James Lovelock's Gaia hypothesis: "A New Look at Life on Earth" ... for the Life and the Earth sciences

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James Lovelock (b. 1919) was described by the curators of an exhibition at London's *Science Museum* in 2014 as a "scientist, inventor and maverick."[1] He was clearly an eclectic inventor from the very beginning of his career as a research engineer in the 1940's. He was an accomplished scientist before formulating the Gaia hypothesis in the 1970's, with pioneering work in analytical chemistry, biochemistry and cryobiology. He was perhaps a maverick, when he quit academia in 1964, at age 45 to settle as an "independent scientist."

But the Gaia hypothesis, his major accomplishment, is that of a dreamer. As he described it, Gaia was

> for those who like to walk or simply stand and stare, to wonder about the Earth and the life it bears, and to speculate about the consequences of our own presence here.[2]

From the very beginning, the Gaia hypothesis was thought as something big, challenging the paradigmatic views prevailing in the earth and life sciences, redefining the boundaries and questions of these disciplines, providing a new conception of life, nature and the Earth.

But for many biologists, the Gaia hypothesis was just the dream of a "romantic and new-ager"[3] wandering, astray from science. Here is what the microbiologist John Postgate says about it:

> Gaia - the great mother Earth! The planetary organism! Am I the only biologist to suffer a nasty twitch, a feeling of unreality, when the media invite me yet again to take her seriously? [4]

Was Gaia just a misty dream? Was it only an evocative *metaphor* comparing Earth with an organism, as it has often been resumed to? By postulating a new entity emerging from the interconnection of life and geological processes, the Gaia hypothesis not only had a revolutionary influence on the constitution of a new scientific field of the Earth sciences, but on the way we collectively think about nature.

Dreaming about life in the solar system ... and back to Earth

Lovelock received, on October, 19th, 1961, a letter of invitation from NASA to work at the *Jet Propulsion Laboratory* (JPL), Pasadena, as a consultant engineer on instruments related to space exploration – a chromatograph for the 1964 Mariner B mission to Mars. As a science-fiction reader, Lovelock was thrilled and accepted.

As he commonly tells the story, the Gaia hypothesis traces back to a very practical problem he encountered while working at JPL: how would one detect life on a further planet, such as Mars or Venus? In 1965, Lovelock turned his back from the *biochemical* approaches to life, prevailing in exobiology, to hinge on physical, thermodynamical approaches.[5] He pointed out that Earth's atmosphere is in great thermodynamic disequilibrium: e.g. methane and oxygen coexist in proportion orders of magnitude out of what thermodynamic equilibrium would predict. And this, he underlined, is the consequence of living beings' influence on their planetary environment (constantly producing methane and oxygen). Important thermodynamic disequilibrium would thus be a sign for the presence of life.

This proposal challenged and redirected research in the nascent field of exobiology. Back to Earth, the crucial recognition that life massively influences its planetary environment soon lead Lovelock to the development of the Gaia hypothesis. In 1968, at a NASA meeting on origins of life, Lovelock met Lynn Margulis (1938 - 2011), at that time a young microbiologist. They collaborated to develop the Gaia hypothesis in a series of co-written papers from 1973 through 1978, before the publication of Lovelock's book.[6]

The Gaia hypothesis was meant to account for the long term stability of Earth's environment, which had kept the Earth habitable by life for billions of years in spite of external perturbations, such as the increase of solar luminosity. The Gaia hypothesis accounted for this stability by positing that:

> the ensemble of living organisms which constitute the biosphere might act as a single entity to regulate chemical composition, surface pH, and possibly also climate.[7]

It is these supposed regulatory properties which then lead Lovelock to compare Gaia, the entity composed of the living beings and the geological environment with which they interact, with a living, homeostatic entity.[8]

After 1978, Lovelock and Margulis published separately. They came from two very different intellectual backgrounds[9] – Margulis clung explicitly to a 19th century romantic and naturalist tradition, foreign to Lovelock's chemical and cybernetic background – and had different views about Gaia. After 1979, Gaia became Lovelock's major and central scientific concern. For Margulis, Gaia was an instance of a more general notion, that of symbiosis, encompassing cellular and microbial associations as much as relationships between living beings at a global scale. For this and other reasons, Lovelock is often presented as *the* author of the Gaia hypothesis. Yet Margulis had a decisive role in the 1970's: she drew Lovelock's attention to microbes' major ecological role, she brought Gaia into evolutionary biology, and she had an important role in the diffusion of Gaia in American counterculture.[10]

