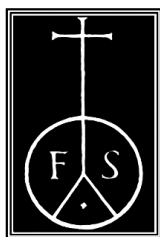


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ADAPTATION, EVOLUTION AND REPRODUCTION OF GAIA BY THE MEANS OF OUR SPECIES

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CONTENTS: 1. Introduction. 2. Methods. 3. Results and Discussion. 3.1. *Confuting the First Criticism: Teleology and Natural Selection.* 3.2. *Confuting the Second Main Criticism: Reproducibility.* 3.3. *Confuting the Third Criticism: Replicability.* 4. Conclusion.

KEYWORDS: Gaia's adaptation, Gaia's evolution, Gaia's reproduction, Symbiosis, Biophora.

ABSTRACT: Nowadays, the idea that life affects the development of the planetary environment, and can, in turn, affect the future evolution of itself (in a coevolutionary way) is well-accepted. However, since the proposal of the Gaia hypothesis, there has been widespread criticism. Most of it is related to teleology, the absence of natural selection at a universal scale, and the lack of planetary reproduction. Some of the problems concerning the 'internal' logic of the idea have been resolved. Nevertheless, it is not sure 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 propose why and suggest how a Gaian system should be considered alive in any evolutionary sense. I take into consideration the three principal criticisms and I analyse them following a logic-inductive reason-

ing. I use thought experiments and analogical arguments to analyse the rationale and the mechanisms by which Gaia evolves and may reproduce. This reasoning could allow rejecting the aforementioned criticisms as outdated and insufficient to discredit the main idea. I argue that without invoking teleology – so without any foresight or planning – a Gaian planet can be considered 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 transfer her planetary genome to other uninhabited or inhabited planets. Then I suggest 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 this evidence, also in light of the recent discovery of a new solar system with Earth-like planets by NASA.

1. INTRODUCTION

THE Anthropocene is considered as an epoch dating from the beginning of significant human impact on the Earth's geology and ecosystems [Crutzen 2002]. Besides suggesting the existence of a Biosphere, which was lately scientifically shaped in the Gaia theory, Vladimir Vernadsky [1945] proposed an early concept for the Anthropocene, that was the Noosphere. He argued that a Biosphere in which a

combination of human actions and thoughts will come to play a critical role [Vernadsky 1945, 2007] can be considered as a planetary phenomenon [Callicott 2013].

Although the ecologist Eugene F. Stoermer used «anthropocene» in the 1980s, the term was widely popularized in 2000 by atmospheric chemist Paul J. Crutzen [Crutzen and Stoermer 2000]. They showed that the recent influence of human activities on Earth, and in particular on its atmosphere, is so significant as to be considered the beginning of a new geological epoch.

Even if this new epoch has no agreed start-date because some scientists consider the atmospheric changes start with the Industrial Revolution at the end of the 17th century and others identified the rise of agriculture and the Neolithic Revolution (around 12,000 years BP) as its beginning [Zalasiewicz *et alii* 2008].

In any case, the evidence of human impacts on Earth, such as land change, ecosystems degradation, biodiversity drop, and species extinction is undeniable and remarkable [Dawson 2016].

In her paper entitled *On the Origin of Mitosing Cells*, Lynn (Sagan) Margulis [1967] argued that the organelles in the eukaryotic cells are the result of an ancient symbiosis between prokaryotes.

After that, a few years later, the same author contributed to the development of a wider-scale endosymbiotic framework, anticipated by Vernadsky's Biosphere, such as the proposal that planet Earth is a symbiotic, self-regulating system sustained by complex feedback between biotic and abiotic components. This proposal was, finally, summarised in the Gaia hypothesis [Lovelock 1972].

Lovelock's hypothesis was very close to the notion of the Anthropocene. However, the unfounded claim that, with this idea, James Lovelock proposed that there is a planetary teleology and human beings are nothing more than the most destructive event in our Earth's biological history [Bondi 2015] resulted in vehement opposition and criticism by many biologists [Doolittle 1981; Dawkins 1986; Gould 1988; Volk 1998; for a summary see Turney 2003]. Most of them have focused on the need for evolutionary mechanisms by which regulatory feedback could have arisen or been maintained [Lenton 1998]. It was proposed that because traits are by-products of small-scale selection (and rarely are they selected for their environmental effects), changes in the environment can control the growth of organisms through feedback mechanisms [Lenton 2004].

Nevertheless, one of the frequent but weak critiques was that the Gaia hypothesis implies teleology, a kind of conscious foresight or planning by the biota [Dawkins 1999]. Most of the others principally were concerned with the absence of natural selection operated over planets on a universal scale: *i.e.*, Earth is not a unit of selection, therefore Gaia cannot adapt in *sensu stricto* according to Darwinian evolution not being subjected to «planetary selection» [Volk 1997; Dawkins 1999; Tyrrell 2013]. A final and 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 James 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 this latter.

