INSIGHTS

PERSPECTIVES

SUSTAINABILITY

Gaia 2.0

Could humans add some level of self-awareness to Earth's self-regulation?

By **Timothy M. Lenton**[1] *and* **Bruno Latour**[2]

According to Lovelock and Margulis's Gaia hypothesis, living things are part of a planetary-scale self-regulating system that has maintained habitable conditions for the past 3.5 billion years (*1*, *2*). Gaia has operated without foresight or planning on the part of organisms, but the evolution of humans and their technology are changing that. Earth has now entered a new epoch called the Anthropocene (*3*), and humans are beginning to become aware of the global consequences of their actions. As a result, deliberate self-regulation—from personal action to global geoengineering schemes—is either happening or imminently possible. Making such conscious choices to operate within Gaia constitutes a fundamental new state of Gaia, which we call Gaia 2.0. By emphasizing the agency of life-forms and their ability to set goals, Gaia 2.0 may be an effective framework for fostering global sustainability.

At first sight, the potential for a successful Gaia 2.0 does not seem promising. Despite large-scale mobilization of scientists, activists, and citizens, large parts of the human population are indifferent to the Anthropocene, and many deny anthropogenic climate change (*4*). In addition, there is no proof that consciousness in this context is anything but the belated and retrospective realization that mistakes had been made and might be partially redressed. Indeed, the first formulation of the Gaia hypothesis (*1*) is almost exactly contemporary with what is now seen as the start of the Anthropocene (*3*). Furthermore, the examples of social Darwinism, sociobiology, and dialectical materialism suggest that drawing political lessons from nature is problematic.

Nevertheless, it is important to have a second look at the connection between the original Gaia concept and a possible Gaia 2.0, because the original Gaia has many traits that were not detectable in earlier notions of nature associated with the development of Western civilization. Before the Anthropocene, Western societies saw themselves as the only conscious agents in a passive material environment. Today, they must cope with the brutal reactions of living organisms that are continually reshaping their surroundings, creating in part their own conditions for survival (*4*, *5*). Gaia thus establishes a new continuity between humans and nonhumans that was not visible before—a relation

The commercial Earth observation satellite WorldView-4 has been providing high-resolution imagery since its launch in 2016 from Vandenberg Air Force Base in California.

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[1]*Global Systems Institute, University of Exeter, Exeter EX4 4QE, UK.* [2]*Sciences Po, 75337 Paris Cedex 07, France. Email: t.m.lenton@exeter.ac.uk*

between free agents (*4*). This understanding offers the potential to learn from features of Gaia to create a Gaia 2.0. We focus here on three of these features: autotrophy, networks, and heterarchy.

AUTOTROPHY

Autotrophs use free energy to continually remake themselves out of simple substances that are present in their surroundings. Earth's surface, where most of the biosphere resides, is a very nearly materially closed system. Hence, like an autotroph, the collective flourishing of life for the past 3.5 billion years has depended on the internal recycling of materials, powered by solar energy (*6*). The origin of these material recycling loops is at least partially understood (*7*). There needs to be a source of free energy to support recycling, which usually comes from the Sun and enters the system via photosynthetic primary producers. Recycling is built on metabolic by-products, with one organism's waste becoming another's food. Closure of a recycling loop triggers a self-perpetuating feedback process: The participants in the recycling loop are no longer limited by what comes into their world, but rather by how efficiently they can recycle resources. For example, coral reefs and the Amazon rainforest thrive on recycling in otherwise low-nutrient conditions.

If, by contrast, we consider the state of the technosphere in the Anthropocene (*5*), an audit made by Gaia would question the purported quality of many innovations and note that from an engineering standpoint, they perform poorly. Humans currently extract fossil energy, rock phosphate, and other raw materials from Earth's crust far faster than they would normally come to the surface, and then dump the waste products on land, in the atmosphere, and in the ocean. Compared to Gaia, this is a very poorly coupled and unsustainable set of inventions.

This does not mean that humans should stop inventing, but rather that engineering should shift attention to become as smart as Gaia in achieving nearly closed material cycling powered by sustainable energy. The input of solar energy has the potential to far outstrip current fossil energy consumption, and renewables are rapidly becoming cost-competitive with fossil fuel energy for electricity generation (*8*). There should thus be no long-term shortage of energy. The challenge is to design and incentivize a transition to a circular economy. As in the original Gaia, this must be built on waste products becoming useful resources to make new products. Despite practical obstacles and thermodynamic constraints, there is huge potential to increase material recycling in Gaia 2.0 (*9*).

NETWORKS

Gaia was built by adaptive networks of microbial actors that exchanged materials, electrons, and information (*10*), the latter through ubiquitous horizontal gene transfer. These microbial networks form the basis of the recycling loops that make up global biogeochemical cycles. Functional roles in these networks have been retained even when the taxa performing them were replaced (*11*). Therefore, sufficient biodiversity to provide functional redundancy contributes to the robust self-regulation of Gaia.

