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Is Gaia alive? The future of a symbiotic planet

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ABSTRACT

Life affecting first the development of the planetary environment, which, in turn, affects the future evolution of life in a coevolutionary way is a well-established idea now. Nevertheless, with the proposal of the Gaia hypothesis, there has been widespread criticism of some of its elements. Most critiques are related to teleology, the absence of natural selection at a universal scale, and the absence of planetary reproduction. Even if some of the problems concerning the rationale of this hypothesis have been resolved, it is not clear whether Earth can be considered a unit of selection and, therefore, Gaia can adapt according to Darwinian evolution. After Lovelock and Margulis, Gaia has been considered a symbiotic planet composed of biotic (the biosphere) and abiotic (the geosphere-atmosphere) interacting with and coevolving elements.

Here, I took into consideration the main concerns raised on the Gaia hypothesis and I analysed them following a logic-deductive reasoning together with thought experiments, sometimes adopting analogical arguments. I propose why and suggest how, a Gaian system, considered as a "symbiotic planet" composed by biotic (the biosphere) and abiotic (the geosphere-atmosphere) interacting and coevolving elements, should be considered alive in an evolutionary sense.

I argue that, without invoking teleology, so without any foresight or planning, a Gaian planet can be considered the same as a coevolutionary system analogous to a multicellular body: a super-unit of selection. I describe different situations according to which "Gaia" is able to reproduce and to transfer her planetary genome to other uninhabited or inhabited planets. Then I show that Gaia can face exclusion-competition-coexistence states depending on the fitness of her biota compared to those of the other reproducing biospheres. This demonstrates that Gaia can reproduce and evolve in competition-cooperation with other planets. Some deep implications arise from these pieces of evidence in the light of the recent discovery of a new solar system with Earth-like planets.

1. Introduction

In her article "On the Origin of Mitosing Cells", Lynn Margulis (Sagan 1967) proposed that the organelles in the eukaryotic cells are the result of an ancient symbiosis between prokaryotes. She suggested that the mitochondria and the photosynthetic plastids were prokaryotes acquired and evolved symbiotically to form anaerobic bacteria, photosynthetic bacteria and eventually algae. This idea, which is well-accepted now (although that basal body of flagella, which Margulis called "undulipodia", were so acquired is most certainly not; Gray (2017)), followed a difficult road to be published and found concerns and severe attacks at that time (Gray, 2017).

After that, a few years later, Lynn Margulis contributed to the development of a wider-scale symbiotic framework, such as the

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proposal that planet Earth can be a symbiotic self-regulating system sustained by the multiple feedbacks between biotic and the abiotic components. This proposal was summarized in the Gaia hypothesis (Lovelock, 1972). The idea resulted in a huge number of oppositions and criticisms by many biologists (Dawkins, 1986; Doolittle, 1981; Gould, 1988; Volk, 1998; for a summary see Turney, 2003). Most of them focused on the need for evolutionary mechanisms by which regulatory feedbacks could have arisen or maintained (Lenton, 1998). It was proposed that because traits are rarely selected for their environmental effects and are by-products of small-scale selection, changes in the environment can control the growth of organisms through feedbacks (Lenton, 2004).

Nevertheless, one of the main criticisms was that the Gaia hypothesis implies teleology, a kind of conscious foresight or planning by the biota (Dawkins, 1999). Other concerns principally referred to the absence of natural selection operated over planets in the universal scale: Earth is not a unit of selection, therefore Gaia cannot adapt in *sensu stricto* according to Darwinian evolution being not subjected to “planetary selection” (Dawkins, 1999; Tyrrell, 2013; Volk, 1997). Another fundamental criticism relates to the previous ones and is a consequence of them: every unit of selection needs to reproduce and if it cannot do that, no selection can be argued. Even Lovelock (1991) himself in a table of his book “Gaia: the practical science of planetary medicine” specified that, beyond many analogous life processes, the only difference among a bacterium, a mammal, a tree and Gaia is the absence of reproduction in the latter.

Even though some preliminary attempts tried to explain, with mathematical models, the evolutionary patterns underpinned by the hypothesis, most of the objections still discredit the idea that Gaia could be compared to an “evolving organism” (Dawkins, 1999).

