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What Exactly Is the Role of Gaia?

Timothy Lenton and Sébastien Dutreuil

The Providential Story: No Role for Gaia

We have become accustomed to the following story about life on Earth. We are supposed to live on a planet where providential conditions have endured ever since the origin of life: liquid water has been present at the surface of the Earth; the ozone layer in the atmosphere has protected life from dangerous solar radiation; and the climate has remained within comfortable bounds in spite of the constantly increasing luminosity of the Sun. Compared to the inferno of Venus or the freezer of Mars, Earth has always provided a paradise for life in the solar system, and perhaps in the universe. Whenever fluctuations have occurred, or more dramatic perturbation events took place, such as a meteorite strike in the late Cretaceous or massive volcanic eruptions in the late Permian, life has persisted: former species disappeared, but new ones, with different environmental needs and strategies, emerged. Over the ages, the parameters necessary for life – free energy, abundance of water, pH, pressure, temperature – have remained within the same broad range.

In this familiar story, geology has provided a stage, independent of life's activities, to which life's only duty is to adapt. Earth has been made already habitable by geology. To be sure, some biologists did tell us that local environments can be changed by life – algae can change the chemical composition of a pond, termites can build mounds, and beavers can build dams and change the flow of rivers – but the Earth itself – the atmosphere, the oceans, the crust – is nothing more than the external framework inside which life has to fit.

There are two things in this story that seem very odd. The first is that it transforms the continuity and development of Life on Earth (see Dutreuil, “Gaia Is Alive,” this volume, xxx–xxx) into the result of a miraculous harmony. By chance, or should we say, by providential foresight, geology has made itself “just perfect” as a paradise of organisms. But who created this paradise? Is there a mysterious power above Earth and Life? It is strange that such a miracle could have passed for a scientific argument ...

The second feature is even stranger: if you consider the metabolism of any organism – for instance, one of those termites inside their termite mounds – it's clear that it keeps taking in the chemical compounds on which it thrives, and excreting other chemical waste products. So, any observer of life forms will be tempted to follow the long trail of transformations that metabolism leaves behind – which provides new conditions for other life forms to sustain their own existence. No organism simply sits in its surroundings; it metamorphoses them, so

that the organism ends up fully entangled in the consequences of the metabolism of its predecessors, thus creating a cascade of modifications. If we follow the cascade far and long enough, the idea that an organism resides in an untouched environment becomes ridiculous: what surrounds an organism are all the chemical transformations generated by all the other organisms living before and alongside it. Habitability is a joint venture (Lenton and Dutreuil, “Distinguishing Gaia from the Earth System(s),” this volume, xxx–xxx). The question becomes *how long and how far* are you prepared to go: one termite, one termite mound, many termite mounds?

Well, it turns out that going far and staying awake long enough to do so is the only way to contest the providential account and a fairly good way to respect the specific agency of life forms. On one condition: that you don’t jump too quickly to give a precise role to the agent on stage. Please accept *not* knowing what sort of character it is, and let it be defined not by what it is (or rather what you wrongly believe it is) but by what *it does*. To make sure we don’t mischaracterize this agent, let’s simply call it X. The following is a provisional list of what X does.

X Keeps the Atmosphere Out of Equilibrium

The providential story will have you believe that by an incredible chance the atmospheric composition of gases is just what is needed for life to thrive. It turns out that the atmosphere today is composed of 78% nitrogen (N₂), 21% dioxygen (O₂), only 0.04% carbon dioxide (CO₂), and minor but very chemically significant amounts of methane, hydrogen, nitrous oxide, and other biogenic gases.^[1] James Lovelock is one scientist who found such a story difficult to swallow, and for a good, hard chemical reason: methane and oxygen cannot sit together without reacting (methane with oxygen would produce CO₂ and water). So, Lovelock asked his geological colleagues: How do you explain that the concentration of methane in this oxygen-rich atmosphere is a factor of $\sim 10^{30}$ greater than expected at equilibrium? How can this state so far from equilibrium be maintained through time? An estimated ~ 0.7 TW (the equivalent of around seven hundred nuclear power plants) is required just to maintain the O₂-CH₄ coexistence.