Although some preliminary attempts tried to explain, with formally mathematical approaches (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'. Ford Doolittle [2014] argued that some types of evolution may work even for isolated-non-reproducing individuals and evolution does not compulsory require natural selection between multiple entities. Effectively, there is no need for competition between reproducing individuals to be considered naturally selected [Cazzolla Gatti 2011]. In fact, cooperative and symbiotic individuals evolve easier, and sometimes faster, than competing ones [Margulis 1998; Nowak 2006]. However, the fact that «differential survival of non-competing and non-reproducing individuals will also result in increased frequencies of survival-promoting 'adaptations' among survivors, and this is also a kind of natural selection» [Doolittle 2014] does not prove that reproduction is not needed for evolution. If we agree that biological diversity is a pre-requisite for the existence of life itself [Cazzolla Gatti *et alii* 2017] because we cannot have either only one species or non-interacting individuals living on a planet, because there wouldn't be any feedback and trade-off, fundamental for the maintenance of life, adaptation alone doesn't work for evolution. There is a compulsory need for speciation on any alive planet, and speciation means reproduction, therefore, reproductive isolation. No reproduction would mean no species, even if the absence of reproduction does not prevent adaptation by natural selection (as Dolittle argued).

Hence, to demonstrate that something is alive in an ecological and evolutionary context there is the need to show how it can reproduce, even if it could never do it. There is no species on Earth that never reproduces, even if rarely or accidentally. Some individuals can just adapt for a long time before dying (such as in the case of both clonal and modular organisms, *e.g.*, Siphonophora, colonial fungi, corals, etc.) but the species they belong to (at least, a percentage of its individuals) always reproduce. Potentially and theoretically (in mathematical models) there could be evolution without reproduction, but in the real Nature, since no unique and/or isolated individual or species can survive (there is no case for monospecific ecosystems on our planet, except for those temporarily maintained by human beings), evolution always implies speciation, therefore reproduction. This could mean that, if we consider that Gaia is alive, the condition that there is 'just one planet with life' could result impossible.

At least 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 following years [Lenton and Lovelock 2000, 2001]. This model, although it does not distinguish between species-level and individual-level phenomena (and sheds little light on some selection processes), had the value of demonstrating two fundamental aspects: 1. that a large number of species provides a beneficial effect on the entire planet (*i.e.*, that biodiversity is valuable); and 2. that biologically mediated homeostasis does not require a teleological explanation in favour of stability. Nevertheless, Lenton and Watson [2011] in a recent book admit that the burden of proving a «probable Gaia» was an objective of Daisyworld in favour of stability. Because Daisyworld is a very special case in which what

is good for the individual is automatically good for the planet, recently, other modelling approaches to Gaia have been developed and are more general [see, for a summary, Nicholson *et alii* 2017].

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

Currently, the idea that the biota on Earth could maintain favourable conditions for living beings in different and sometimes uncertain ways – and indeed has been doing it since the appearance of the first life forms around 4.1 billion years ago [Bell *et alii* 2015] – is widely accepted [Schneider *et alii* 2004]. This is why the original hypothesis was divided into two main categories (with many slightly different versions of them; see Free and Barton 2007 for extended definitions): the weak and the strong. The weak or Undeniable Gaia proposes that organisms on Earth have radically altered its composition by coevolutionary processes (a «Coevolutionary Gaia») and that this consequently, but not deliberately, has allowed the persistence of life on the planet. It can be intended either as a consequence of resistance or resilience. The Homeostatic Gaia can be the result of chance (a «Lucky Gaia») or by-products of local adaptation through feedbacks (the «Probable Gaia»).

The strong form (or «Radical Gaia»), suggests that the biota effectively act as if they were a self-organizing system to keep it in a sort of equilibrium that is advantageous for life. This latter has not been accepted as valid by many scientists and was, therefore, 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» [de Chardin 1955], 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 (if it is examined both under its weak and strong hypotheses' versions) should be considered alive in any evolutionary sense. With the term 'Gaia' I mean the system composed by symbiotic (the biosphere) and abiotic (the geosphere-atmosphere) interacting and coevolving elements.

2. METHODS

I took into consideration the three principal criticisms argued against the Gaia hypothesis since it was proposed and then, repeatedly, refined. Then, I analysed them following a logic-inductive argument together with some thought experiments

[Einstein 1982; McAllister 1996] and sometimes adopting analogical reasoning [Lorenz 1973]. By following this approach I suggest the rationale why and the mechanisms how, Gaia evolves and may reproduce, allowing a rejection of these criticisms as outdated and insufficient to discredit the main idea.