At least, lately, some of the problems related to the “internal” logic of the idea have been resolved (Staley, 2004). Watson and Lovelock (1983) developed the model Daisyworld, further implemented during the next few decades (Lenton & Lovelock, 2000, 2001). Although this model does not distinguish between species-level and individual-level phenomena (and sheds poor light on some selection processes), it has the value of demonstrating two fundamental aspects: 1) that a large number of species provides a beneficial effect to the entire planet (i.e., that biodiversity is valuable); and 2) that biologically mediated homeostasis does not require a teleological explanation. Neverthless, Lenton and Watson (2011) in a recent book admit that the burden of proving a “probable Gaia” was a purpose of Daisyworld in favour of stability.

Yet, Margulis (1998) argued that there was a misunderstanding over the first paper and that only homeorethic (unfixed equilibrium points oscillating during the time), and not homeostatic, balances were considered as involved in the self-regulating Earth. In other words, the composition of atmosphere, lithosphere and hydrosphere is regulated by biological processes around “set points” as in homeostasis, but those set points change with time (even though, as for any evolutionary process, Gaia’s adaptedness must be considered as a posteriori result rather than an a priori goal-seeking (Mayr, 1992)). Margulis (1998) wrote, in her book entitled *Symbiotic planet* (a title that recalled the quote of a student of her that “Gaia is just symbiosis as seen from the space”): “we are symbionts on a symbiotic planet, and if we care to, we can find symbiosis everywhere”.

Currently, the idea that the biota on Earth could maintain (and, by chance, has been doing it since the appearance of the first life form, around 4.1 billion years ago; see Bell, Boehnke, Harrison, and Mao (2015)) in different, even if not always clear, ways favourable conditions for life, is accepted with few minor oppositions (Scheider et al., 2004). This is the reason why the original hypothesis was divided into two forms (with many versions of them; see Free and Barton (2007) for extended definitions): the weak and the strong. The weak one (or Undeniable Gaia) briefly proposes that organisms on Earth have radically altered (by coevolutionary processes, as a “Coevolutionary Gaia”) its composition and that this consequently, but not deliberately, allows the persistence of life on the planet (either, if it is intended as a consequence of resistance and resilience, as an “Homeostatic Gaia”, which can be the result of chance as a “Lucky Gaia” or, as a result of by-products of local adaptation, as a “Probable Gaia”) through feedbacks.

The other form, the strong one (or radical Gaia), suggests that the biota effectively acts as if it were a self-organizing system to keep it in a state of equilibrium that is advantageous for life. This latter has not been accepted as valid by many scientists and was, then, divided into two main versions: the “Optimizing Gaia”, which affirms that biota manipulates the physical environment creating a biologically favourable status with the purpose of optimizing its life conditions; and the “Omega Gaia”, which invokes cosmogenesis and a final evolutionary stage called “omega point”.

Here I will not analyse every form and version of the Gaia hypothesis, but I will propose why and suggest how Gaia (both if it is examined under its weak or strong hypotheses’ versions) – and with Gaia I mean the system composed by symbiotic (the biosphere) and abiotic (the geosphere-atmosphere) interacting and coevolving elements – should be considered alive in an evolutionary sense.

2. Methods

I took into consideration the main criticisms argued against the Gaia hypothesis since it was proposed and then repeatedly reformulated. Then, I analysed them following a logic-deductive reasoning together with thought experiments, sometimes adopting analogical arguments (Lorenz, 1973) and suggesting the rationale why and the mechanisms how Gaia evolves and may reproduce, allowing to reject those criticisms as outdated and insufficient to discredit the main idea.

One of the main concerns is that organisms could not act in concert as this would require foresight and planning from them because, according to the opponent authors, it seems unlikely that feedback loops could stabilize the system. I borrowed Margulis’ (1998) original idea of a symbiotic planet and Lewontin’s (2001) coupled differential equations from the “Coevolutionary Gaia” hypothesis and I adapted them to a similar condition which could clarify this criticism through an analogical reasoning.

Another important criticism is that Gaia cannot reproduce herself, and so she cannot be considered alive in any meaningful sense. Since one of the hallmarks of every living organism is its ability to replicate and transfer its genetic information to following generations, it seems that Gaia cannot be subject to natural selection and should not be considered as an individual. Moreover, being alive is not the same thing of being a unit of selection. To consider Gaia as “alive” we need to demonstrate that she is part of a population of entities showing heritable variation in fitness. Thus, I borrowed the competitive Lotka-Volterra (Lotka, 1925; Volterra, 1926) equations and adapted them to an analogous situation, which could clarify this criticism.

