EARTH AS A SELF-REGULATING SYSTEM

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Summary

It has long been recognized that the workings of Earth in some ways resemble the physiology of an organism. Since 1965, the development of the Gaia theory of Earth as a self-regulating system has given this ancient concept a modern scientific basis. The Gaia theory postulates that Earth's surface is maintained in a habitable state by feedback mechanisms involving organisms tightly coupled to their environment. The concept arose from the observations that (a) the atmosphere is an extreme state of thermodynamic disequilibrium due to the activities of life, yet its composition is remarkably stable; (b) present conditions at the surface of the Earth are close to optimal for the dominant, eukaryotic, multicellular organisms; (c) life has persisted for ~3.8 billion years despite increasing solar luminosity and varying exchange of matter with inner Earth; and (d) the Earth system has recovered from repeated perturbations, including the impact of planetesimals (huge meteorites). Feedback mechanisms have

been proposed to regulate key global environmental variables, including climate, atmospheric oxygen, carbon dioxide and methane, ocean nutrient levels (especially nitrate and phosphate), and the cycling of biologically important elements. Evidence has been gathered supporting the existence of these mechanisms, and computer models have been used to test their effectiveness. Feedbacks between life and its environment also exist across the range of scales between the individual and the global, especially at ecosystem and biome levels. The outstanding challenge for the Gaia theory is to explain how global self-regulation can arise and dominate over destabilizing effects of life on its environment. Current human activities are a striking example of an internally generated, destabilizing perturbation of the Earth. Yet, the self-regulating Earth is our life support system. Recognizing what we are tampering with may be critical to determining our destiny as a species.

1. History and Foundations of the Concept

"…Is this world to be considered merely as a machine, to last no longer than its parts retain their present position, their proper forms and qualities? Or may it not be also considered as an organized body? Such as has a constitution in which the necessary decay of the machine is naturally repaired… This is the view in which we are now to examine the globe; to see if there be in the constitution of this world a reproductive operation, by which a ruined constitution may again be repaired, and a duration or stability thus procured to the machine considered as a world sustaining plants and animals."
James Hutton, 1785