The first main criticism is that organisms could not act in concert, as this would require foresight and planning on their part. In fact, according to the opponent authors, it seems unlikely that cycles (in the form of feedback loops) could stabilise the system. I borrowed Margulis's original idea of a symbiotic planet and Lewontin's [2001] coupled differential equations from the «Coevolutionary Gaia» hypothesis to clarify the first criticism through an analogical reasoning.

The second main criticism is that Gaia cannot reproduce herself, thus she cannot be considered alive in any meaningful sense. Because 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 subjected to natural selection and should not be considered an 'individual organism'. Moreover, being alive is not the same thing as 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 the second criticism.

The third main claim is that, even if the two previous criticisms were rejected, the Gaia hypothesis would not be valid because it is impossible to test it by controlled experiment [Dawkins 1982; Lineweaver 2005]. In other words, there is an absence of replicates, because, evidently, there is only one Earth. I will suggest two approaches (in macro and micro scale), which could confute this last point.

3. RESULTS AND DISCUSSION

3.1. *Confuting the First Criticism: Teleology and Natural Selection*

The first main criticism (about teleology and natural selection) can be summarized as follows: the idea that Gaia possesses some mechanisms (such as feedback loops) that increase the likelihood of biosphere long-term survival is incorrect. This is because this feedback could not evolve because it would require a higher-level selection (group or super-organism selection), which is too weak to overcome an individual-level selection [Wilkinson 2004]. To disentangle it, I carried out a thought experiment in which I consider the cell (and not the gene or the multicellular individual) as the unit of selection. Cells are the simplest 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 compulsorily 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 whole information it carries because of the lack of enzymes able to allow its transcription,

which should be produced by other genes). Thus, they should not be considered as units of selection.

If we want to identify a fundamental unit of selection in biology we need to find the simplest self and autonomous reproducing object: this is not the gene that needs other components (such as organelles) to reproduce; this is not the virus or the bacteriophage that needs to 'parasitize' their hosts to reproduce; similarly, this is not the case for the multicellular organism that is just a complex of specialised cells that can independently reproduce (either through meiosis or mitosis). The simplest self and autonomous reproducing biological object is the cell (both prokaryotic and eukaryotic). Only the cell (*i.e.*, a unicellular individual) has the ability to reproduce itself independently from any other element. If we consider the eukaryotic cell, which is composed of endosymbiotic organelles, it seems that this restricts the concept of life to groups of organisms involved in symbioses. But even proteobacteria (which are considered some of the first endosymbionts but, most of them, are not made up by symbiosis and do not contain any organelle) and prokaryotic cells (which have only ribosomes as additional elements of their cytoplasm) can reproduce autonomously. This extends the definition of the fundamental unit of selection to all cells.

Nevertheless, the possibility that even ribosomes in proteobacteria are the result of an endosymbiosis [Cazzolla Gatti 2017] opens the door to considering symbiosis the *condicio sine qua non* the reproduction of the fundamental units of selection (*i.e.*, cells) and, higher up in the hierarchy, the multicellular individuals can take place.

As Margulis [1967] pointed out, cells are made of (endo)symbiotic relationships. Even genes coming from external sources and carriers (mostly viruses and bacteriophages) have been suggested to integrate with the whole genome of the multicellular individual through endogenosymbiosis [Cazzolla Gatti 2016a]. 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 genetic information of the unicellular component by means of multicellular individuals. These 'colonies of unicellular individuals' are based as well 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 became no longer autonomous after the integration [Cazzolla Gatti 2017]. Similarly, living beings are no longer autonomous once they establish symbiotic relationships within Gaia.

Different types of cells integrate so deeply that we now call them 'microbiota': the ecological community of commensal, symbiotic and pathogenic microorganisms that composes the multicellular body [Lederberg and McCray 2001]. Since 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 easily compared by analogy 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 maximisation of the individual fitness, is also fundamental to Gaia's emergent properties.

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 and Barton 2007]. They are just colonies of unicellular individuals, which employed the adaptive solution of multicellularity [Miller 2010] to cope with external conditions, in order to increase their fitness.

Thus, we can consider that every organism living on our planet derived from the same genetic code, as well as every multicellular individual, is made up by multiple cells with an acquired similar genotype (therefore it is an aggregate of unicellular individuals). Therefore, it seems clear that what we struggle to accept as true for Gaia, namely that even though the absence of foresight and planning there are feedback loops which could stabilize the system, is exactly what happens to unicellular individuals in a multicellular body.