3. Results and discussion

The criticism about teleology and natural selection can be summarized as follows: the idea that Gaia possesses feedback loops that increase the likelihood of the long-term survival of the biosphere is incorrect because these feedbacks could not evolve due to the requirement of an higher-level selection (group or super-organism selection), which is too week to overcome an individual-level selection (Wilkinson, 2004). To disentangle this, I carried out a thought experiment in which I consider the cell (and not the gene or the multicellular individual) as the main unit of selection. Cells are the smallest complete organisms which are able to reproduce themselves in absolute autonomy, following the laws of natural selection. Contrary to what was suggested by one of the opponents to the Gaia hypothesis (Dawkins, 2006), genes cannot reproduce by themselves because they always need other components (enzymes, lipid membranes, endoplasmic reticula or something similar, organelles, capsids with glycoproteins, etc.) and the presence of other different genes (an isolated gene cannot express the information it carries because the enzymes derived from other genes, able to transcript it, are absent). Although it has been shown that ribozymes (RNA molecules that are capable of catalysing specific biochemical reactions, similar to the action of protein enzymes) are capable of catalysing their own synthesis from activated monomers under very specific conditions, isolated genes should not be considered as units of selection.

As Lynn Margulis (Sagan 1967) pointed out, the cells are made of (endo)symbiotic relationships. Even genes coming from external sources and carriers (mostly viruses and phages) have been suggested to integrate with the whole genome of the multicellular individual through (endogeno)symbiosis (Cazzolla Gatti, 2016a, 2018a). Thus, the multicellular organisms are an aggregation of unicellular individuals, a sort of colony where cells with almost the same genotype but different tasks, work together to allow the propagation of the genetic information of the unicellular component by the means of the multicellular individuals. These “colonies of multicellular individuals” are based on symbiotic relations among them and with other types of cells coming from the external environment (bacteria, fungi, parasites, viruses, etc.). Certainly, organelles described by Margulis and most of the viral genomes comprising parts of our genome become no longer autonomous after the integration. Similarly, entities are no longer autonomous once they establish symbiotic relationships within a Gaian framework.

Different types of cells integrate so deeply that we now call them “microbiota”: the ecological community of commensal, symbiotic and pathogenic microorganisms that compose the body (Lederberg & McCray, 2001). As symbiosis is a common process in ecology, interactions among individuals in the body of Gaia (either intended as by-product mutualisms or as emergent mutualisms; Wilkinson, 2004) can be analogically compared to the interactions among cells in a multicellular body. The density-dependent regulation on the growth of individuals, which is not a direct result of selection but a by-product of the individuals’ maximization of their own fitness, is also the base of the Gaia’s emergent properties (Cazzolla Gatti, Fath, Hordijk, Kauffman, & Ulanowicz, 2018).

It follows that multicellular organisms evolved relatively late in the history of Earth because they are not a fundamental feature of a Gaian planet (Free & Barton, 2007). They are just carriers of unicellular individuals, which employed the adaptive solution of multicellularity (Miller, 2010) to cope with external conditions in order to increase their fitness.

Thus, every organism living on our planet today shares the same genetic code as well as every multicellular individual is made by multiple cells with a similar genotype (i.e. it is an aggregate of unicellular individuals). What we struggle to accept as true for Gaia is exactly what happens to unicellular individuals in a multicellular body. In fact, even in the absence of foresight and planning, there are feedback loops which could stabilize the whole system.

If cells were able to think about the system where they are living in, they would probably find difficult to accept that an aggregation of other cells, similar to themselves, is able to keep the whole system alive. As argued by Watson (2004), adapting the anthropic principle, observer species (such as humans) may evolve only on “Gaian” planets, i.e. “where the biosphere tends to regulate planetary conditions. This follows because observers are unlikely to evolve on any planet in a much shorter period than we ourselves have evolved”. I will add to this, and I will clarify later the reasons why, that *observer species may evolve on Gaian planets that are, at least potentially, able to reproduce*.

Furthermore, Chopra and Lineweaver (2016) stated that “if life emerges on a planet, it only rarely evolves quickly enough to regulate greenhouse gases and albedo, thereby maintaining surface temperatures compatible with liquid water and habitability”. Thus – Chopra and Lineweaver (2016) specified – planets need to be inhabited to remain habitable. Recently, it has been suggested that life might play a crucial role in determining the long-term habitability of planets through “Gaian bottlenecks” – a phenomenon whereby life either rapidly goes extinct leaving an inhospitable planet or survives indefinitely maintaining planetary habitability (Nicholson, Wilkinson, Williams, & Lenton, 2018).

