, abrupt catastrophic shifts (e.g. loss of almost
480 90% of the biosphere) and tipping points (Lenton et al, 2008) from Pangea to the current continental
481 configuration (Lenton and Watson, 2011) Gaia phenomenon has persisted. Indeed, whereas self-production by
482 closure to efficient causation persists, multiple interdependent structural changes can take place and when one
483 structural dimension is changed, the complete structure of the system may undergo correlative changes
484 (Maturana, 1980; Maturana and Mpodozis, 2000). In this interpretation, bifurcations, critical transitions, tipping
485 points and tipping cascades (Scheffer, 2009; Ashwin et al., 2012; Lenton and Williams, 2013; Steffen et al.,

486 2018), may be associated with structural changes constrained by the conservation of Earth's self-production by
487 closure to efficient causation. The structural changes in the Precambrian Vendian shows, for example, that the
488 phenotypic transformation of multicellular organisms took place along with the transformation of the
489 lithosphere, atmosphere and the complete biosphere through the conservation of the Gaia phenomenon
490 (Levchenko et al., 2012). Even when the Earth has been impacted by planetesimals (Abramov and Mojzsis
491 2009), the Gaia phenomenon has persisted.

492

493 However, the explanatory scope of the theory and realization of (M,R)-autopoietic systems foresees
494 that some structural perturbations (e.g. the loss of crucial information of the replication map β in the M,R-
495 system) can send Gaia into an 'autopoietic oscillator dead' (Friston 2013) or more broadly into 'system
496 degeneracy' (see Rosen (1988a, 1978b)), such that the conservation of system's organization, therefore its
497 living, is lost (Letelier et al., 2006; Maturana, 1980; Maturana and Varela, 1980).

498

499 What we have discussed so far provides a plausible, empirically supported account of (M,R)-
500 autopoiesis behind the Gaia phenomenon that goes beyond the somehow superficial 'aquarium poetic view'
501 ascribed to it by Doolittle (2017). It turns out that the (M,R)-autopoiesis surrogates the Gaia phenomenon to a
502 self-referential system (Soto-Andrade et al., 2011). Next, we discuss the implication of it on *simulable*
503 approaches of the Gaia phenomenon.

504 **6. Daisyworld is a mechanism, the Gaia phenomenon is not.**

505

506 According to Rosen's *Life Itself*, in a mechanism "*there can be no closed path of efficient causation*"
507 (Rosen, 1991a, p. 241). Moreover, a natural system is said to be a "*mechanism if every model of it can be*
508 *simulated on a mathematical Turing machine*" (Rosen, 1991a)(the standard form of computing today). In other
509 words, mechanisms are simple systems which obey dynamics that can be encoded in the form of algorithms, i.e.
510 the system is open to efficient causation, hence its model is simulable. Mechanisms can have very complicated
511 simulations, and the complicated connections between chemical and physical processes are captured with
512 complicated codes resolving atmospheric and oceanic fluid motion such as general circulation models and
513 modern Earth system simulations.

514 With this point of view, the Gaia phenomenon can be captured by mechanisms with even simpler
515 simulation programmes such as the Daisyworld(s) (Watson and Lovelock, 1983). The chain of feedbacks
516 described by Daisyworld constitutes a mechanism, in the sense that it can be captured by a recursive algorithm.
517 It is standard to attempt capturing biological systems with algorithms. Von Neumann's self-reproducing

518 automata (Von Neumann, 1966), neural networks, agent-based models, machine learning, deep learning and AI
519 in general follow this principle. Under this rubric, the ‘degree’ of complexity would be related to connectivity,
520 nonlinearity and size: “*there exists a critical size below which the process of synthesis is degenerative, but*
521 *above which the phenomenon of synthesis, if properly arranged, can become explosive*” (Von Neumann, 1966,
522 p. 80). Following this view, the Gaia phenomenon can be identified with ‘self-organized criticality’ (Bak, 1993),
523 ‘adaptive’ systems (Lenton and van Oijen, 2002; Levin, 1998) or more complicated phenomena representing
524 learning (ultrastability) at the planetary scale showing an ‘emergent’ and nonlinear and adaptive behaviour
525 (Lenton et al. 2018). Such a system can be large, but which is still formally equivalent to a dynamical system
526 that can be encoded as a (large) numerical algorithm.