If cells were able to think about the system within which they are living, they would probably find it difficult to accept that an aggregation of other self-similar cells is able to keep the whole system alive. As Watson [2004] argued, adapting the anthropic principle, observer species (such as human beings) 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 a 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, recently 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, these authors specified that planets must be inhabited if they are to remain habitable.

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 recent discoveries of the genetic variation of human body's cells [Pack *et alii* 2005; Macaulay and Voet 2014], we can guess that the evolutionary process that gives cells of the same multicellular body a slight difference in the information and expression contained in the genes is very close to that operating to differentiate individuals and species. For instance, even within the same multicellular individual, the genetic differences between cells, such as a neurone and an osteocyte, that define their shapes and functions are, in scale, similar to the genetic differences in species that address their phenotypes and ecological needs. The same applies during the developmental differentiation of the body's cells [Cai *et alii* 2014]. Moreover, almost half of the cells of a multicellular 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, genetic diversity is a matter of time and space. There is a kind of relative space-temporal, scale-dependent threshold of differentiation beyond which two cells, two individuals, or two species begin to be substantially different from one another. As Margulis [1967, 1986, 1998] and other researchers [Blank and Trench 1985; Margulis and Fester 1991; Kaneko 2002; Bordenstein 2003; Kutschera and Niklas 2005; Kikuchi *et alii* 2009; Brucker and Bordenstein 2012, 2013; Shropshire and Bordenstein 2016] suggested, symbiosis is an important driver of speciation and, hence, diversity.

It follows that a planetary scale of diversity shows a higher rate of genetic differentiation than that of species, which is higher than those of multicellular and, then, unicellular individuals. This is evident considering the difference in lifespan and in 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 and autocatalytic manner: from cells to individuals, to populations and species, to community and ecosystems, up to the whole biota, and thus towards an increasing planetary diversity [Cazzolla Gatti *et alii* 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, on a larger scale, to the slight difference in genome that makes every species (or every individual) unique for its niche (*i.e.*, for its ecological functions) in Gaia’s body.

According to the logic-inductive reasoning above, it is, therefore, possible to adapt by analogy Lewontin’s coupled differential equation, used to describe the «Coevolutionary Gaia», to a cellular-based point of view:

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

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

Only homeorhesis, intended as a steady flow, and not homoeostasis, is considered here. The dynamical systems described (the cell and the multicellular body) return to a trajectory (homeorhesis), and not to a particular homoeostatic state.

This shows that organisms – as cells in a multicellular body – could act in concert (symbiotically) without a foresight and planning (apart from the need to reproduce their individuality). Moreover, this proves that feedback loops between life beings

(unicellular organisms, as 'fundamental-selection units' and multicellular colonies of unicellular individuals, as 'macro-selection units') and environment could stabilise the system by emergent properties, exactly as feedback loops between differentiated cells and a multicellular body do.

There is an external environment for the species in the body of Gaia as well as there is one for cells in the multicellular body. After considering the cell the fundamental unit of selection and the multicellular individual (which is an aggregation of fundamental units) the macro-unit of selection, to demonstrate that Gaia can be effectively considered as a super-organism, through an inductive argument, I will now refer to her as a 'super-unit of selection'. A steady flow (homeorhesis) is the characteristic of all three units of selection: the fundamental, the macro and the super.

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 organisation) has to be subjected 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 and 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 that 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 criticised the Gaia hypothesis, the main forces of evolution seem to be symbiosis [Margulis 1998], cooperation [Cazzolla Gatti 2011] and altruism (in a Hamiltonian sense) among co-evolving hierarchical systems, and not pure selfishness [Dawkins 2006]. But I would avoid spending more words on this argument because I prefer to focus on the analogy between cells in a body and individuals on a planet.

3.2. *Confuting the Second Main Criticism: Reproducibility*

The fact that Gaia is actually a super-unit of selection can be demonstrated by confuting the second main criticism that she cannot reproduce herself. Indeed, she can. Beyond any teleology, if we look back in time with a natural historical perspective, life on Earth evolved towards a species that is able to spill out (physically or by the means of artefacts) from its body of belonging (its planet) and potentially to reach other multicellular species (as macro-units of selection), and/or unicellular species (microorganisms: as fundamental units of selection), on other planets. Doing this, a species (an outcome of billion years of evolution of fundamental units of selec-

tion, through macro-units of selection, within the super-unit of selection) is potentially able to reach life (biota) on other planets and start a new coevolutionary system (an O-E system in Lewontin's terms). This means that Gaia can reproduce herself through the 'germinal elements' of its 'multicellular body'. As the final aim of a unicellular or multicellular individual is to extend some germinal fundamental units of selection to reproduce itself, the final goal of Gaia can be realised by the extension of some of her macro-units of selection onto other planets. This can be considered a sort of asexual reproduction. Sexual reproduction events can also occur, and I will explain how thereafter.