Certainly, the parallel between a multicellular individual and Gaia does not seem to take into consideration that every cell of a multicellular individual is (almost) identical in genotype, even if it has a different shape and task, whilst every individual or species has its own specific genotype. Indeed, after the recent discoveries of the genetic variation of human body’s cells (Macaulay & Voet, 2014; Pack et al., 2005), we can guess that the evolutionary process that gives cells of the same body a slight difference in genes (information and expression) is very close to that operating to differentiate individuals and species. Even the same individual, during its lifespan, can accumulate so many genetic variations on its genome (deletion, insertion, inversion, translocations, etc.) that in the adulthood it can be assumed completely different if compared to its early days (Cai et al., 2014). Moreover, almost half of the cells of a body are commensal, mutualistic and parasitic microorganisms. Therefore somatic cell diversity, in a multicellular body, increases with time and with the number of symbiotic (microbiotic) interactions, and the basic body genotype (hologenome) is then transferred, through reproduction and carried by germinal cells. Analogously, the diversity of individuals/species in the body of a Gaian planet increases with time and the number of symbiotic (micro and macrobiotic) interactions, and the basic genome (hologenome) of the planet could be transferred, through reproduction, carried by “germinal individuals/species”.

In other words, biological diversity is a matter of time and space (Cazzolla Gatti, 2018b). There is a kind of relative spacetemporal and scale-dependent threshold of differentiation beyond which two cells, two individuals, or two taxa begin to be substantially different from one another. As Margulis and Sagan (1986); Margulis (1998), and Lynn Margulis (Sagan 1967) suggested, symbiosis is one of the main drivers of speciation and, hence, diversity.

It follows that a planetary scale diversity shows a rate of a higher genetic differentiation than that of species, which in turn, is higher than those of multicellular and then unicellular individuals. This is evident considering the difference in the lifespan and in the spatial scale of a single organism and of a planet (like Earth). Space and time contribute together to increasing the likelihood of genetic differentiation of ecological entities (Haila, 1999) in a hierarchical manner: from cells to individuals, through populations and species, to community and ecosystems, up to the whole biota, and thus towards an increasing planetary diversity (Cazzolla Gatti, Hordijk, & Kauffman, 2017).

Therefore, if we apply the proportional scale to both systems (the individual and the planet), we see that a slight difference in genetic information and expression in each cell of multicellular individuals corresponds, at a larger scale, to the slight genomic difference that makes every species (and every individual within species) unique for its niche (i.e., for its ecological functions) in Gaia's body.

According to the logic-deductive reasoning above, a Lewontin's coupled differential equation system, which models cells instead of individuals, could be analogously adaptable to a "Coevolutionary Gaia":

$$\begin{cases} \frac{dC}{dt} = f(C, B) \\ \frac{dB}{dt} = g(C, B) \end{cases} \tag{1}$$

where C is the cell (instead of Organism, O, as in the original formulation) and B is the body (instead of Environment, E, as in the original formulation). A Coevolutionary Gaia describes the now well-accepted idea (Free & Barton, 2007) that life affects the development of the planetary environment, which, in turn, affects the future evolution of life. Similarly, the proposed functions *f* and *g*, for Cell (C) and Body (B), suggest that cells affect the development of a body (their environment), which affects the future evolution of cells.

This shows that organisms – as cells in a body – could act in concert (symbiotically) without foresight and planning (apart from the need to reproduce their individuality). Moreover, this also shows that feedback loops between life (considered as an aggregate of individuals that I will call "macro-selection units") and its environment could stabilize the system by emergent properties (Cazzolla Gatti et al., 2018), exactly as feedback loops between cells (which I will call "fundamental-selection units") and a body do.

There is an external environment for species in the body of Gaia as well as there is one for cells in the organismal body. After considering the cell the fundamental unit of selection and the multicellular individual the macro-unit of selection (which is an aggregation of fundamental-units), to demonstrate that Gaia can be effectively considered as a super-organism, I will now refer to her as a "super-unit of selection".

Defining our planet as a super-unit of selection, made of macro-units of selection (multicellular individuals), composed by fundamental-units of selection (cells), means that Gaia (the highest level of biological organization) has to be subject to natural selection, that is to say: she must adapt and reproduce to evolve. This approach undertakes a kind of planetary extended phenotype (Dawkins, 1999; Free & Barton, 2007) with an inclusive fitness (Hamilton, 1964). In this perspective, if we acknowledge the cell as the unit of selection, its inclusive fitness is that of the whole body. This is because from a gene's point of view its evolutionary success ultimately depends on leaving behind the maximum number of copies of itself in the population. Shifting to a cell's point of view, evolutionary success similarly depends on how many copies of itself the cell leaves in the population. The same applies to individuals (macro-unit of selection) and ultimately to living planets (super-unit of selections). This approach looks at Gaia as an evolutionary element which evolves according to the hierarchy of feedbacks, an idea used also by Lenton (1998) to attempt a synthesis of natural selection and environmental feedback.