The standard account: evolutionary biology ridiculed Gaia as pseudo-science

The standard account of the reception of the Gaia hypothesis, the most popular in the life sciences, claims that it was rejected by scientists after famous critiques made by evolutionary biologists Ford Doolittle (see Chapter 7) and Richard Dawkins in the early 1980's.[11]

The supposed idea that living organisms may act *in order* to regulate a larger whole seemed to reintroduce agency in the natural world at the wrong level of the biological hierarchy, and reminded evolutionary biologists of the heated debate of the 1960's and 1970's over the explanation of biological altruism, where benefit to the whole emerged from the altruistic actions of the individuals.[12]

These early critiques paved the way for the denunciation of Gaia as *pseudo-science*, barely good for neo-pagan worshipers of mother Earth.

The idea that the Earth or the cosmos is (like) a living creature finds roots in stoic philosophy and was dismissed with the rise of modern and mechanistic science, and partly revived in the *Naturphilosophie* of 19th century German romanticism. For contemporary scientists, and evolutionary biologists in particular, Gaia also reminded them of the idea, linked with natural theology, that there is a "balance of nature". The Gaia hypothesis was altogether considered to be an extreme form of holism and of naively benevolent views of nature: a metaphor at best, pseudo-scientific mysticism at worse.[13]

What is particularly remarkable when looking at Gaia's reception *in evolutionary biology*, is its homogeneity in the entire field: Gaia has been dismissed by Richard Dawkins but also, and sometimes on the ground of strikingly similar arguments, by people who usually disagree about every single other matter with Dawkins, such as Stephen Jay Gould and Richard Lewontin.[14] The fame of these biologists' critiques ultimately contributed to the diffusion of this standard account about Gaia.

In spite of its popularity, nothing of this standard account of Lovelock's hypothesis sounds right. It gives the impression that Lovelock was some kind of guru of a neo-pagan community, or a retired romantic in the countryside writing green poetry about a re-enchanted nature, or an evolutionary biologists with odd ideas. As we shall see, the reality of Lovelock's approach could not be more different.

Lovelock: an independent and practical scientist, a chemist, an engineer

Lovelock was born in Hertfordshire on July, 26th, 1919 and grew up in London. His parents owned a small painting shop in Brixton. But Lovelock was more moved by his early and frequents visit to the *Science Museum* than by the artistic environment which surrounded him. He graduated in chemistry at the University of Manchester in 1941. He started working at the National Institute for Medical Research at Hampstead and obtained a PhD in medicine in the London School of Hygiene and Tropical Medicine. For twenty years, he worked on biochemical and engineering issues related to medical problems. He published an important number of pioneering articles in *Nature*, some of them being cited hundreds of times, on various issues: transmission of infections, the effect of heat on biological tissues and blood coagulation, cryobiology and resurrection of frozen hamsters.

He excelled in the invention of small-scale instruments, usually made to detect chemical substances. His most renown invention, the one to which he owes his invitation from NASA, and in 1997, the *Blue Planet Prize*, remains the Electron Capture Detector (ECD) which he invented in 1957. This small device enables scientists to detect minute quantities of chemical compounds (with a precision orders of magnitude above what was attainable beforehand).

So before the 1960's, Lovelock was already an accomplished scientist and a gifted engineer. In 1964 he quit academia to "bury [himself] in the country village of Bowerchalke,"[15] in the southwest of England. Reflecting an important romantic theme, he constantly presents himself with an ethos of a solitary and creative thinker, doing his best when working alone, out of every institutional constraint and the bureaucracy of contemporary science, and finding his inspiration in the walks he made in the countryside.

But make no mistake about what this "independent scientist" status meant concretely. The first thing he purchased was a Hewlett-Packard 9800 to solve differential equations for his ECD. In Bowerchalke, he did not settle into a library with rare alchemical books, but a home made laboratory in the garage with chromatographs and electronic circuits. He quickly obtained a formal attachment to the University of Reading, in the department of Cybernetics, since one of his papers had been refused because he only had a private address, and no institutional one. To pay for his living expenses and his own research expenses, like other "scientific entrepreneurs" of the 1960's and 1970's, he worked as a consultant engineer in big industries: Shell and Hewlett Packard mostly – not the typical places where you expect to find beardy wizards making naked incantation to mother nature[16].

If Lovelock had a disciplinary home, it was chemistry. He was trained early on as a practical chemist while a laboratory assistant, a job he obtained after high school where, he says, he learned "to regard accuracy in measurements as almost sacred."[17] The 1960's marked, for Lovelock, the transition from the study of the chemistry of living bodies (biochemistry), to the chemistry of Earth's surface (geochemistry), a field foreign to him before the late 1960's.