However, so far the natural selection acting over the super-unit of selection (outside Gaia) seems to be less evident than the one operating over macro and fundamental units of selection (inside Gaia). But we need to reconsider it.

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 alii* 2014), and produces waste in the form of heat (entropy) and organic/inorganic materials dispersed beyond the atmosphere [Rossi *et alii* 1998; Checinska *et alii* 2015]. As the evolutionary success of the whole multicellular body depends on the fitness of the totality of cell types, the evolutionary success of Gaia depends on the fitness of the totality of the species/individuals that are components of the biosphere.

Considering the abovementioned ways by which a Gaian planet can reproduce itself [Sagan 1990], it is possible to characterise how natural selection could operate over super-units of selection like Gaia.

Let's carry out another thought experiment: imagine a two-planet system in which one of the planets 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 out their 'germinal units' on two distinct uninhabited planets (intended as 'without any form of life'). In this case, the 'asexual reproduction' of the two new colonized planets proceed with weak competition, because the fitness depends only on the adaptability of the immigrated organisms to the new environmental conditions (as with a bacterial species 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 out 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 – except from the complete elimination of one of the two because of competitive exclusion – a merging of the biotas would lead to a kind of 'sexual recombination' of the genetic pools. In all of these cases, trait selection plays a fundamental role in determining the fittest biota or if both can survive and merge in a newly adapted biota (as two bacterial species transferred in the same Petri dish that could evolve from

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

3. each planet spreads out its 'germinal units' on two distinct inhabited planets (intended as 'with some forms of life'). 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 out, is evolved and healthy, the new biota can be almost completely rejected or, at least, be unable to survive. In some cases an integration ('sexual recombination') of the new biota can be possible (as a bacterial species transferred in a Petri dish where there is already a well-developed bacterial community);
4. each planet spreads its 'germinal units' on the same inhabited planet. In this case, competition-hybridization-cooperation can arise between the two new biotas and among them and the endemic one. This would generate a three-biota system where the result can be the survival of: i. all of them ('sexual reproduction'); ii. the endemic one only ('no reproduction'); iii. either one of ('asexual reproduction') or both ('sexual reproduction') the two new biotas; iv. one of the two new and the endemic biota ('sexual reproduction'). In this case the immigrated biota (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 to 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 either it ceases to exist (mass extinction due to species impacts and/or environmental impacts on the whole biotic community: a kind of 'planetary extinction') before it is able to reproduce, or because it is able to develop germinal units but unable to spread them out ('planetary infertility'). In these two cases, the fitness of that biota is reduced to the minimum level.

Two basic assumptions apply to the situations described above:

1. the first one is that I assume there is life on other planets besides Gaia (as many likelihood models confirmed with a high level of confidence; Franck *et alii* 2004);
2. the second one is that I assume all forms of life in the Universe are based on the same genetic code and structural materials (carbon-based). However, even if it is unlikely [Pace 2001] for some different materials (based on other molecules as different classes of carbon compounds, on compounds of another element or on another solvent in place of water, etc.) to represent the way other biotas evolve on other planets, there is a minimal possibility [Davila and McKay 2014]. This means that in the case of an encounter – as in the situations 2, 3 and 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

microorganisms lived in the past or still existed today; see Davies *et alii* 2009]; or ii. live together merging some features of their adaptations based on different biochemistries, and evolving 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 and Copley 2005].

The situations 2 and 3 described above can be formally defined, as done for the confutation of the first criticism, borrowing other coupled differential equations, this time those belonging to the Lotka-Volterra system:

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

where B_1 and B_2 are the interacting biotas from the two planets (in the situations abovementioned), 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.

I borrowed the Lotka-Volterra competition model to show that, exactly as two competing species, Gaia (although she is the result of multiple symbiotic relationships) can be considered a competitive super-unit of selection if she could compete with another 'super-unit of selection', *i.e.*, another Gaia-like planet. I assume here that the stable equilibrium point occurs in a system with competition and density-dependence.

Rearranging these two equations in order to detect the zero-growth isocline ($\frac{dB_x}{dt} = 0$, solving for B_x , with the same procedure used for the original Lotka-Volterra's coupled differential equations) there are 4 possible outcomes (FIG. 1):

- only biota 1 (B_1) survives (to the detriment of B_2);
- only biota 2 (B_2) survives (to the detriment of B_1);
- 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);
- there is a stable equilibrium between them (both survive, could merge and reproduce, spreading to another planet).