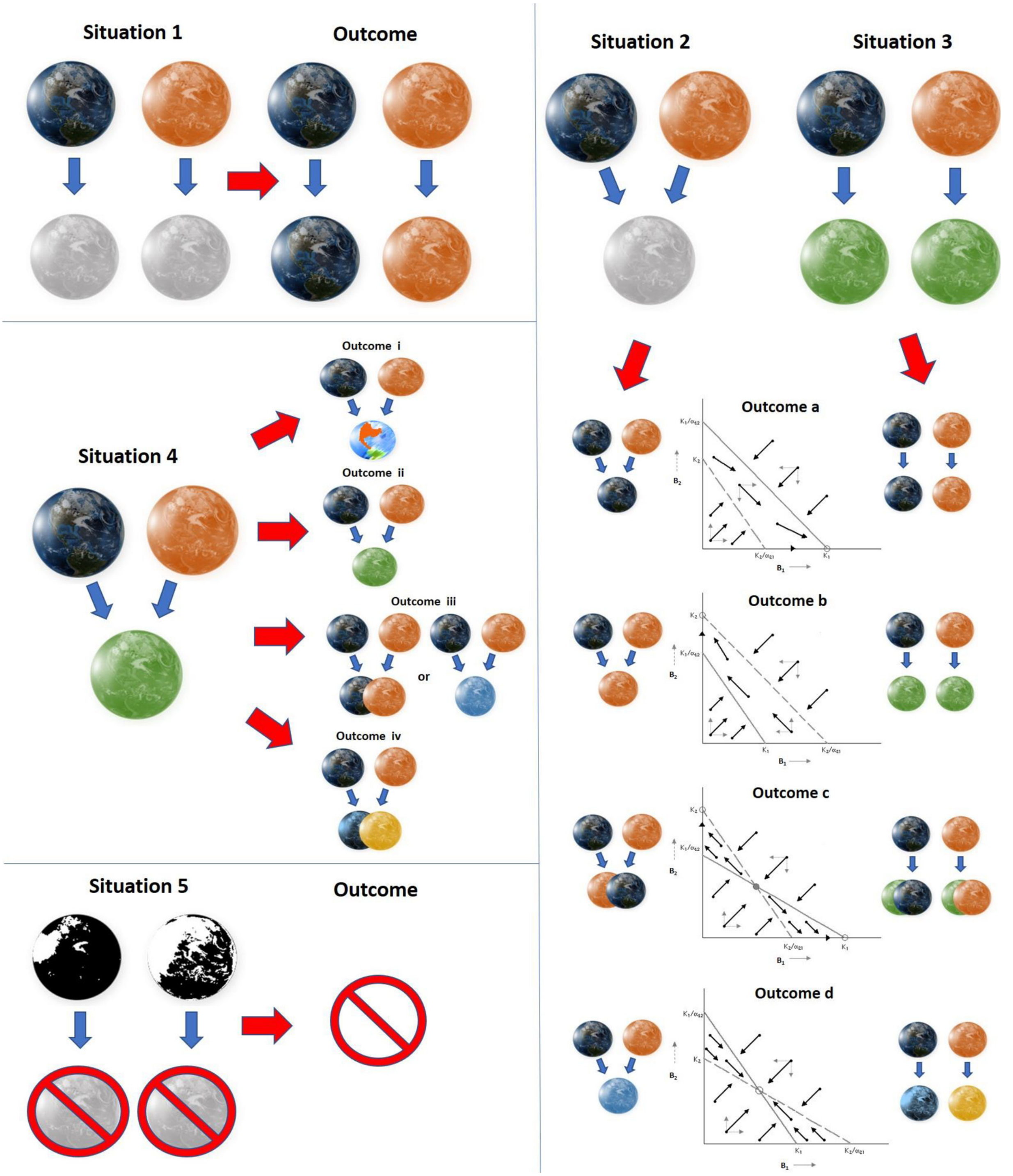
Therefore, contrary to what was suggested by some authors who criticized the Gaia hypothesis, the main forces of evolution seem to be symbiosis (Cazzolla Gatti, 2018a; Margulis, 1998), cooperation (Cazzolla Gatti, 2011) and altruism (in Hamiltonian sense; Hamilton (1964)) among coevolving hierarchical systems, and not pure selfishness (Dawkins, 2006).