Microbial networks also created long-lived products that sometimes accumulated globally—notably oxygen in the atmosphere. This in turn facilitated an increase in the diversity of life and metabolisms and enabled the evolution of new levels of biological organization and connectedness (*6*), with new mechanisms of coordination. Humans and our adaptive social networks are the latest realization of this process.

In Gaia 2.0, horizontal transfer of information, functional diversity with redundancy, and distributed control will likely be important to a successful circular economy. The challenge is to support diverse, autocatalytic networks of human agents that can propel transformations toward goals such as sustainable energy, fueling the efficient cycling of resources. This is particularly challenging given a social and economic paradigm of short-term localized gain and relatively weak global, unifying, long-term structures to counteract this paradigm.

HETERARCHY

Depending on the scale and time span considered, completely different mechanisms are at work within Gaia (*7*). This heterarchy is particularly visible in the climate regulation that has received so much political attention of late. Some of Earth's climate self-regulation mechanisms (*6*) are purely physical and chemical, but many involve biology. On time scales of hundreds of thousands of years, changes in global temperature are counteracted by biologically amplified changes in the removal of CO_2 by silicate weathering. On intermediate time scales of millennia, the dissolution of carbonate sediments on land and the ocean floor increases CO_2 storage in the ocean. On even shorter time scales of years to centuries, land and ocean carbon sinks roughly halve the rate of CO_2 rise and climate change.

Thus, each mechanism in Gaia has its own capacity for resistance and expansion. Natural selection can only help to explain environmental regulation at small scales of space and time (*7*). At large space and time scales, simpler dynamical mechanisms are at play (*7*): Systems that find self-stabilizing configurations tend to persist (*12*), and systems that persist have a greater likelihood of acquiring further persistence-enhancing properties (*11*, *13*). Through these cruder selection mechanisms, Earth may have acquired and accumulated stabilizing feedback mechanisms involving life (*7*).

The upshot is that Gaia's self-regulation of climate is probably fairly crude compared to its efficient recycling of resources. The recent glacial-interglacial cycles indicate that the climate system can be quite unstable and thus vulnerable to human interference, which has already increased atmospheric CO_2 to levels last seen 3 to 5 million years ago. This heterarchy of mechanisms of different reliability makes the task of Gaia 2.0 to restabilize the climate especially daunting. Simultaneously, humans are altering nutrient cycles relatively more than the carbon cycle, posing an additional challenge for Gaia 2.0 to restabilize nutrient cycling.

Implementation of alternative forms of climate control to reduce production of CO_2 or augment existing feedbacks (*14*) depends on who is in charge of such voluntary activity. The results would clearly be different if the Intergovernmental Panel on Climate Change, President Putin, the California legislature, or President Trump had their finger on the proverbial thermostat. In reality, all these agents and many others have some grip on the thermostat, and their combined effect is not simple to predict.

POLITICS

Drawing a parallel between the original Gaia concept and a possible Gaia 2.0 gives an occasion to reevaluate our collective goals, as well as the means of achieving them. A central goal for this century is surely to achieve a flourishing future for all life on this planet, including a projected 9 to 11 billion people. Human flourishing is not possible without a biodiverse, life-sustaining Earth system. This is recognized in the United Nations' 17 Sustainable Development Goals. But achieving those goals requires that human societies exercise self-aware self-regulation (*14*).

Yet, maintaining a self-regulating, human life–supporting planet is not the primary goal of some dominant modes of collective human activity today. Despite a flood of monitoring information, present industrial societies seem less able to track changes in their environment than the life-forms that compose Gaia, because that information is often ignored where it matters by those in power. It's as if purposelessness had shifted from the natural to the social domain.

There is clearly at this point a political question of orientation toward or away

ILLUSTRATION: ADAM SIMPSON/HEART AGENCY

from the lessons to be drawn from Gaia. The resulting conflict takes precedence over all others. The climate science controversies demonstrate that scientists are now drawn into knowledge and power struggles for which they are not well prepared. Yet, people inspired by Gaia will not necessarily be endowed with deeper foresight. In matters of politics, it is prudent to follow John Dewey's advice (*15*) that we cannot expect to know the best solution in advance, but only that we can improve the quality of the sensors—both instruments and people—that detect shortcomings and the speed with which we rectify the course. If in politics the blind lead the blind, then hope rests on finding the best way to activate the white cane to fumble in the dark.

This is where the scientific establishment will play a crucial role in multiplying the sensors, improving their qualities, speeding the dissemination of their results, improving models, and proposing alternative explanations to phenomena. Such an infrastructure cannot, however, be limited to scientists: They must collaborate with citizens, activists, and politicians to quickly realize where things are going wrong.