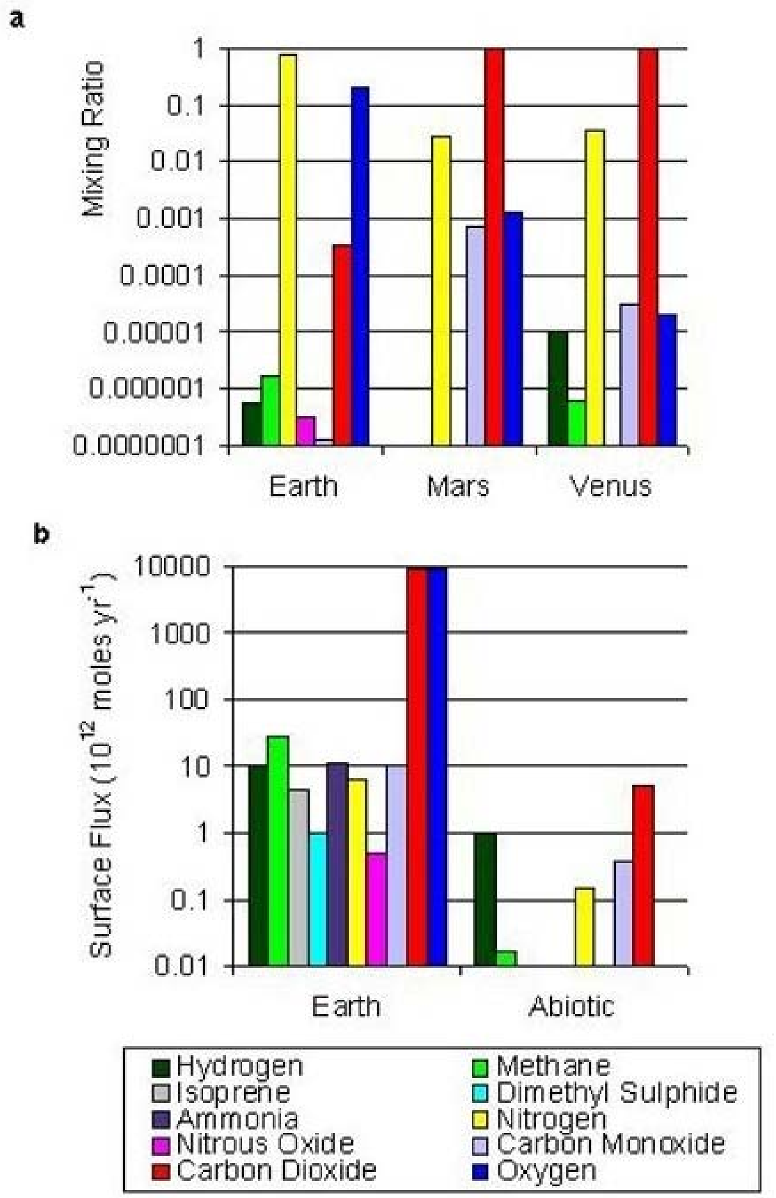
Figure 1. Earth from space

The broad analogy between Earth and an organism is of great antiquity and usually carried religious symbolism—the figure of "mother Earth" appears repeatedly in many traditions. James Hutton (1726–1797), the "father" of geology who trained as a physician, was among the first natural philosophers to take a physiological look at the Earth, likening its workings to those of an organism. The concept received relatively little scientific attention for much of the next two centuries, with a few notable exceptions. For example, Eduard Suess (1831–1914) coined the term "biosphere" in 1875 and wrote of an imaginary space traveler discovering the face of planet Earth. Vladimir I. Vernadsky (1863–1945) portrayed "living matter" as the greatest of all geological forces, and discussed the coevolution of life and its environment, but apparently did not recognize emergent properties of the whole system. In the mid-twentieth century, G. Evelyn Hutchinson pioneered systems thinking in ecology and its application to "the large self-regulatory cycles of the biosphere." Alfred C. Redfield approached the cycling of elements in the sea "in much the same way as a physiologist examines the general metabolism of an individual organism," and suggested that organisms control the oxygen content of the atmosphere. Lars G. Sillén remarked on the disequilibrium of nitrogen in the atmosphere (the chemically stable form under oxidizing conditions should be as nitrate in the ocean). However, it was not until humanity got its first view of Earth from space (Figure 1) that a truly holistic, "top-down" science of Earth reemerged.

1.1. Origin of the Gaia Hypothesis

The Gaia hypothesis arose from the involvement of the British independent scientist and inventor, James E. Lovelock, in the 1960s space program. Lovelock was employed by NASA, as part of the team that aimed to detect whether there was life on Mars. While the other scientists designed experiments to detect life at the surface, on the assumption that it would be like that on the Earth, Lovelock's interest in atmospheric chemistry led him to seek a more general, physical basis for detecting the presence of life on a planet. He recognized that most organisms shift their physical environment away from equilibrium, in particular, organisms use the atmosphere to supply resources and as a repository for waste products. In contrast, the atmosphere of a planet without life should be closer to thermodynamic equilibrium, in a state attributable to photochemistry (chemical reactions triggered by solar ultraviolet radiation). Thus, the presence of abundant life on a planet may be detectable by atmospheric analysis. Such analysis can be conducted from Earth using an infrared spectrometer (that detects the characteristic absorption due to specific gases) linked to a telescope. Using this technique, Lovelock and colleagues discovered that the atmospheres of Mars and Venus are dominated by carbon dioxide and relatively close to chemical equilibrium, suggesting that they are lifeless (Figure 2a). In contrast, the atmosphere of Earth is in an extreme state of disequilibrium due to the activities of life, in which highly reactive gases, such as methane and oxygen, coexist many orders of magnitude from photochemical steady state. Large, biogenic fluxes of gases maintain this disequilibrium (Figure 2b). Yet, the composition of Earth's atmosphere was known to be fairly stable over geologic periods of time. This led Lovelock to a "Eureka!" moment; he realized that life must regulate the composition of Earth's atmosphere.

Lovelock also noted that the composition of Earth's atmosphere (Figure 2a) is particularly suited to the dominant organisms. For example, nitrogen maintains much of the atmospheric pressure and serves to dilute oxygen, which at 21% of the atmosphere is just below the level at which fires would disrupt land life. Yet, oxygen is sufficiently abundant to support the metabolism of large respiring organisms such as humans. Both oxygen and nitrogen are biological products—oxygen is the product of past photosynthesis, while the gaseous nitrogen reservoir is largely maintained by the actions of denitrifying organisms (which use nitrate as a source of oxygen and release nitrogen gas). Furthermore, the oxygen content of the atmosphere has remained within narrow bounds for over 350 million years (see case study, 3.2. below).



The effect of life on the Earth's atmosphere. **a** Atmospheric compositions of Earth, Mars and Venus (excluding water vapour and noble gases). **b** Fluxes of gases at the Earth's surface with life (pre-industry) and without life.