The answer is easy to find and no one disagreed with the result: the methane in the atmosphere is the product of some of the oldest organisms on the planet that we now call archaea, and the oxygen is almost entirely produced by cyanobacteria, algae, and plants in the process of (oxygenic) photosynthesis. Without them, surface concentrations of oxygen would be around 1 part in 10^{12} (1,000,000,000,000) of the atmosphere, rather than 1 part in 5.

Production of oxygen by Life ($\sim 10^{16}$ molO₂/yr) is over 4 orders of magnitude (10,000) larger than from purely physical and chemical processes ($\sim 4 \times 10^{11}$ molO₂/yr). Thus, while the total amount of oxygen in the atmosphere is massive (3.7×10^{19} mol), it is all processed through life forms roughly once every four thousand years. So here is a nice case of life forms breathing what is in effect the excretion of other life forms. Oxygen is to organisms what the termite mound is to all the beings inside it: not an “environment,” but the byproduct of other organisms inside which they find themselves entangled.

Another byproduct that the providential story takes as a given is the protective ozone layer itself, since it is fairly obvious that without abundant dioxygen (O₂) there would be no ozone (O₃) and no ozone layer. It is an entirely biological product that surrounds all life forms, offering a sort of protecting envelope that is under the control of the life forms themselves.

The comparison is even more striking when the amount of oxygen is taken into account. If there is too much oxygen, everything burns; too little, every aerobic organism dies. And yet oxygen has always remained within 17–25% of the atmosphere for the last 400 million years. There must be something counteracting changes in oxygen level. In one incarnation of this adjustment, fires suppress vegetation and transfer phosphorus from the land to the ocean, where less oxygen is produced per atom of phosphorus. In a different variant, fires suppressing vegetation also suppress phosphorus weathering, thus limiting oxygen production. Whatever the exact model, we have to consider that what appears as “outside” – the atmospheric conditions of all other life forms – is, strangely enough, “inside” some sort of envelope, what we call, for want of a better term, a feedback.

Although everyone today is rightly concerned by the amount of CO₂ released by human industry, what is rather extraordinary – but not miraculous! – is actually its scarcity. It’s another key feature of the disequilibrium of Earth’s atmosphere when compared to Mars and Venus, which have atmospheres dominated by CO₂. If the atmosphere were just a stage offered to the actions of organisms, atmospheric CO₂ would be an estimated ~10- to 100-fold higher. Here again, a feedback is visible where life forms, over billions of years, have turned CO₂ from a dominant component of the atmosphere to a trace gas. Firstly, they have locked up organic carbon in sedimentary rocks, including the vast quantities of coal and oil that are the remnants of past living organisms. Secondly, they have accelerated the weathering of continental silicate rocks, like granite, and combined the alkaline ions (Ca²⁺, Mg²⁺) thus liberated with CO₂ to form new carbonate sediments ((Ca,Mg)CO₃) – locking up atmospheric CO₂.

This is what makes the providential story so improbable: without the very activity of life forms, Earth's atmosphere would be closer to chemical equilibrium, much richer in CO₂, would contain barely any O₂, and would even have greater atmospheric pressure because living beings have progressively locked up its main constituent, N₂. A story using geology as a stable frame for organisms that do nothing in it would mean only one thing: planet Earth would be simply uninhabitable, just as Venus and Mars are. Organisms have given a new twist to the saying "God (or rather Geology) helps only those who help themselves."

X Is Not Very Visible and Has a Strange Way of Looking Big

Don't forget that the only way to escape the providential story is not to jump too fast to a conclusion and shout: "I know who the culprit is!" This is not a whodunit. And for one good reason: when we suggest that organisms have played this role in creating the livable conditions of their successors, the risk is that readers will imagine that these organisms are amazingly powerful and fully united as one single agent. None of this is true. Again, no Providential God/Geology is at work. The proof is that, if we collect elementary numbers to give some scale to the activity of life forms compared to those attributed to the activity of the Sun, the life forms appear to have a minuscule presence.