As a cell, Gaia is an homeorethic delimited open system with a semipermeable membrane (the atmosphere), which is fed by solar energy (and water that probably condensed on the surface at her origins; see Cleeves et al., 2014), and produces waste in the form of heat (entropy) and organic/inorganic materials dispersed beyond the atmosphere (Checinska et al., 2015; Rossi, Anselmo, Cordelli, Farinella, & Pardini, 1998). As the evolutionary success of the whole multicellular body depends on the fitness of the totality of its cell types, the evolutionary success of Gaia depends on the fitness of the totality of the taxa/individuals and the components of its biosphere.

Considering the abovementioned ways through which a Gaian planet can reproduce herself, it is possible to characterize how natural selection could operate over a super-units of selection like Gaia.

Let's carry out another thought experiment: imagine a two-planet system in which one of them is Gaia. Gaia is about to reproduce by the dispersal of some of her "germinal" units of selection (be them fundamental or macro, but it is more likely that a macro-unit could act as the carrier of a mix of fundamental-units) and the other planet (with a similar level of biotic evolution) from another solar system is about to do the same. We can have five different situations (Fig. 1):

1 the two planets can spread their "germinal units" on two distinct uninhabited (intended as "without any form of life") planets. In this case the "asexual reproduction" of the two new colonized planets proceed with weak competition, because the fitness depends



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only on the adaptability of the immigrated organisms to the new environmental conditions (as a bacterium in a new empty Petri dish free to adapt to the new substrate, grow and spread out everywhere in it);

2 the two planets can spread their "germinal units" on the same uninhabited planet. In this situation, there can be competition, hybridization or cooperation between the two different biotic groups, but in any case – apart from the complete elimination of one of the two biotas because of competitive exclusion – a merging of them would lead to a kind of "sexual recombination" of genetic pools. In all of these cases, trait selection plays a fundamental role in determining the fittest biota or whether both can survive and merge in a newly adapted biota (as two bacteria species transferred in the same Petri dish that could evolve from competition to

Fig. 1. The evolutionary dynamics of Gaia-like planets (adapted from Cazzolla Gatti (2017)). Five situations (explained in detail in the text) are shown. Blue arrows represent reproductive events (i.e. the transfer of planetary genome to another planet). Red arrows are the results (outcomes) of the reproductive events. Three biospheres are considered: B_1 blue planet (e.g. Gaia); B_2 red planet (a Gaian planet); B_3 green planet (another Gaian planet). Situation 1 is a reproduction of B_1 and B_2 on distinct uninhabited planets with the survival of both biotas. Situation 2 and 3 are reproductions of B_1 and B_2 on either the same uninhabited planet or two distinct inhabited planets, respectively, with 4 possible outcomes (from a to d as explained in the text) deriving from the competition-exclusion-cooperation dynamics of the Lotka-Volterra model (the 4 state-space graphs with the related isoclines for B_1 and B_2 are shown). Situation 4 is a 3-planet system where B_1 and B_2 spread their “germinal units” on the same inhabited planet B_3, an N-biotas model with the 4 outcomes (from i to iv as explained in the text) resulting from the equation of each biota as $dB_i/dt = r_iB_i(1 - \Sigma^N j = 1\ \alpha_{i,j}Bj/K_i)$. Situation 5 is when life on a planet is unable to spill over because either it ceases to exist before (“planetary extinction”) it is able to reproduce or it is unable to spread germinal units out (“planetary infertility”) with the result of no reproduction on other planets. Black and white planets in Situation 5 represents dead biospheres. The outcomes of planetary reproductions are represented as merged colours (hybridisation of the biotas) or coupled planets (survival of either biota). See the text for more details. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).

cooperation/mutualism and share/recombine their genetic information in order to adapt to the new substrate);