527 However, the Gaia phenomenon by means of the closure to efficient causation suggests on formal
528 grounds, that there is a fundamental gap between the Gaia as a biological phenomenon and any algorithmic
529 representation (Letelier et al., 2006; Louie, 2007; Luz Cárdenas et al., 2010; Maturana, 1980; Rosen, 1988b).
530 That is, the realization of the living cannot be implemented in a Turing machine and “*accordingly must have a*
531 *nonsimulable model*” (Rosen, 1999, p. 292). No matter the resolution, in principle it will never be filled in with
532 computing power or be *completely* surrogated to algorithmic procedures. The discrepancy of efficient causation
533 between the Gaia as a biological phenomenon and algorithms is so severe that the former cannot even be
534 mapped onto a dynamical system (Rosen, 1991b, 1973), self-reproducing automata (Rosen 1959, 1975;
535 Maturana, 1980) or a collection of sequential recursive algorithms (Ashby’s ultrastability) (Maturana, 2011;
536 Rosen, 1985b). In the Daisyworld(s), sequential selection or even in any other Earth system simulation likewise
537 as in chemical reactions described above, the recursive functions of the algorithms correspond to the repetition
538 of a set of rules that are explicitly specified to the system from the *outside* and are implementable in a Turing
539 machine.

540 This suggest that the distinction between mechanisms of cybernetic systems and the living of biological
541 systems is not a matter of degree, but of character. Such as in a cellular or any other biological system, Gaia
542 phenomenon either occurs or not. There are no increasing degrees of complexity, connectivity and gradual
543 assembling operations in its generation. It is all or nothing phenomenon. Quoting Rosen in contrast to Von
544 Neumann’s ‘critical size’: “*this characterization has nothing to do with more complication, or with counting of*
545 *parts or interactions; such notions, being themselves predicative, are beside the point... Just as ‘infinite’ is not*
546 *just ‘big finite,’ impredicativities (self-production by closure to efficient causation) are not just big*
547 *(complicated) predicativities. In both cases, there is no threshold to cross, in terms of how many repetitions of a*
548 *rote operation such as ‘add one’ are required to carry one from one realm to the other, nor yet back again*”
549 (Rosen, 1999, p. 44, parentheses are ours).

550 Moreover, the Gaia phenomenon by means of the closure to efficient causation entails the existence of
551 an self-referential (impredicative) "effective" process ("effective" because it is physical) (Rosen, 1991a; Soto-
552 Andrade et al., 2011) that rises paradoxes to Von Neumann's self-reproducing automata and AI in general
553 (Ashby, 1962b; Rosen, 1959; Ben-David et al., 2019, Reyzin, 2019). Therefore, Gaia as a biological
554 phenomenon may be of a non-simulable, non-algorithmic, and hence non-computable character (Letelier et al.,
555 2006; Louie, 2007; Luz Cárdenas et al., 2010; Maturana, 1980; Rosen, 1988b, 1989). That is, the Gaia
556 phenomenon, in principle, may have at least one model that cannot be simulated by finite-state machines (e.g.,
557 Turing machines) (Louie, 2007; Luz Cárdenas et al., 2010). Therefore, in a fundamental way, the Gaia
558 phenomenon, although physical, is neither a mechanism nor a machine (Maturana 1980; Rosen, 1991a, 1985a).

559 The relation between the biological character of the Gaia phenomenon and the mechanical simulable
560 (algorithmic) models of it (Daisyworld(s)) may be linked to the situation faced by early cartographers, who were
561 attempting to map the surface of a sphere while armed only with pieces of (tangent) planes. As long as we only
562 map local regions, the planar approximations (mechanisms) suffice, but as we try to map larger and larger
563 regions, the discrepancy between the map and the surface grows. Thus, if we want to make accurate maps of
564 large regions of the sphere, we have to keep shifting our tangent planes. The surface of the sphere is in some
565 sense a limit of its planar approximations, but to specify it in this way requires a *new concept* (the topology of
566 the sphere) that cannot be inferred from local planar maps alone (Rosen 1985). Similarly, the (M,R)-system
567 model of Gaian autopoiesis implies that we need to widen our concept of what the Gaia phenomenon is, or
568 should be.