Creating an infrastructure of sensors that allows tracking the lag time between environmental changes and reactions of societies is the only practical way in which we can hope to add some self-awareness to Gaia's self-regulation. This framing of the problem gives a clear ethical direction: Any attempt to tamper with the sensors or slow down the reaction to errors jeopardizes the chance to learn from Gaia how to close the loops that would enable Gaia 2.0 to better sustain the human population than the present world. ■

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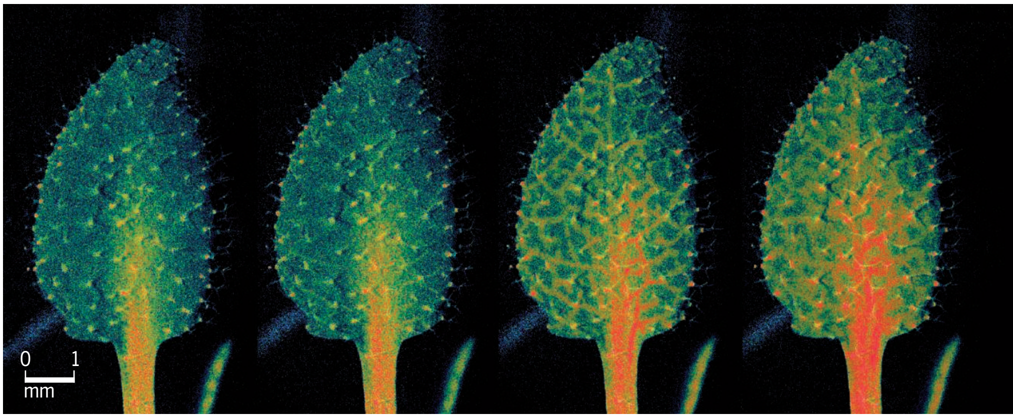

PHOTO: M. TOYOTA *ET AL.* (*1*)

PLANT BIOLOGY

Nervous system-like signaling in plant defense

Herbivory induces rapid long-distance calcium signals through glutamate-like receptors

By **Gloria K. Muday** *and* **Heather Brown-Harding**

The ability to initiate a rapid defense against biotic attacks and mechanical damage is critical for all organisms. Multicellular organisms have developed mechanisms to systemically communicate the occurrence of a wound to help them escape or defend themselves from predators. Because plants are stationary and cannot escape herbivory, they must respond with chemical defenses to deter herbivores and repair damaged tissue. On page 1112 of this issue, Toyota *et al.* (*1*) report long-distance calcium ion signaling in the model plant *Arabidopsis thaliana* in response to caterpillar herbivory or mechanical wounding (see the image). They uncover long-distance calcium signals that require glutamate-like receptor (GLR) channels for signal propagation. These channels are activated by extracellular glutamate, a well-known mammalian neurotransmitter and a more recently uncovered developmental signal in plants (*2*). In mammals, glutamate receptors are central to fast excitatory neurotransmission, which is an intriguing parallel to their role as long-distance signals in wounding and defense in plants.

This study combines genetic and imaging approaches to reveal a rapid and long-distance signaling pathway that communicates leaf damage to intact leaves that are spatially and developmentally distant from the wounded leaf. Toyota *et al.* detect increased calcium signals at the site of both herbivory and mechanical wounding within 2 s and in distant leaves within 2 min after damage. This signal moves through the plant vasculature at rates of ~1 mm/s, which is faster than can be explained by diffusion. This systemic calcium response can be induced through application of glutamate, but not with other amino acids, suggesting a role of GLRs. These GLRs are ion channels that open upon binding glutamate to allow calcium influx. Toyota *et al.* demonstrate that this long-distance signaling is lost in plants with mutations in *GLR3.3* and *GLR3.6*. These GLRs have sequence and structural similarity to mammalian ionotropic glutamate receptors (iGRs), which are critical in learning and memory in mammals, suggesting that very different physiological processes can be mediated by related proteins from the plant and animal kingdoms.

This work builds on detailed structural and functional characterization of mammalian iGRs (*3*). Plant GLRs and animal iGRs have similarities in structure and abundance in genomes (*4*, *5*). The plant GLR genes are classified into three clades: *GLR3.3* and *GLR3.6* are in the third clade and have a "gate" domain, where glutamate is predicted to bind and open the channel, with the highest similarity to mammalian iGRs (*4*). One member of clade 3, the plasma

Department of Biology and Center for Molecular Signaling, Wake Forest University, 455 Vine Street, Winston Salem, NC 27101, USA. Email: muday@wfu.edu

Science

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Timothy M. Lenton and Bruno Latour

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