It's convenient to give a scale of the life forms' activity by measuring it in terawatts (TW), much as we do when measuring a power plant. (To give an idea of the scale, humans run their civilization at around 17 TW and mantle convection is driven by an estimated 12 TW.) To put this in context, the total free energy input or power supply for organisms is ~264 TW. But this is nothing compared to the radiative energy balance of the planet, which absorbs ~120,000 TW, ~80,000 TW of which is at the surface. In their 4.5 billion years of history, organisms managed to capture through photosynthesis only about 1% of the solar energy reaching the Earth's surface, and to convert only ~0.3% into usable chemical energy. Around half of this is respired by the photosynthesizing organisms, and the other half provides food supply (net primary production) to all the other life forms.

So, however you imagine X to act, don't grant it too grandiose a role. Organisms don't occupy all the stage. Put together, they are of a comparable magnitude to the ~900 TW power supply available from atmospheric circulation and run at least at three times the surface power supply from Earth's internal heat source. If nonetheless, life forms have managed to have the effects mentioned earlier, you have to imagine that they have spread "everywhere" in time and space but in a very odd manner, much like a network, impressive by its extension, not by its surface.

Such an original way of playing a role is even more striking when considering that, according to the providential story, Earth is not even able to provide enough elements for organisms to survive on. What a strange sort of Providence: left to its original frame, organisms would be famished! They are composed mainly of carbon, hydrogen, oxygen, nitrogen, sulfur, phosphorous, and minor quantities of other elements. The inputs of these essential elements to the Earth's surface are generally meager compared to their total requirements. Thus, they had to devise ways to artificially increase the inputs of the essential elements they need. The solution resembles the tactic of film directors wanting to shoot a whole battle scene on a tight budget: they have to ask the same actors to pass by many times over to give the impression of a large crowd. This is called recycling: the waste of one metabolism is the food of another.

We begin to grasp the source of the efficiency of life forms when we compare the disproportion between the amount of ingredients available at the start and the immensely larger amount organisms have access to today. The difference between the two figures gives a rough idea of the number of times the same element is being recycled. In the end, the lone actor has indeed become an army! The measure is given here in the number of atoms (moles) available per year.

Carbon is the backbone of life's chemistry: photosynthesis reduces atmospheric CO_2 into organic matter, and respiration releases it back to the atmosphere. These biological fluxes of carbon ($\sim 10^{16}$ molC/yr today) are around *four hundred times* larger than the inputs/outputs of carbon to/from the solid Earth ($\sim 2.7 \times 10^{13}$ molC/yr).

Nitrogen is abundant in the atmosphere but in a nearly inert form (N_2). Yet, certain bacteria can nonetheless split N_2 and fix nitrogen into organic matter (at great energetic cost). The resulting supply flux ($\sim 1.5 \times 10^{13}$ molN/yr) of biologically available nitrogen (NO_3^- and NH_4^+) is around *forty times* the abiotic source from lightning strikes ($\sim 0.35 \times 10^{12}$ molN yr⁻¹). Nitrogen uptake in net primary production ($\sim 1.5 \times 10^{15}$ molN/yr) is a further *one hundred times* larger indicating organisms recycle nitrogen around a hundred times before denitrification returns it to the atmosphere, or it is buried in sediments. Organisms are responsible for all the key transformations in the nitrogen cycle, making it an essentially biological cycle.

Phosphorus has no significant gaseous form; its abundance in the crust is modest, and biologically available phosphorus all ultimately derives from continental chemical weathering. Phosphorus is preferentially weathered, relative to the bulk rock matrix, by biological innovations including organic acid production and selective dissolution of P-rich

mineral inclusions (apatite) in rocks. Conceivably, organisms at least double the bio-available phosphorus input ($\sim 4 \times 10^{10}$ molP/yr). Still, phosphorus uptake in net primary production ($\sim 5 \times 10^{13}$ molP/yr) is more than *one thousand times* larger, indicating a corresponding global recycling ratio, higher than that of nitrogen and consistent with the accepted notion that phosphorus is the “ultimate limiting nutrient.”