569 **7. Concluding Remarks**

570

571 In this paper, we have examined the Gaia hypothesis from a fundamental biological standpoint offered
572 by the (M,R)-system as a formal theory and autopoiesis as the realization of the living. We have considered that
573 the Gaia phenomenon was identified by observing the qualitative difference among Earth, Mars and Venus, i.e.
574 from differential observables in planetary systems. Such differences between these planets, and the unique
575 quality on Earth, has given rise to the Gaia hypothesis, which raises Schrodinger's question, 'What is life?', a
576 central question of biology, at the planetary scale. We have pointed out that the lack of use of a clear-cut formal
577 criterion and characterization of biological systems has led to use the adaptationist programme and the *regulator*
578 *thesis*, with so-called strong and weak interpretations of the Gaia hypothesis. This has configured the present-
579 day Gaia theory, but obliterated the Gaia hypothesis and thus Schrodinger's question.

580 We have further argued that (M,R)-Autopoiesis offers a necessary and sufficient answer to
581 Schrodinger's question and therefore it characterizes and explains what life is in terms of what life does, i.e.
582 *self-produce* by *closure to efficient causation*. Then, based on the modelling relation, a set of interacting causal

583 processes operating on a wide range of spatial time scales through the atmosphere, lithosphere, hydrosphere, and
584 biosphere of the Earth system has been categorized within the relational and systemic entailments of (M,R)-
585 Autopoiesis. Consequently, we suggested a one-to-one realization map between (M,R)-Autopoiesis and the Gaia
586 phenomenon. In other words, the Gaia phenomenon realizes the inferential and causal entailments of (M,R)-
587 Autopoiesis, such that it generates metabolic molecular closure to efficient causation on the planetary domain.
588 This suggests that the Earth is an organized system, not of cells, multicellular or ecosystems, but of their
589 molecular products that together with the atmosphere, the hydrosphere and the lithosphere self-produce by
590 metabolic closure. The Gaia phenomenon is, therefore, a *sui generis* biological system and the embodiment of
591 *Life itself in the planetary domain*. Moreover, if something has to be regulated, it has to be produced in the first
592 place. Hence, self-production by closure to efficient causation is more fundamental than self-regulation by
593 feedback mechanisms.

594 Biologizing Gaia theory as such provides a rigorous basis to the claim that planetary biology elsewhere
595 in the universe must involve and have a formal equivalence to self-referential physical processes, which has at
596 least one model that cannot be implemented by a Turing machine and, therefore, is of a non-simulable, non-
597 algorithmic, and non-computable character.