3. each planet spreads its “germinal units” on two distinct inhabited (intended as “with some forms of life”) planets. In this case, competition-hybridization-cooperation can arise from the interaction between the endemic biota and the new one. According to planet Earth’s natural laws, it is very likely that if the system where the germinal units are spread is evolved and healthy, the alien biota can be almost completely rejected or unable to survive. In some cases, an integration (“sexual recombination”) of the alien biota with the endemic one can be possible (as a bacterium transferred in a Petri dish where a well-developed bacterial community already thrives);
4. each planet spreads its “germinal units” on the same inhabited planet. In this case, competition-hybridization-cooperation can arise between the two alien biotas and among them and the endemic one. This would generate a three-biota system where the result can be the survival of all of them (“sexual reproduction”); of only the endemic one (“no reproduction”); of only one (“asexual reproduction”) or both (“sexual reproduction”) the two alien biotas; or of one of the two alien and the endemic biota (“sexual reproduction”). In this case the “immigrated” biotas (or, at least, some species of them) could adapt to the new conditions, but the endemic biota has more chances to be the fittest and to competitively exclude (or, at least partially integrate) the others (as two different species of bacteria transferred together in a new Petri dish where there is already a well-developed bacterial community);
5. there could also be situations where life on a planet is unable to spill over because it ceases to exist (mass extinction due to species impacts, environmental-geological events or both on the biotic community: a kind of planetary “disease”) before it is able to reproduce, or because it is able to develop germinal units but unable to spread them (“infertility”). In these two cases, the fitness of that biota is reduced to the minimum level.

There are, also, two basic assumptions that apply to the situations described above:

1. the first one is that life exists on other planets besides Gaia (as many likelihood models confirmed with a high level of confidence; Franck, von Bloh, Bounama, & Schellnhuber, 2004);
2. the second one is that all forms of life in the Universe are based on the same genetic code and structural materials (i.e., are carbon-based). However, even if it is unlikely (Pace, 2001) for some different materials (based on other molecules as different classes of carbon compounds, compounds of another element or another solvent in place of water, etc.) to represent the way other biotas evolve on other planets, there is a minimal possibility (Davila & McKay, 2014). This means that in the case of an encounter – as in the situations 2–4 described above – between two (or three, as in case 4, or even more) biotas with different biochemistries, a “true reproduction” seems to be apparently impossible. But even in this event, the two biotas could: i) evolve in parallel (as it could have been for Gaia itself, if a sort of shadow biosphere made of biochemically unfamiliar micro-organisms lived in the past, or still existed today; see Davies et al., 2009); or ii) live together merging some features of their adaptations based on different biochemistries, and evolving into a third new biota based on an intermediate biochemistry (a kind of “biochemical evolution”). These two latter possibilities, although unlikely, are not biochemically impossible (Cleland & Copley, 2005).

The situations 2 and 3 described above can be formally defined by borrowing other coupled differential equations, this time those belonging to the competitive Lotka-Volterra system:

$$\begin{cases} \frac{dB_1}{dt} = r_1 B_1 \left(1 - \left(\frac{B_1 - \alpha_{1,2} B_2}{K_1}\right)\right) \\ \frac{dB_2}{dt} = r_2 B_2 \left(1 - \left(\frac{B_2 - \alpha_{2,1} B_1}{K_2}\right)\right) \end{cases} \tag{2}$$

where B_1 and B_2 are the interacting biotas from the two planets (in the abovementioned situations), K is the carrying capacity of each biota, r is the intrinsic rate of growth of each biota, and α represents the effect of one biota on the other one.

Rearranging these two equations in order to detect the zero-growth isocline (with the same procedure employed for the original Lotka-Volterra’s coupled differential equations, not graphically repeated here) 4 possible outcomes arise:

1. only biota 1 (B_1) survives (to the detriment of B_2);
2. only biota 2 (B_2) survives (to the detriment of B_1);
3. there is an unstable equilibrium between them (both, only one, or maybe none, can be able to ultimately survive up to a new “planetary reproduction” event);
4. there is a stable equilibrium between them (both survive, could merge and reproduce spreading over another planet).

As already said, the system of coupled differential equations (2) accounts for the abovementioned situations 2 and 3 and their respective cases. Instead, situation 1 (which was suggested to be a possible case also for planet Earth colonized from Mars; see Davies, 1998) can be easily represented by the logistic equation $dB/dt = rB(1 - B/K)$. Situation 4 is an *N-biotas* model (3 biotas in this case, but they might be more) with the equation for each biota as $\frac{dB_i}{d_t} = r_i B_i \left(1 - \sum_{j=1}^{N} \frac{a_{i,j} B_j}{K_i}\right)$.

The applicability of a model originally designed to describe the population dynamics of two (or more) species in competition, which is subject to natural selection, to the dynamics of two or multiple Gaian planets is a clear evidence of how a Gaian system adhere to evolutionary patterns as any other organism.