Figure 2. The effect of life on Earth's atmosphere
a) Atmospheric compositions of Earth, Mars, and Venus (excluding water vapor and noble gases)
b) Fluxes of gases at Earth's surface with life (pre-industry) and without life

At the time, Lovelock shared an office with the astronomer Carl Sagan, who told him about the "faint young sun paradox." Stars on the main sequence, such as our Sun, gradually become more luminous with time as the hydrogen in their core is converted to helium (increasing their density and accelerating the fusion reaction; **see *History of Sun***). The Sun was about 25% less luminous when life originated on Earth, over 3.8

billion years ago. This increase in solar output alone should raise Earth's surface temperature by about 20 ºC. Yet, the current average temperature is only 15 ºC. This begs the question of why the early Earth wasn't frozen. The answer is probably that the atmosphere was richer in greenhouse gases. So, why isn't Earth considerably hotter now? Some cooling processes must have counteracted increasing solar luminosity. The continuous habitability of Earth despite solar warming led Lovelock to suggest that life has been regulating Earth's climate together with its atmospheric composition.

The idea was named "Gaia" after the Greek goddess of the Earth, by the novelist William Golding, who was Lovelock's friend and neighbor. The first scientific paper presenting "Gaia as seen through the atmosphere" was published in 1972. Lovelock then sought an understanding of the organisms that might be involved in regulating the planetary environment. Lynn Margulis was already developing the theory of symbiogenesis—that eukaryotic cells (those with genetic material contained within a distinct nucleus) evolved from the symbiotic merger of previously free-living prokaryotes (organisms including bacteria, whose genetic material is not enclosed within a cell nucleus). Margulis contributed her intimate knowledge of microorganisms and the diversity of chemical transformations that they mediate, to the development of what became the Gaia hypothesis that "the environment at the surface of Earth is homeostated by and for the benefit of the biota."

The Gaia hypothesis was used to make predictions, for example, that marine organisms would make volatile compounds that can transfer essential elements from the ocean back to the land. Lovelock and colleagues tested this ancillary hypothesis on a scientific cruise between England and Antarctica in 1972. They discovered that the gases dimethyl sulfide and methyl iodide produced by marine phytoplankton are the major atmospheric carriers of the sulfur and iodine cycles.

The Gaia hypothesis was greeted with hostility from many scientists and leading scientific journals, partly because of its mythological name. In response to the difficulty of getting "Gaia" published in scientific journals, Lovelock wrote his first book, *Gaia—A New Look at Life on Earth*, which was published in 1979. Written for a popular audience, it highlighted the remarkable properties of Earth that demand an explanation, and suggested some mechanisms by which the environment could be regulated. For example, forest fires were argued to play a role in regulating the oxygen content of the atmosphere (see case study 3.2. below). The book succeeded in catalyzing wider debate on the Gaia hypothesis.

The first scientific criticism of the Gaia hypothesis was that it implies teleology, some conscious foresight or planning by the biota. Most subsequent criticisms have focused on the need for evolutionary mechanisms (**see *Evolutionary Mechanisms and Processes***) by which regulatory feedback loops could have arisen or be maintained. As Richard Dawkins pointed out, Earth is not a unit of selection therefore if it has self-regulating properties. These cannot be "adaptations" in a strict neo-Darwinian sense, because they cannot have been refined by natural selection. This posed a challenge to explain how such properties could arise.