Aside from chemistry, the other intellectual matrix which played a prominent role in shaping Lovelock's researches was cybernetics. When forced to represent what Gaia is, to draw what his vision of Gaia is, Lovelock does not call for the graphic artists Cameron hired for *Avatar* to picture a network of interrelated animated entities, he designs an electronic circuit (figure 1). Electronic circuits were central components in most of the small-scale devices he invented as an engineer. And first order cybernetics, the science of thermostats, systems and feedbacks, occupies a central place in Gaian publications, when it comes to propose a mechanism which would maintain Earth's stability.

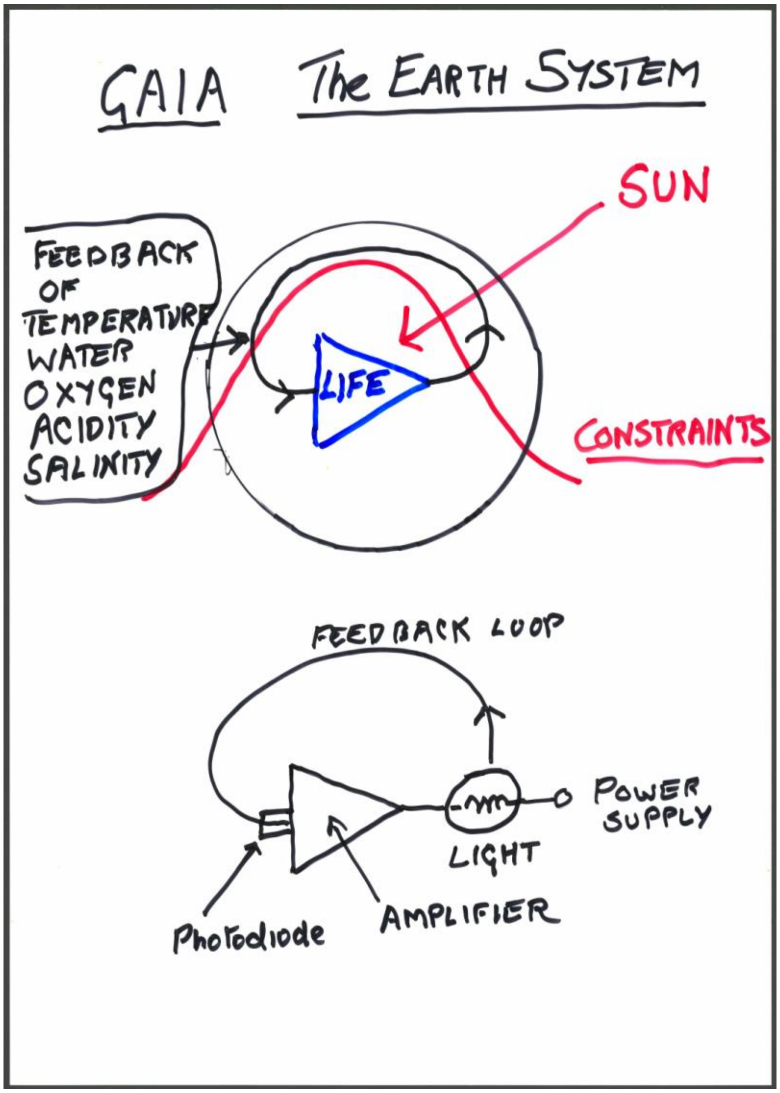

Figure 1: Lovelock's illustration of Gaia, showing the importance of cybernetics in his thinking and underlining the peculiar and central role he attributed to life in the Earth system. Copyright *Science Museum*.

Various moving passages of Lovelock's autobiography as well as scientific papers he published reveal his style of science in the 1960's and 1970's. As he recalls, "it was a family ritual at Bowerchalke to measure the haze density using a sun photometer"[18] (see figure 2). Troubled by an unusual presence of fog, persuaded that it was of anthropic origin, he settled to measure and trace the presence of Chlorofluorocarbons (CFCs), a compound only produced by artificial means, to show that the atmospheric masses had been polluted. In the early 1970's, Lovelock embarked in the marine vessel Shackleton to measure the CFCs over the Atlantic, thanks to his ECD. These first global measure of CFCs[19] were decisive for the imputation of these compounds as the causal agents of ozone destruction by Mario Molina and Franklin Rowland,[20] winners of the Nobel Prize for this discovery. Intrigued by certain predictions of Molina and Rowland's theory, Lovelock did not propose an alternative theory: he found a meteorological plane flying at stratospheric heights which would enable him to make the chemical measurements he needed. On board of the marine vessel Shakleton, Lovelock also measured the quantities of Dimethylsuphide (DMS). He had earlier realized that this sulfur compound was produced in great quantities by algae as he walked along his cottage in Ireland, identifying algae and measuring their emissions with a chromatographs. These DMS measures were for him linked with the Gaia hypothesis. In 1973, in a famous paper published in *Nature*, he suggested that the important emission of DMS by algae were essential for the closing of the global sulphur cycle.[21]