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893 **Footnotes**

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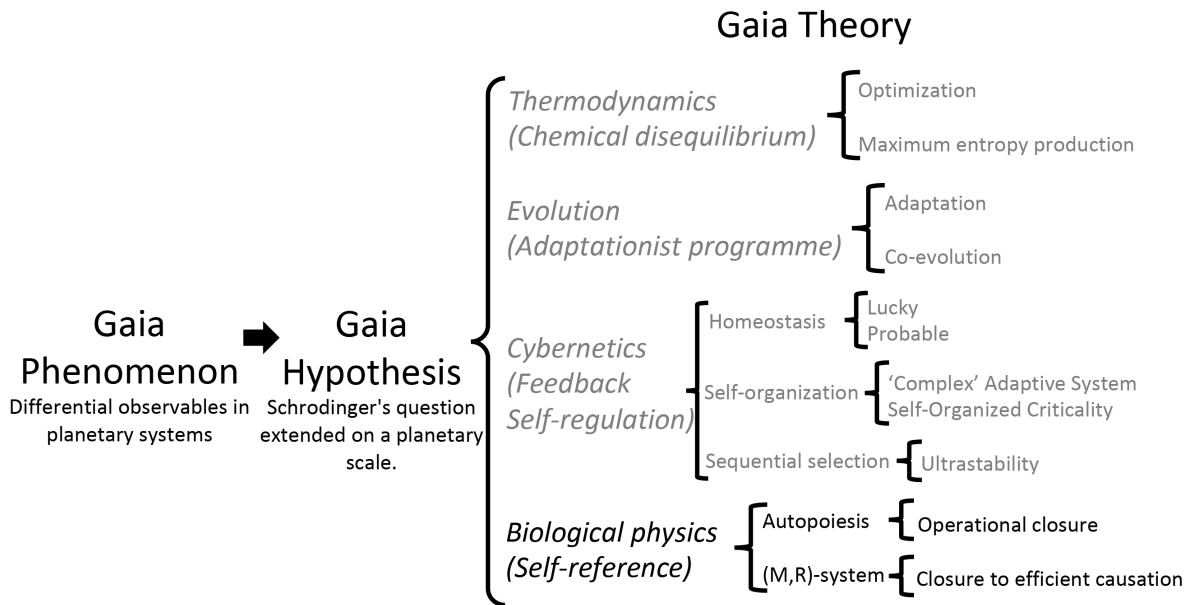
895 ¹The Nobel-laureate physicist Erwin Schrödinger suggested that biological phenomenon, contrary to the second
896 law of thermodynamics, decreases or maintains its entropy by feeding on *negative entropy*. Schrödinger remarks
897 on his usage of the term negative entropy: *‘Let me say first, that if I had been catering for them [physicists]
898 alone I should have let the discussion turn on free energy instead. It is the more familiar notion in this context.
899 But this highly technical term seemed linguistically too near to energy for making the average reader alive to
900 the contrast between the two things’* (Schrödinger, 1945, p. 74).

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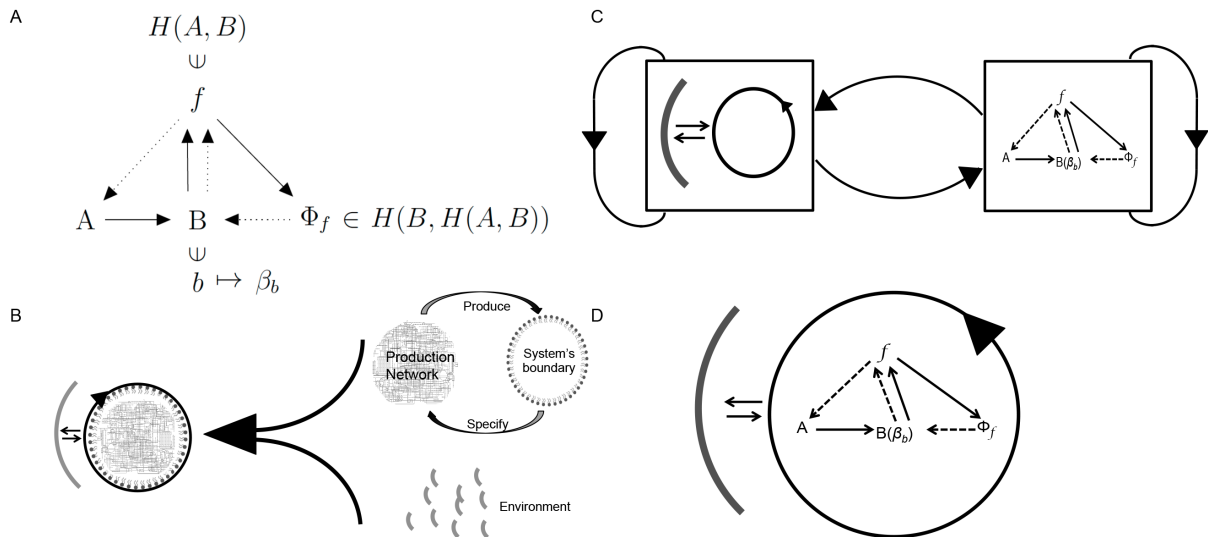
902 ²An infinite regress arises, in a series of propositions, if the truth of proposition P₁ requires the support of
903 proposition P₂, the truth of proposition P₂ requires the support of proposition P₃, and so on, *ad infinitum*.