Sulfur is widely used by Life in varying and remarkably poorly known proportions, with C:S ranging over ~ 50 – 200 for marine phytoplankton, and up to ~ 300 – 600 for terrestrial plants. The corresponding uptake of sulfur in net primary production ($\sim (0.3\text{--}1.2) \times 10^{14}$ molS/yr) is ~ 10 – 40 times the supply ($\sim 3.2 \times 10^{12}$ molS/yr) from the solid Earth.

If organisms had not twisted the system to “help themselves” against the miserly allocation granted them by the providential story, the cycling of carbon, nitrogen, phosphorus, and sulfur within the surface system would be small. With recycling, however, organisms have increased their total productivity by at least a *thousand-fold* more. This is why the role of X is so difficult to pinpoint: on the one hand it’s nothing, but on the other it’s amazingly big.

X Expands Its Control Quite Far

If we follow the cascade of metabolism far and long enough, we begin to suspect that what the providential story takes as its starting point – Earth’s habitability provided by water and geology – might actually not be a given at all. Once again, most of the activity attributed to the outside framework might be the result of those very organisms which were supposed to simply “adapt to their environment.” This is probably the case for the major condition of existence, namely water. Who or what is doing the job of keeping it in place?

By some estimates, an Earth without Life (and its lowering of CO₂) would be very close to – and might already have passed – the threshold of having a “moist greenhouse” (pressure-cooker) atmosphere – with surface temperatures > 50 °C. In this runaway transition, increased water vapor in the atmosphere traps more heat radiation, further increasing water vapor. The wet atmosphere would then lose its water – through hydrogen loss to space – ultimately making the planet uninhabitable. Organisms have also helped retain water by producing the oxygen-rich atmosphere, the ozone layer, and the resulting strong thermal stratification of the “stratosphere,” which creates an effective “cold trap” at the tropopause that prevents water from reaching the upper atmosphere where it can be split apart and its hydrogen lost to space. Thus, water is not just “there”; it is kept in place by life forms.

The same misattribution of agency might have occurred about the rock framework implied in the canonical story. Organisms seem to have an uncanny ability to make their own rock as well as to keep their water and provide their own atmospheric conditions. It is well known that many rocks are biological products, such as the white chalk cliffs of south England and northern France, and limestone more generally. In fact, a large fraction of the diversity of Earth's 4,300 minerals are either biologically precipitated or require oxygen (a biological product) in their creation and hence would not exist without life forms.

Since they have spread over all of Earth's surfaces, living things have affected the surface color and reflectivity (albedo) and hence affected the total amount of solar radiation absorbed at the surface. Vegetation generally lowers land surface albedo, particularly in the boreal high latitudes. Phytoplankton in the upper layer of Earth's oceans generally lower ocean surface albedo. So, without such life forms, Earth's surface would be paler and different in color. Clouds, in contrast, would be darker. Overall the planet would probably be less reflective, and there would probably be less aerosol scattering by the atmosphere – meaning less dramatic sunsets! This is how X manages to expand everywhere while not being very easy to spot.

There is nothing miraculous in this alternative story; you just have to pursue longer and in vaster aggregates what is so clearly visible at a smaller scale and for a limited range of organisms. For example, just as plants have contributed over hundreds of millions of years to maintaining the overall conditions in which they could thrive, over a shorter period of time, living beings can also contribute to regulating the climate and to maintaining their own conditions of existence. It is very well known that there would not be enough rain to maintain the Amazon rainforest without the actions of the forest itself: through evapotranspiration, bringing soil water up into the atmosphere, the Amazon rainforest contributes to maintaining the precipitation it needs to thrive. In the long run, therefore, plants have not *adapted* to a given climate: they have contributed to *maintaining* a climate in which they can persist.

It has also been argued that planktonic calcifying organisms – the ones that produced the carbonate shells that made limestone cliffs – have stabilized the carbon cycle by buffering the carbonate-ion concentration in the oceans. Their evolution during the Phanerozoic may thus have prevented the return of catastrophic “snowball Earth” events that occurred earlier in Earth's history – in which the entire surface of the Earth was frozen over. All of this is supported by recent modeling that has captured the interacting effects of water vapor, CO₂, and N₂, which suggests the “habitable zone” would be disappearing in the absence of the organisms that have broadened it considerably.