The idea that Gaia traces back to Lovelock's thinking about life detection has been prominently put to the fore by Lovelock. Yet after the mid 1960's and up to the early 1980's, Lovelock central scientific activities were not focused on this issue but on global pollution, a problem rendered central to Lovelock's thinking and preoccupations through his work as a consultant for the greatest chemical and petroleum industries. And these thoughts were at that time central to the elaboration of Gaia.

Figure 2: Lovelock and his daughter collecting air samples in the summer of 1970, County Cork. These measures of air composition were but one among many he carried out in the early 1970's in connection with the Gaia hypothesis. Courtesy of *The Irish Examiner*.

This quick overview enables us to acknowledge that Lovelock was not a philosopher or a poet trying to resurrect a romantic view of nature. He was not even a theoretician, but a chemist and engineer, with a hard core ethos of a practical scientist. His problems and arguments, he did not find in books[22], but in the chemical compounds he smelled and measured. In the early 1970's, the foundational decade of the Gaia hypothesis, Lovelock was not creating a mathematical model of the genetics of a population, sorting *Drosophila* in the lab, making ethological observations of chimpanzees in central Africa, dancing and making invocations with druids: he was measuring chemical compounds across the Atlantic, in the stratosphere, and in the English and Irish countryside.

The institutional context in which Gaia developed and spread: Earth sciences and environmental counterculture

The community to which Gaia was explicitly addressed was originally that of Earth scientists, mostly geochemists. At NASA's meetings in the 1960's, Lovelock had not only met Lynn Margulis but also Lars Sillén (1916 - 1970), a Swedish chemist who had a decisive influence on oceanography and geochemistry, and Heinrich 'Dick' Holland (1927 - 2012), a top-notch contemporary geochemist of Earth's atmosphere and oceans. Dawkins can nag that Gaia reminds him of naive views of a "balance of nature", but he entirely missed that Lovelock had no interest whatsoever in *plant and animal* demography – the epicenter of the balance of nature tradition ever since Linnaeus.[23] If Lovelock was interested in demography, it was that of atmospheric gases. And, back in the early 1970's, the unravelling of the long term chemical *history* of Earth's atmosphere and oceans was in its infancy. Three central and pioneering figures of these geochemical researches, Robert Garrels, Abraham Lerman and Fred Mackenzie, in a 1976 famous paper entitled "Controls of Atmospheric O2 and CO2: Past, Present, and Future"[24] presented a conclusion "in agreement with Lovelock and Margulis's "Gaia" hypothesis (1974)". This conclusion is that of a paper that used box models to describe geochemical processes to estimate the long term evolution of atmospheric O_2 and CO_2 – not of two pages of abstract argument over group selection and altruism, as was Dawkins' argument. This is not to say that all geochemists embraced Gaia enthusiastically. In the 1970's, Gaian papers were not cited that much.

Yet in the 1980's, Gaia became a major topic. Not only because Lovelock changed his audience and published a book for the general public, but in part thanks to the crucial editorial work of the famous climatologist Stephen Schneider. Though wary and cautious about the meaning of the Gaia hypothesis, Schneider wanted Gaia to be subject to *scientific* debate.[25] In 1988, he organized, with Penelope Boston, the first international scientific conference on Gaia as a Chapman conference of the American Geophysical Union (AGU). In 2000, he co-organized the second such conference. In the early 2000’s, he managed a space for the discussion of Gaia in his journal *Climatic Change*.

If Schneider carried out this work, it is because he did not want to leave Gaia to American and environmental counterculture. In the 1970’s, and early 1980’s, papers by Lovelock and Margulis, but also Doolittle’s famous critique, were published in Stewart Brand’s journal, *Coevolution Quarterly*. This journal was the successor of the famous *Whole Earth Catalog*, which sold millions of copies and enabled Brand to became a central figure of American counterculture, in which contemporary cyberculture finds its roots.[26] Gaian systemic and cybernetic views of the Earth deeply resonated with the spirit of *Coevolution Quarterly*. And this journal had a very important role in the diffusion of Gaian papers. In addition, Lovelock (and Margulis) also published on Gaia in the two major environmentalist journals in the UK: *Resurgence* and *The Ecologist*, the last one having been founded by Lovelock’s friend and sponsor, Edward Goldsmith.