As already said, the system of coupled differential Eqs. (2) accounts for the above-mentioned situations 2 and 3 and their respective cases. Instead, the situation 1 (which was suggested to be a possible case also for planet Earth colonised from Mars; see Davies 1998) can be easily represented by the logistic equation $dB/dt = rB(1 - B/K)$. The situation 4 is an N -biotas model (3 biotas, B_1 , B_2 , and B_3 in this case, but they could be more) with the equation for each biota as $dB_i/dt = r_i B_i (1 - \sum_{j=1}^N \alpha_{ij} B_j / K_i)$.

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

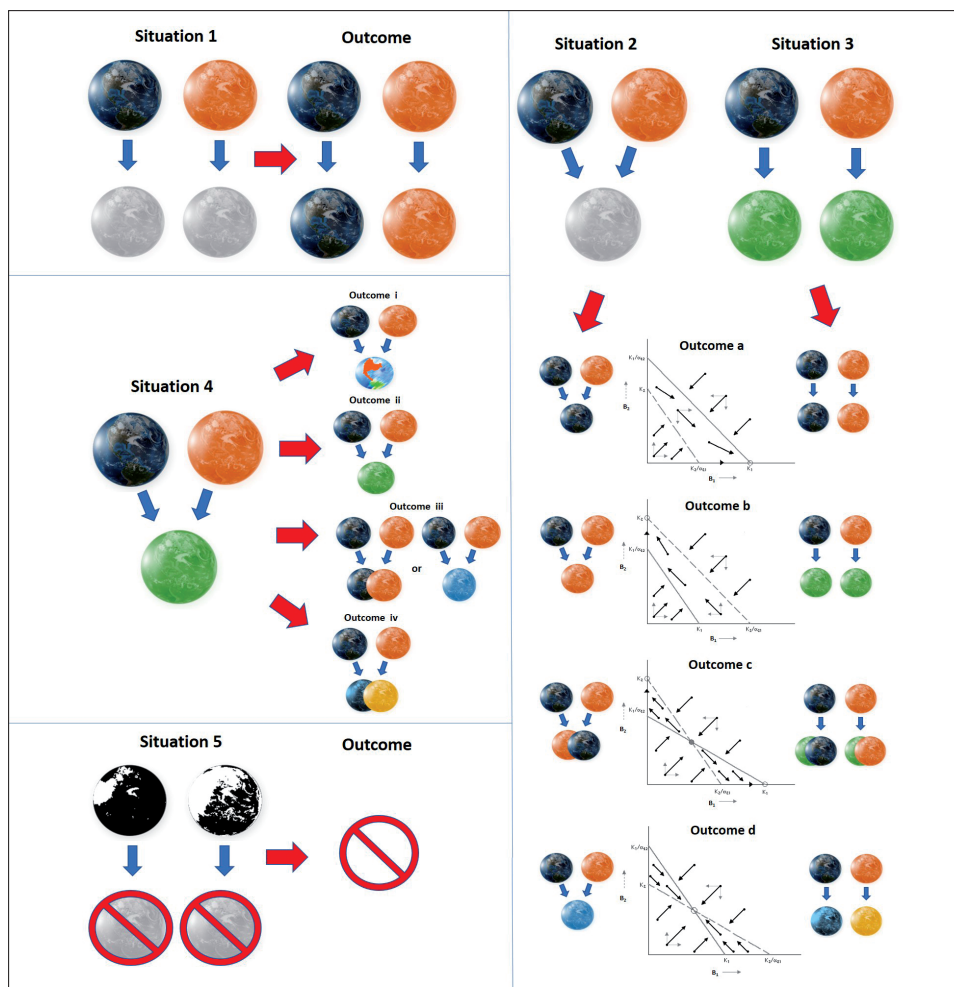


FIG. 1. The evolutionary dynamics of Gaia-like planets. Five situations (explained in detail in the text) are shown. Blue arrows represent reproductive events (*i.e.*, the transfer of planetary genome to another planet). Red arrows are the results (outcomes) of the reproductive events. Three biospheres are considered: B₁ blue planet (*e.g.*, Gaia); B₂ red planet (an Earth-like planet); B₃ green planet (another Earth-like planet). Situation 1 is the reproduction of B₁ and B₂ on distinct uninhabited planets with the survival of both biotas. Situation 2 and 3 are the reproductions of B₁ and B₂ 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 B₁ and B₂ are shown). Situation 4 is a 3-planet system where B₁ and B₂ spread out their 'germinal units' on the same inhabited planet B₃, 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 $dB_i/dt = r_i B_i (1 - \sum_{j=1}^N \alpha_{ij} B_j / K_j)$. 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 shown as merged colours (hybridisation of the biotas) or coupled planets (survival of either biota). See the text for more details.