More fundamentally, organisms may have altered even the planet's rock cycle. They clearly have the energetic potential to do so since, as we saw, the current power supply of Life (264 TW) exceeds the power driving mantle convection (~12 TW) by a factor >20, and that driving crust cycling (26 TW) by a factor of ~10. It also exceeds the work done by the atmospheric heat engine in physical weathering (<50 TW) and sediment transport (<13 TW).

Recently it has been hypothesized that by permeating the seafloor crust, early life forms hydrated it and thus started the formation of micro-continents around four billion years ago. The production of the continental crust as granites required hydration of the oceanic crust. This effect could have been energetically limited prior to the evolution of oxygenic photosynthesis, which greatly increased the power supply to life forms. The onset of modern-style plate tectonics ~3.0 Ga is at least consistent with current evidence for the timing of the origin of oxygenic photosynthesis. Hence, the link between organisms and continent formation is energetically plausible, and if corroborated would represent one of the most extraordinary consequences of Life. Organisms able to provide their own continents – that, for sure, does not fit in with the story of passive passengers having to survive “inside” an environment.

Gaia Is the Name of This Cascade of Entangled Metabolisms

The usual path of scientific reasoning is to avoid miraculous explanations as much as possible. The problem with the providential story we have disputed is that it implies that some mysterious power from above has maintained a harmony between its geological framework and the multitude of organisms “adapting” to it. We now understand that an alternative narrative may be offered by granting some agency back to the multitude of organisms, each generating unwanted consequences – positive as well as negative – for its successors and partners. Each modifies the habitability range of the others. Although this is easy to follow at the local level – termites produce their own termite mound environments – a split has occurred among scientists when they study things at larger scales: then, they strangely separate what organisms have done and where they live. Hence the appeal to a providential harmony to reconvene the two.

To avoid such a reliance on Providence, it is sufficient to follow the cascade of entangled organisms as far and as long as possible. Then, habitability, far from providing a given framework, turns out to be the partial product of all its inhabitants. Taken together, life forms can be called “Life” with a capital L (see Dutreuil, “Gaia Is Alive,” this volume, xxx–xxx), which includes organisms *and* the long trail they leave on the previous conditions they

started with. Life's massive impact on its environment leads to complex interactions and interdependencies. Thus, Lovelock's and Margulis's realization that Life massively alters its environment led them to suggest that a new entity is formed by the interactions between Life and its consequences – Gaia – and that this “influence” may not be “for nothing”: it accounts for the very survival and thriving of Life itself. Through a strange twist in the history of science (see Dutreuil, “Gaia Is Alive,” this volume, xxx–xxx), it was Lovelock's and Margulis's vision that has been accused of appealing to some mystic entity, when it was, on the contrary, a fairly down-to-earth theory to *counteract* the providential story.

The myth that Life is just a passive actor adapting to a stage set by physical, chemical, and geological processes has exploded in the face of the knowledge summarized here. With just a tiny fraction of incoming solar energy, Life has largely freed itself from the constraints imposed by physical, chemical, and geological processes, principally by cycling the chemical elements it needs within the Critical Zone. Life has changed Earth's atmospheric composition, distribution of clouds, land and ocean surface color, and climate. Life has also contributed to the retention of water on the planet and may even have contributed to producing the continental crust beneath our feet. Earth is widely recognized as a unique planet in the solar system because it shelters three singularities: Life, liquid water at the surface, and plate tectonics comprising both oceanic and continental crust. Usually the causality is seen as flowing in only one direction – from rocks and water to life. Instead, it may be flowing in both directions.

References

[1] All references to precise data cited here are to be found in Timothy M. Lenton, Sébastien Dutreuil, and Bruno Latour, “Life on Earth Is Hard to Spot,” *The Anthropocene Review* (forthcoming). To learn more about the figures listed here, see also Timothy Lenton, *Earth System Science: A Very Short Introduction* (Oxford: Oxford University Press, 2016); and Timothy M. Lenton and Andrew Watson, *Revolutions That Made the Earth* (Oxford: Oxford University Press, 2011).