The development of the hypothesis and theory

Initially many critics complained about the paucity of mechanisms that could account for global homeostasis. In the 1980's, Lovelock and others offered such mechanisms in three major papers.

In 1983, Andrew Watson and Lovelock published the computational model Daisyworld, developed specifically to address biologists' critiques and to show that the regulation of a global environmental variable could emerge from the influence of living organisms on their environment. The model depicted a fictive planet in which temperature is regulated by the proportion of population of black and white daisies influencing the climate through their albedo. This Daisyworld model sparked over one hundred of papers proposing variants of the original model.[27] The two other major papers of the 1980's were not abstract mathematical models but specific empirical mechanisms. The first one, published in *Nature* by Lovelock and Michael Whitfield in 1982[28], proposed a mechanism by which life, through its influence on rock weathering, may have counteracted the long term increase of solar luminosity over Earth's long history, and thus maintained Earth habitable. This paper was an important stepping stone in the study of Earth's chemical and climatic history. Finally, in 1987, the paper exposing what would soon be known as the

CLAW hypothesis was published in *Nature*.[29] The hypothesis suggested that algae may regulate the climate through a negative feedback loop involving the emission of DMS, which has a crucial role in cloud formation. This paper has been cited more than 3000 times and certain atmospheric scientists have devoted their career to the influence of DMS on contemporary climate.

Lovelock considered these three mechanisms (rock weathering, DMS and Daisyworld) as "arguments" in favor of the Gaia hypothesis: the empirical examples were for geochemists and climatologists, Daisyworld was for evolutionary biologists. Clearly, for Lovelock, "Gaia" was the name of a hypothesis (and then a theory), that is, a general proposition which can make predictions and can be *tested* against empirical facts. A particular emphasis on Gaia as a theory or hypothesis was brought by Lovelock in the early 1990's[30], after the famous critiques made by the geomorphologist James Kirchner in his Popperian lecture. Kirchner distinguished four or five different formulations of the Gaia hypothesis. He then argued that the weaker versions were trivial, and the stronger ones were not testable.

After the 1990's, the development of the Gaia theory continued, focused on the elaboration of new versions of Daisyworld. Timothy Lenton, now a climate and Earth system scientist, who did his PhD under the supervision of Andrew Watson (and Lovelock), pursued this development with Watson and a team of students in England[31].

Overall, scientists were very much willing to discuss life's influence on rock weathering, DMS influence on climate, and Daisyworld modelling in different specialized journals of (bio)geochemistry, climatic sciences and biological theory. Yet Gaia, as a more general hypothesis or theory, was *not* discussed in specialized journals, as we expect every run-of-the-mill scientific hypothesis to be. The contexts of publications *on Gaia* per se were always *exceptional*: one to three international conferences per decade, a general paper in *Nature* and *Science* in some occasions, special issues of *Climatic Change*, books, but not regular discussion in *specialized* journals such as, say, *Geochemistry, Geophysics, Geosystems*. Scientists normally don't write books to discuss and test run-of-the-mill scientific hypotheses. But it is thanks to books that Lovelock was mostly known for Gaia and through which Gaia was criticized.[32]

Gaia, the great research program

For Lovelock, Margulis, and other Gaia supporters, Gaia was not *only* the name of a hypothesis to be tested with empirical arguments and elaborated with mathematical models, but that of a research program or a paradigm, a new discipline, a new way of doing science, of viewing and studying the world. Rather than talking about "Gaian science" they tried several terms such as "geophysiology" or "geognosy." Gaian science or geophysiology were often compared, contrasted or opposed to other names of established scientific *disciplines*: geochemistry, biogeochemistry, chemical oceanography, microbial ecology, ecology, environmental science.

This research program made explicit methodological claims. The first claim was that the influence of living beings on their geological environment must be recognized and taken into account. In the 1970's, this claim was addressed to Earth scientists. They were accused of only considering rocks and chemistry and neglecting the pervasive influence of living beings. Then, beginning in 1983, Lovelock started to criticize the notion of adaptation. He argued that the fit which exists between life and its environment could be the result of life's influence on its geological environment, rather than the result of organisms adapting to their environment.