However, only if a Gaian system is healthy, differentiated and homeorhetic, it is able to evolve until its reproductive stage. If biodiversity and ecosystems are not preserved intact up to the reproduction of a Gaian system, the propagation of the planetary genome could not proceed.

It follows that *Homo sapiens sapiens* is an important species, but not the most important one in the in the framework of Gaia. Humans could act as germinal cells carrying a specific planetary genome, but it is unlikely for them to reproduce (or survive disconnected from Earth) on another Gaian system. As a spermatozoon, which loses its flagellum and acrosome while entering into the egg of another body, therefore changing its identity, a human being can be considered just as a carrier of its body’s (i.e., Gaia’s) genetic information, not of himself: *a means more than an aim*. Many other taxa could have evolved and been able to operate as germinal units of propagation, which might be the case on other Gaian planets.

Thus, our species can act either as a germinal cell, transferring Gaia’s genome and allowing her reproduction, or – if it continues to grow unconditionally and to consume the fundamental resources for the survival of the other components of the biosphere – as a cancer cell, impairing Gaia with a disease on her somatic cells (other taxa) and organs (ecosystems). This, subsequently, will affect her germinal cells (human beings), preventing her from any possibility of reproduction (apart from an accidental spread due to asteroids impacts).

Our species, as a result of billion years of symbiotic evolution and differentiation (or better, from a cell’s point of view, of “development”) within Gaia, has the possibility and the privilege to allow Gaia’s continuation, evolution and reproduction. This result could be achieved only if we keep biodiversity and ecosystems, living within Gaia, healthy, and we continue to study and protect them (Cazzolla Gatti, 2016b) because they are the supporting and essential components of the body of Gaia. Moreover, we should put efforts into the search for other Gaian planets in the Universe and, more importantly, into the technological advancements to transfer Gaia’s genome on other potentially suitable reproductive sites (uninhabited and/or potentially inhabited planets).

Since our planet is at three-quarter of its lifespan (1.75–3.25 billion years are left before the sun heats up so much to impede life on Earth; Rushby, Claire, Osborn, & Watson, 2013) and we are not able to transfer Gaia’s genetic information on other potential planets yet, there is another reason why we need to allow Gaia to live as long as possible: taking enough time to develop technological means for this purpose.

I suggested (Cazzolla Gatti, 2017) to start a specific research program divided in two phases, to search for the most suitable, diverse and genetically representative mix of Gaia’s microorganisms that are likely to survive, evolve and reproduce on other planets (methanogens, extremophiles, phototrophic and chemotrophic bacteria, etc.) that can be transferred in what I called “biophore” (from the Greek: βίος, “life”, and φορά, “to carry”; i.e., a conveyor capsule of life). Furthermore, it is necessary to invest in the development of technologies that are able to transfer the “biophores” over long distances. This transfer can be either direct (if human beings are able to carry the biophores directly on the other planets), or indirect (if the spread occurs by the means of technological devices – a sort of artificial extensions of human beings, as Gaia’s germinal cells); either passive (if the dispersion is made without recipient targets, such as plant seeds dispersed by wind), or active (if the biophores are delivered on suitable planets detected beforehand).

According to Franck et al. (2004), there are at least half a million Gaian planets just in the Milky Way. This means that there are many potential mates for Gaia, scattered everywhere. Moreover, millions of uninhabited planets could be suitable for Gaia reproduction. For the first time, recently, researchers discovered three Earth-like planets orbiting an ultracool dwarf star 40 light-years away in another star system (Gillon et al., 2016).

4. Conclusion

In this paper, I tried to keep the door open to the fundamental debate on how our planet works and maintains its stability. My thought experiments aim to keep alive and stimulate the discussion about Gaia theory and its implications for our and the whole biosphere’s future.

I proposed, with a logic-deductive reasoning and analogical arguments that, without invoking teleology, so without any foresight or planning, a Gaian planet can be considered as a coevolutionary symbiotic system analogous to a multicellular body. Cells coevolve with a body as well as individuals/species coevolve with Gaia. In this way, I suggest that Gaia can be indeed considered subject to natural selection and can face exclusion-competition-coexistence states depending on the fitness of her biota compared to those of the other reproducing biospheres.

This reproductive capacity, together with the definition of her external environment and energy exchange, can arguably confer Gaia the status of a living system. Some deep implications arise from this evidence.

Our symbiotic planet, transferring its planetary genome by means of biophores delivered by its human germinal cells, could reproduce on other sides of the Universe the “endless forms most beautiful and most wonderful” with which we share our life.

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