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 906 **Figure legends**
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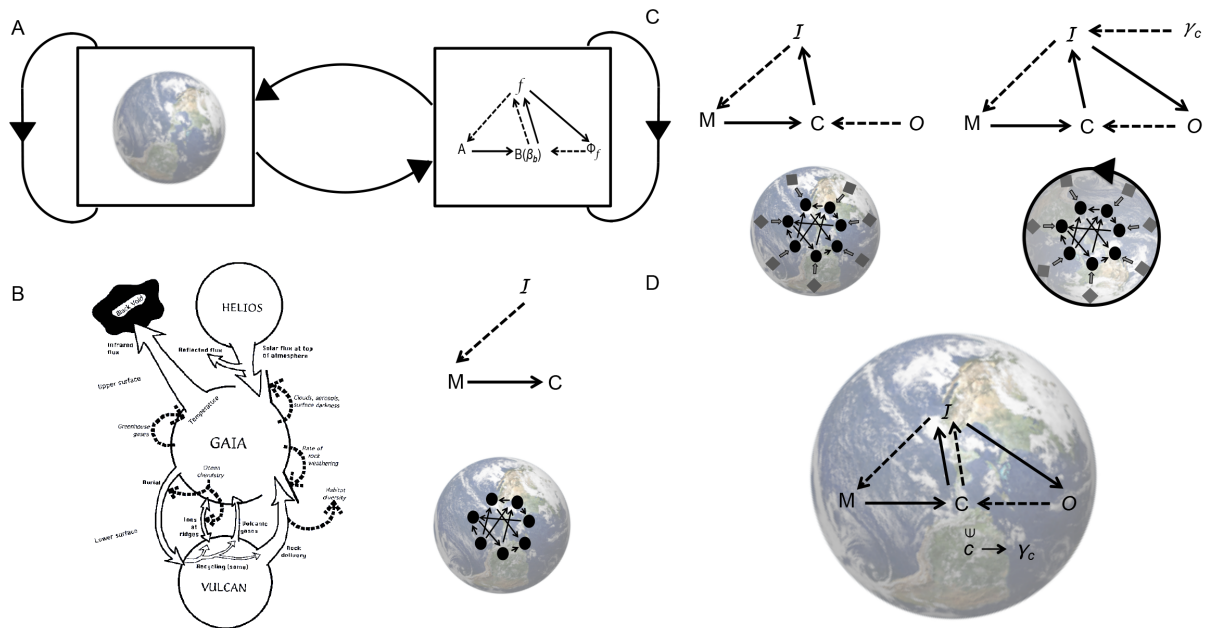


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 910 **Figure 1. Explanatory genealogy of the Gaia theory.** In grey are represented the present-day Gaia theory
 911 explaining the Gaia phenomenon as a self-regulated and optimized system through feedbacks, entropy flows and
 912 adaptation. A biological-centred theory is represented in black, and explains the Gaia phenomenon as self-
 913 production by operational closure to efficient causation.



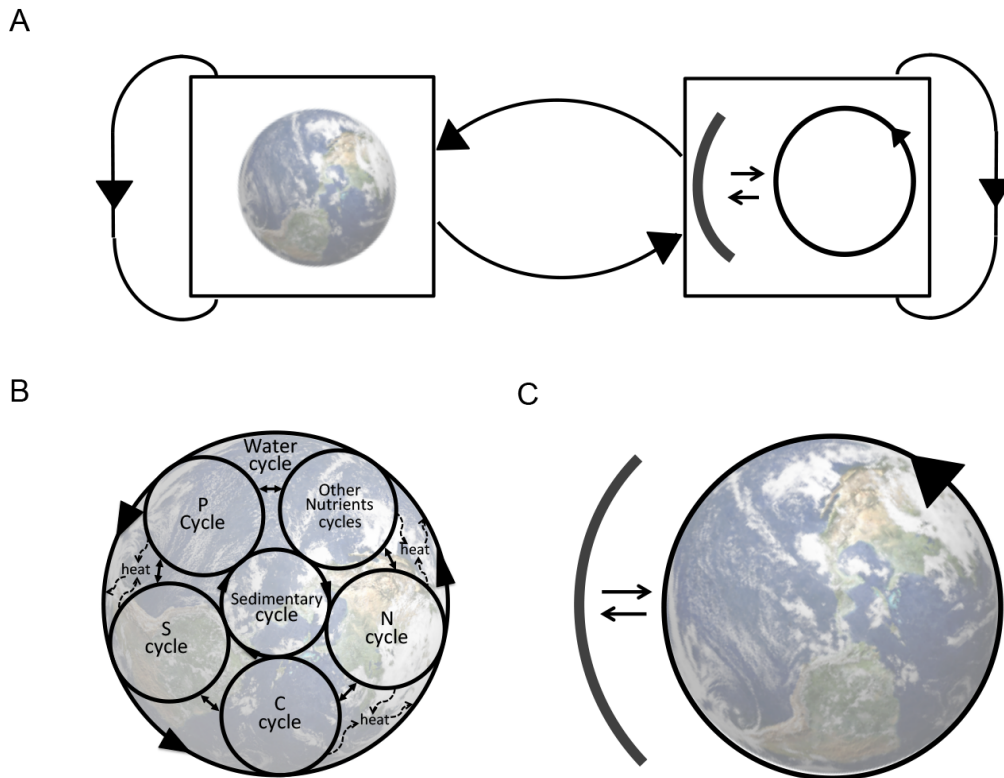
914
 915 **Figure 2. The (M,R)-Autopoiesis and Modelling relation.** A) The categorical representation of the (M,R)-
 916 system formal model of biological systems. Continuous arrows and broken arrows represent material and
 917 efficient causation respectively. B) Autopoiesis is self-production by operational closure (circular arrow) and
 918 hence the living realization (implementation) of a (M,R)-system. Autopoiesis take place by a form of