The second methodological claim was that Earth should be studied "as a system," "as a whole," or with a holistic and not a reductionist perspective. Lovelock and Margulis lamented over the separation between life and Earth sciences, as well as the splitting of the Earth sciences into atmospheric chemistry, climatology, fluid dynamics, study of rocks, etc. On many occasions they used Gaia as the name of a revolutionary way of doing science, that resolved the two centuries long divorce between biology and geology. All these entities of Earth's surface, such as rocks, bacteria, soils, chemical compounds of the oceans and atmospheres, were to be studied into one unified science.

These methodological claims rapidly turned into historiographical claims: for its authors, the emergent "Earth System Science" were Gaia's research program with another name. Earth System Science emerged in the 1990's and 2000's with new departments, institutes, centers, chairs and textbooks of Earth System Science out of the institutional work carried out by NASA and then the International Geosphere-Biosphere Program (IGBP) in the 1980's. Earth System Science was not so much conceived as a new scientific discipline, but as an entirely new and revolutionary way of looking at the Earth and of organizing the Earth sciences in an interdisciplinary fashion. Its central aim was:

> To describe and understand the interactive physical, chemical, and biological processes that regulate the total Earth system, the unique environment that it provides for

> life, the changes that are occurring in this system, and the manner in which they are influenced by human actions.[33]

Interestingly, even those sceptical about Gaia as a hypothesis, or wary of some of Lovelock's environmental and political claims, such as Stephen Schneider and Ann Henderson-Sellers, credited Lovelock with having brought climatologists' attention to the pervasive influence of life on Earth's history. Ecosystem ecologists, such as Eugen Odum, who shared a cybernetic and systemic framework with Gaia theory, also pointed to Gaia's important role in emphasizing life's influence on planetary chemical cycles and in contributing to the emergence of global ecology.[34] And so did the founders of a new field, "geobiology", studying the interactions between the history of life and its environment, a research agenda departing from the one of the paleobiology of the 1970's.[35]

Most importantly, major actors of Earth System Science acknowledged Gaia's decisive role in calling scientists' attention to the existence of a new object of study: the "Earth System."[36]

Gaia, philosophy of nature and environmental prescriptions

Finally, Gaia was also for Lovelock the name of a philosophy of nature:

> [Gaia] is an alternative to that pessimistic view which sees nature as a primitive force to be subdued and conquered. It is also an alternative to that equally depressing picture of our planet as a demented spaceship, forever travelling, driverless and purposeless, around an inner circle of the sun. [37]

The first sentence opposes our modern view of nature inherited from Bacon and Descartes.[38] The second opposes the metaphor of the spaceship Earth, very popular in the 1970's, conceiving the Earth as a vessel, which environmental problems ought to be managed by experts.[39] Though, again, Lovelock is not anchored in a literary philosophical tradition, there is no doubt that Gaia was to propose a reconception of important and related concepts which were: life, nature, the environment. And certainly his philosophy of nature is not to be found in his explicit reflections over the categories of life and nature, but in the tacit assumptions he made while building models, in what needs to be taken for granted to engage in the research questions he envisaged.

To address Gaia as a philosophy of nature, the relevant attitude is not to "test" it against empirical facts. It is not to argue about the priority of such and such scientific issues or about the way scientific institutions should be organized, as it was for Gaia as a research program. It is to embrace and elaborate Gaia's categories and worldviews or to reject and dismiss them.

Another attitude one can adopt is to make explicit Lovelock's metaphysics, ontology or categories and to contrast them with other ways to think about nature, life, and the world. And here again, Gaia found important echoes. The anthropologist and philosopher Bruno Latour sketched a symmetry between the way Galileo has contributed to overthrow Aristotelian conception of the cosmos and to make us consider alike the physical properties of terrestrial bodies and of celestial bodies, and the way Lovelock has, conversely, managed to render the Earth so peculiar and local in the Solar System, influenced as it is by living entities.[40]

For conservative environmentalists such as Edward Goldsmith, Gaia was truly to be thought as an organismic ordered whole: not to follow the "natural rules" of this ordered whole should be seen as something deeply wrong.

But for Lovelock also, ever since the 1970's, Gaia has not only been a grandiose view of life on Earth but also a framework to think about the very concept of pollution, from which he derived many practical and concrete environmental and political prescriptions. In the 1970's, against the (green) current, he opposed to the ban of CFCs responsible for ozone's hole; he has long been actively militating for nuclear energy; and in the recent years, he has been criticized for taking radical positions ranging from the suspension of democracy and human rights to the proposition of geoengineering techniques going through a more or less voluntary reduction of the world's population.