3.3. *Confuting the Third Criticism: Replicability*

The third criticism about the replicability of a Gaian system for a scientific validation cannot be simply resolved because, for the moment, we only know one planet with life, so we do not have any replicates to test our hypothesis. However, if in future we detect another living planet or we reproduce Gaia's genome on another suitable planet, we will be able to test its replicability. Until that moment we have another possibility to confute this last criticism. Because of the evidence that the evolution of diversity on Earth (that is, of the biosphere) is a matter of space-time, we might reduce the scale of the macro-system we want to validate in micro-replicates of it. For instance, we could build smaller scale systems (e.g., microcosmos, as suggested also by Free and Barton 2007] to validate the patterns observed on our largest scale, which is Gaia. If we are able to show that a differentiated microbial-cosmos can be resilient and resistant to chemical-physical instability through bidirectional feedbacks that create favourable conditions for its life, stabilizing the system, and to keep an oscillating equilibrium of its populations around a changing point (homeorhesis), we will have strong evidence about the replicability of the tested hypothesis (the null hypothesis would be that the microcosmos is unstable and not favourable for the development of life). The confirmation of the replicability of Gaia would also add another evidence to her reproducibility (the second criticism). In fact, even if homeorhesis does not directly imply reproducibility since reproduction is the main purpose of life, we could expect that, if a system is homeorethic, it is so because it can reproduce itself (irrespective if it will actually do it or not). There seems to be no reason why a biological system should be homeorethic if it has no way to reproduce itself (at least potentially). For instance, there are some life beings that are, as any biological object, homeorethic but never reproduce for different reasons (they do not find mates, they die prematurely, they just co-evolve with the changing environment, they are sterile because of diseases, etc.). This does not mean that the absence of reproduction is not related to homeorhesis. Because they are homeorethic they can reproduce, irrespective if they actually do it or not. Because they can reproduce, they must be homeorethic. Briefly: homeorhesis has no sense without reproducibility.

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 ours and the whole biosphere's future.

I propose, with a logic-inductive 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.

Vernadsky [1945] always thought that life existed in the universe before starting to thrive on Earth according to the universal laws of evolution towards the Noösphere and started a speculation on its possible extraterrestrial origin (panspermia). The most corroborated hypothesis on panspermia, up to now, is that meteorites could have brought life from deep space onto Earth. Here I showed that human beings can, similarly but consciously, act as an agent of panspermia, allowing Gaia to reproduce.

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

First of all, it seems obvious that only if a Gaian system is healthy, differentiated and homeorethic, it is able to evolve up to its reproductive stage. If biodiversity and ecosystems were not preserved intact up to the reproduction of a Gaian system, the propagation of the planetary genome could not proceed.

Most scientists agree that human activities during the Anthropocene have accelerated the rate of species extinction that is causing the Earth's sixth major extinction [Leakey and Lewin 1995]. The current extinction rate remains controversial but it oscillates between 100 to 1,000 times the normal background rate of extinction [Kolbert 2014]. This mass biodiversity decline event is underway as a result of the anthropogenic impact on ecosystems, which includes human overpopulation, pollution, overexploitation of natural resources (e.g., deforestation, overfishing, etc.), greenhouse gases (GHG) emissions, etc. [Cazzolla Gatti 2016b, 2017]. Some studies suggested that a high number of animal and plant species that lived on Earth before the beginning of the Anthropocene are already extinct, threatening the basis for human existence too [Zalasiewicz *et alii* 2008; Kolbert 2014].

Moreover, one of the most evident impacts resulting from human activity is the increased atmospheric carbon dioxide (CO₂) content from 280 ppm of the pre-industrial age (chosen as the year 1750 as the baseline related to changes in long-lived, well-mixed greenhouse gases in the Holocene) to more than 400 ppm in 2017 [NOAA-ESRL, Mauna Loa Observatory 2017]. From these considerations, it follows that *Homo sapiens sapiens* is an important species, able even to influence a geological epoch, but not the most important one for Gaia. Humans could act as germinal cells carrying a specific planetary genome, but it is unlikely for them to reproduce (or survive disconnected from Gaia on 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 (Gaia's) genetic information, not of himself: a means more than an aim. Many other species could have evolved and been able to act as germinal units of propagation, like 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 and destroy unconditionally, and to consume 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 species) and organs (ecosystems) that, subsequently, will affect her germinal cells (human beings), preventing her from any possibility of reproduction (except from the accidental spread as a result of asteroid impacts).

The aim of life, which is that of biotas/biospheres and therefore, is that of a Gaian system, is not foreseen or planned but is nothing more than the pure propagation of itself. This goal could be achieved only if the essential meaning of life is to allow its continuation through diversity.