919 operational closure involving the molecular network (f, Φ, β in the M,R-system) and system's boundary. The
 920 self-production process must occur in structural coupling (openness)(arrows in both directions) with the
 921 ambience (curved grey line). C) Modelling relation depicting the Autopoiesis realization as a natural causal
 922 system and the (M,R)-system as a formal inferential system such that self-production by operational closure and
 923 self-fabrication by closure to efficient causation are equivalent (D) such that an (M,R)-autopoietic unity is
 924 distinguished.



925
 926 **Figure 3. The (M,R)-system expression of Gaia hypothesis.** A) Modelling relation depicting the Earth system
 927 and the (M,R)-system as a natural and formal system governed by causal and inferential rules of implication
 928 respectively. B) In the left panel Volk's representation of Gaia flow (thick white arrows) and the efficient causes
 929 of transformation (black broken arrow) of matter and energy. Modified from Volk (cf. 1981, pg. 91). The right
 930 panel above summarizes Volk's representation in a single map $I: M \rightarrow C$. Solid and broken arrows represent the
 931 material and the efficient cause respectively. The right panel below illustrates such single map graphically,
 932 where I is represented as the Earth (containing inorganic pre-metabolic chemical networks), the black dots are
 933 material causes (M) transformed into an interconnected multifaceted, set of geochemical cycles C (black arrows)
 934 involving multiple time scales. C) Left upper panel show O (biosphere) as efficient cause (broken arrow) that
 935 maintains and transforms C into I (continuous black arrow); $O: C \rightarrow I$. In the left panel below grey arrows and
 936 squares represent O . The right upper panel shows Y as an efficient cause (broken arrow) that transforms I into O
 937 (continuous black arrow). The circular arrows that connect all grey squares in the right below panel and the
 938 inverse mapping $C(Y): I \rightarrow O$ in (D) represent the systemic closure to efficient causes at the planetary scale. The
 939 diagrams of the (M,R)-system in (A) and of Gaia in (D) are the same with the correspondences (A, M), (B, C),

940 (f, I) , (Φ, O) , and (β, Y) . This provides the criterion by which the Earth system organization satisfy an (M,R)-
 941 system formal model.



942
 943 **Figure 4. The autopoietic organization of the Earth system.** A) Modelling relation depicting the Earth system
 944 and autopoiesis as natural systems governed by causal implications. B) The Earth's cycled water self-production
 945 is the main driver of geochemical cycles and heat transport. Modified from Schneider and Morton (cf. 1981, pg.
 946 238). C) The autopoietic organization of the Earth as a system of causal processes of self-production through
 947 operational closure to efficient causation (black circular arrow) in structural coupling (black arrows in both
 948 directions) with its ambience (curve grey line).

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