Interestingly, in the three emblematic critiques made *by scientists* to the Gaia *hypothesis* – that of Doolittle and Kirchner in the 1980's, and of Tyrrell in his 2013 book – Lovelock's environmental and political prescriptions made in Gaia's name were mentioned as *the* central nerve and as the reason why it mattered whether Gaia hypothesis was "right or wrong", "true or false". And many supporters of the Gaia *hypothesis* or *research program*, and even way of thinking about nature, found difficult to follow Lovelock's "Gaian" environmental prescriptions.

Conclusion

The Gaian literature is vast, with enthusiasts and critiques, talking about rich and complex issues in very different domains. Gaia was not initially addressed to evolutionary biologists, but to geochemists. The very ambiguity of what Gaia meant had an important role in Gaia's pervasive diffusion and is what makes Gaia so rich and interesting. Lovelock, in the same papers and books, used the word "Gaia" to refer to very different things: a hypothesis, about which you can argue with empirical arguments and mathematical models, dealing with the peculiar influence that life may have had over Earth's history on its geological environment; a research program guiding and imposing the way Earth and life sciences should study Earth's chemistry, climate and living beings; a philosophy of nature challenging our modern conceptions of life and nature. While dismissed as a problematic hypothesis, Gaia has been credited by Earth scientists for its role as fostering new research programs, such as those in the Earth System Science.

Certainly the most decisive and revolutionary contribution of the Gaia hypothesis was an ontological one. Gaia has called for the recognition of a new entity: the system composed of the entire life and the geological environment with which it interacts. It was the the recognition of this new entity, which laid the ground for a new research program in the Earth sciences and offered a new framework to think about nature. Gaia has been central to our contemporary accepted view of the Earth as a planetary system of interrelated entities, teeming with life, but also that of a planet with its stable states which can be overthrown, as is now dramatically pictured by the anthropocene discourse.

Further reading:

Steven Dick and James Strick, *The living Universe: NASA and the development of astrobiology* (New Brunswick: Rutgers University Press, 2004).

Bruno Latour, *Face à Gaïa: huit conférences sur le nouveau régime climatique* (Paris : La Découverte, 2015).

Timothy M. Lenton and Andrew Watson, *Revolutions that made the Earth* (Oxford: Oxford University Press, 2011).

Michael Ruse, *The Gaia Hypothesis - Science on a Pagan Planet* (Chicago: Unversity of Chicago Press, 2013).

Toby Tyrrell, *On Gaia: A Critical Investigation of the Relationship Between Life and Earth* (Princeton: Princeton University Press, 2013).

Notes

1 Exhibition "Unlocking Lovelock: Scientist, Inventor, Maverick", *Science Museum*, London, 2014.

2 James Lovelock. *Gaia: A new look at life on Earth* (Oxford: Oxford University Press, 1979), 11.

3 Stephen Jay Gould, *The structure of evolutionary theory* (Cambridge,

MA: Harvard University Press, 2002), 612.

4 John Postgate, "Gaia gets too big for her boots," *New Scientist*, 1988.

5 James Lovelock, "A physical basis for life detection experiments", *Nature*, 207 (1965): 568. The most detailed historical account of the constitution of exobiology, and of Lovelock's place in this adventure is provided by Steven Dick and James Strick, *The living Universe: NASA and the development of astrobiology* (New Brunswick: Rutgers University Press, 2004).

6 Lovelock, *Gaia.*

7 James Lovelock and Lynn Margulis "Atmospheric homeostasis by and for the biosphere: the Gaia hypothesis," *Tellus*, 26 (1974): 3.

8 Lovelock, *Gaia.*

9 See Michael Ruse, *The Gaia Hypothesis - Science on a Pagan Planet* (Chicago: Unversity of Chicago Press, 2013) with the important following caveat: Ruse presents Lovelock as a typical cartesian, yet, cybernetics and system thinking – Lovelock's disciplinary matrix – have often been considered at odd with typical cartesian science.

10 Margulis introduced Gaia to Doolittle and suggested him to publish his review of Lovelock's book in *Coevolution Quarterly*,

which Doolittle did not know (Doolittle, personal communication). Stewart Brand heard of Gaia through Margulis, thanks to her ex-husband, Carl Sagan (Brand, personal communication).

[11] Ford W. Doolittle, "Is nature really motherly," *CoEvolution Quarterly*, 29 (1981) : 58; Richard Dawkins, *The extended phenotype: The gene as the unit of selection* (Oxford: Oxford University Press, 1982).