Our species, as a result of billion years of symbiotic evolution and differentiation (or better, from a cell's point of view: 'development') within Gaia, has the possibility and the privilege to allow Gaia's continuation and evolution. Assuming we do have this possibility and privilege, it gives us a sort of moral obligation, to allow Gaia's reproduction which would require two conditions:

1. we must keep biodiversity and ecosystems within Gaia alive and healthy and continue to study and protect them because they are the supporting essential components of the body of Gaia;
2. 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).

To achieve the first condition it is fundamental to halt the loss of species, which has increased dramatically during the Anthropocene, and the unsustainable depletion and destruction of ecosystems. At the same time, it is essential to mitigate and allow the adaptation of ours and other species (*i.e.*, of the biosphere) to the current and future global changes, as have always occurred over past geologic eras.

Since our planet is in the third quarter of its lifespan (1.75-3.25 billion years are left before the sun heats up so much as to impede life on Earth; see Rushby *et alii* 2013] and we are not yet able to transfer Gaia's genetic information on other potential planets, there is another reason why we need to allow Gaia to live as long as possible: to take enough time to develop technological means for this purpose.

On current understanding, the Universe is only around 3 times as old as the Earth. As it took some time after the formation of the Universe for life to appear, and it is not obvious how fast life could be spread out from planet to planet and evolve (since most of the planetary reproductions will involve different solar systems) we do not know how many reproduction events and chances for selection have been and will be possible in the Universe. In this regard, the evolution of a high technology civilization could help. Back in 1960, Tommy Gold suggested a «cosmic garbage» theory of «accidental panspermia» (namely that even if an alien astronaut arrived on a planet, the microbes living inside them have a much better chance of colonising the planet than the alien astronaut themselves). Francis Crick and Leslie Orgel [1973] took this further in a paper in *Icarus* and a popular book by Crick [1981], «Life itself», suggesting the deliberate attempt to populate the Universe with life by a high technology society sending out many rockets full of microbial cultures. Such a scenario may speed things up and so partly deal with the «lack of time» worry [D. M. Wilkinson, pers. comm.].

In order to allow Gaia's reproduction, I suggest starting a specific research program divided into two phases, to:

- a) 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 will call a *biophora* (from the Greek: βίος, 'life', and φέρω, 'to carry', i.e., a conveyor capsule of life);
- b) invest in the development of technologies that are able to transfer the 'biophores' over long distances. This transfer can be:
 - i. direct (if human beings are able to carry directly the biophores onto the other planets), or indirect (if the spread occurs by the means of technological devices – a sort of artificial extension of human beings, as Gaia's germinal cells);
 - ii. passive (if the dispersion is made without recipient targets, such as plant seeds dispersed by the wind), or active (if the biophores are delivered on suitable planets detected beforehand).

According to Franck *et alii* [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 (e.g., for the first time, recently, researchers discovered three Earth-like worlds orbiting an ultra-cool dwarf star 40 light-years away in another star system; Gillon *et alii* 2016).

There is a claim [Bondi 2015] according to which Crutzen's analysis of the Anthropocene is just on a scientific level, «assigning humanity the role of geological force for only the last two centuries», whereas Lovelock's argument in favour of Gaia proposes that men are ontologically destroyers of Earth. Although the continuous misunderstanding of Lovelock's ideas that unfairly depicted the father of the Gaia theory as 'against humanity', here I showed that human species has, instead, the chance to change its Anthropocenic destructive fame, shifting it towards a protective and reproductive role for Gaia. However, it is in Vernadsky [2007] and in his ideas of the Biosphere and the Noosphere, that we find a future of growing creative possibilities rather than of self-destruction. According to Vernadsky, humans had come to bear some new responsibility as a natural consequence of scientific progress, because of the immanent direction of the biogeochemical processes themselves towards the advent of the Noosphere. Human activity, as a planetary phenomenon, would inevitably achieve what Vernadsky proposed with the Noosphere concept. As «the latest and greatest morphological development in the evolution of living matter» [Callicott 2013].

The symbiotic planet invoked by Margulis [1998], made up of symbiogenetic evolutionary processes, by transferring its planetary genome by means of biophores delivered by its human germinal cells, could start the reproduction of the «endless forms most beautiful and most wonderful» with which we share our life on other corners of the Universe.

In this way, the Noosphere, considered as a form of «scientific knowledge and its technological application» [Callicott 2013] can be viewed as an evolutionary phe-

nomenon and the emergence of «technological man» as the result of paleontological evolution [Deléage 1997].

Eventually, our species will find a meaning and a role in the evolutionary universe if we will be able to protect the life inside Gaia and allow it to reproduce outside of her body.

Finally, even though some of the arguments proposed here could seem quite speculative and philosophical, as Karl Jaspers [1926] once said, «scientific research becomes philosophical when it consciously pushes itself towards the limits and the origins of our existence».

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