[12] Oren Harman, *The price of altruism: George Price and the search for the origins of kindness* (London: Vintage books, 2011).

[13] In his recent book, Ruse, *Gaia hypothesis*, shows in details how violent the reaction to Gaia was. But by focusing on Gaia's reception *in evolutionary biology*, he neglects the scientific disciplines in which Gaia was meant to contribute: geochemistry and Earth sciences, cf. Sébastien Dutreuil "Review of: Michael Ruse, *The Gaia hypothesis,"History and Philosophy of Life Sciences* 36 (2014): 149.

[14] See Gould, *Structure*, 612 and Richard C. Lewontin, *Biology as ideology: The doctrine of DNA* (Ontario: Anansi Press, 1995), 18.

[15] James Lovelock, *Homage to Gaia: the life of an independent scientist* (Oxford: Oxford University Press, 2000), 2.

[16] On scientific entrepreneurs, see Steven Shapin, *The scientific life: a moral history of a late modern vocation* (Chicago: The University of Chicafo Press, 2008).

[17] Lovelock, *Hommage*, 38.

[18] Lovelock, *Hommage,* 192.

[19] James Lovelock, R.J. Maggs, and R.J. Wade, "Halogenated hydrocarbons in and over the atlantic," *Nature*, 241(1973): 194..

[20] Mario J. Molina and Frank S. Rowland, "Stratospheric sink for chlorofluoromethanes: chlorine atom-catalysed destruction of ozone" *Nature*, 249 (1974): 810.

[21] James Lovelock, R.J. Maggs, and R.A. Rasmussen, "Atmospheric dimethyl sulphide and the natural sulphur cycle," *Nature*, 237 (1972): 452.

[22] In a letter to Arnold Kotler he confesses to scarcely read besides fiction, and most of his intellectual debts go to oral discussion rather than to written materials.

[23] Frank N. Egerton, "Changing concepts of the balance of nature," *Quarterly review of biology*, 48 (1973): 322.

[24] Robert M. Garrels, Abraham Lerman, and Fred T. Mackenzie, "Controls of atmospheric O2 and CO2: past, present, and future," *American Scientist*, 64 (1976): 306.

[25] Stephen H. Schneider, "A goddess of the Earth: The debate on the Gaia Hypothesis," *Climatic Change*, 8 (1986): 1.

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[31] Timothy M. Lenton and Andrew Watson, *Revolutions that made the Earth* (Oxford: Oxford University Press, 2011).

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[33] This is an iconic statement of the first report of the IGBP , *The International Geosphere-Biosphere Programme: A Study of Global Change. Final Report of the Ad Hoc Planning Group, ICSU 21st General Assembly, Berne, Switzerland 14-19 September,* 1986, 3, chaired by the famous swedish meteorologist Bert Bolin, Editor-in-Chief of the journal *Tellus* which published the iconic Lovelock and Margulis, "Atmospheric homeostasis".

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contemporary geobiology. On geobiology's debt toward Gaia, see Andrew H. Knoll, Donald E. Canfield, and Kurt O. Konhauser, *Fundamental of geobiology* (Oxford: Wiley, 2012).

[36] The details of the historical relations between Gaia and Earth System science cannot be fully sketched here – for details see Dutreuil, *Gaïa* (PhD, 2016). It would require a detailed history of various separated disciplines in which Earth System Science finds its roots from 1950's to the 1970's: ecosystem ecology, climatology, biogeochemistry, systems theory but also the geochemistry and Earth's history of Robert Garrels and Heinrich Dick Holland. On NASA, Earth System Science and Gaia, see Erik M. Conway, *Atmospheric science at NASA: a history* (Baltymore: John Hopkins University Press, 2008). On Earth System Science and IGBP, see Chunglin Kwa, "Local ecologies and global science discourses and strategies of the International Geosphere-Biosphere Programme," *Social Studies of Science*, 35 (2005): 923; Ola Uhrqvist, "Seeing and knowing the Earth as a system: an effective history of global environmental change research as scientific and political practice" (PhD diss., University of Linköping, 2014).

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[38] Carolyn Merchant, *The death of nature: women, ecology and the scientific revolution*, (New York: Harper, 1980).

[39] Sebastian Grevsmühl, *La Terre vue d'en haut: l'invention de l'environnement global* (Paris : Seuil, 2014) ; Robert Poole, *Earthrise: How man first saw the Earth* (New Haven: Yale University Press, 2008).

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