1.2. Daisyworld and Feedback Mechanisms

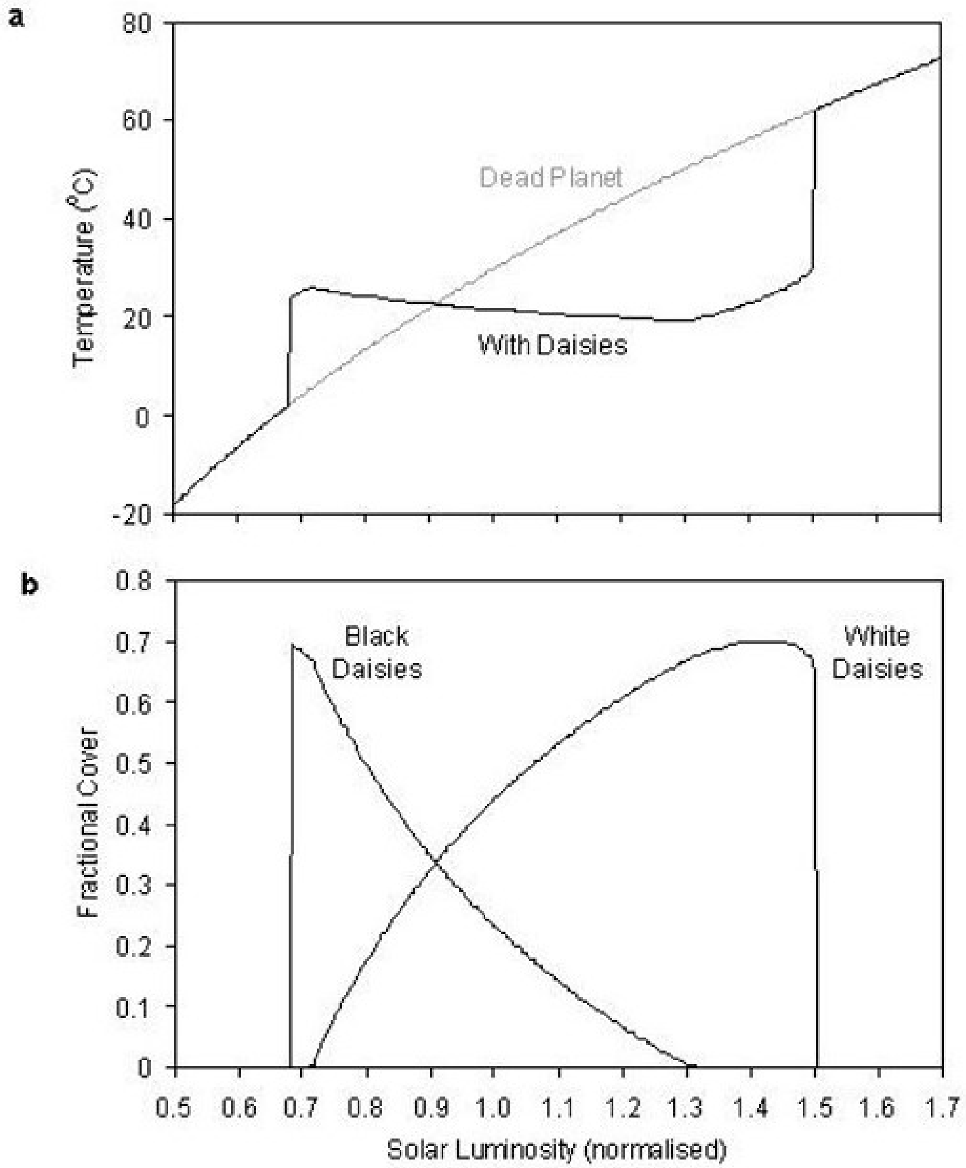


Figure 3. The Daisyworld model
A thought experiment to demonstrate that planetary self-regulation can emerge from natural selection at the individual level between types of life with different environment-altering traits. The traits are "darkness" (albedo = 0.25) and "paleness" (albedo = 0.75) of black and white daisies on a gray planet (albedo = 0.5). a) Planetary temperature as solar luminosity increases, with daisies and without (dead planet). b) Areal cover of black and white daisies.

The Daisyworld model (Figure 3) was formulated by Lovelock over Christmas 1981 to demonstrate that planetary self-regulation does not (necessarily) imply teleology. It was later analyzed with his colleague Andrew J. Watson. Daisyworld provides a hypothetical example of climate regulation emerging from competition and natural selection at the individual level. Daisyworld is an imaginary gray world orbiting, at a similar distance to the Earth, a star like our sun, which gets warmer with time. The world is seeded with two types of life, black and white daisies. These share the same optimum temperature for growth, 22.5 ºC, and limits to growth of 5 ºC and 40 ºC. When the temperature reaches 5 ºC, the first seeds germinate. The paleness of the white daisies makes them cooler than their surroundings, hindering their growth. The black daisies, in contrast, warm their surroundings, enhancing their growth and reproduction. As they spread, the black daisies warm the planet. This further amplifies their growth and they soon fill the world. At this point, the average temperature has risen close to the optimum for daisy growth. As the sun warms, the temperature rises to the point where white daisies begin to appear in the daisy community. As it warms further, the white daisies gain the selective advantage over the black daisies and gradually take over. Eventually, only white daisies are left. When the solar forcing gets too high, regulation collapses. While life is present and the solar input changes over a range equivalent to 45 ºC, the surface of the planet is maintained within a few degrees of the optimum temperature for daisy growth.

Daisyworld illustrates the importance of positive and negative feedback mechanisms for system self-regulation. Feedback occurs when a change in a variable triggers a response that affects the forcing variable. Feedback is said to be "negative" when it tends to damp the initial change and "positive" when it tends to amplify it. On Daisyworld, the initial spread of life is characterized by positive feedback—the more life there is, the more life it can beget. This is coupled to an environmental positive feedback—the warming due to the spread of black daisies enhances their growth and reproduction rates. The long period of stable, regulated temperature on Daisyworld represents a predominance of negative feedback. However, if the temperature of the planet is greatly perturbed by the removal of a large fraction of the daisy population, then positive feedback acts to rapidly restore comfortable conditions and widespread life. The end of regulation on Daisyworld is characterized by a positive feedback decline in white daisies—solar warming triggers a reduction in their population that amplifies the rise in temperature.

The modeling approach pioneered in Daisyworld provided the beginnings of a mathematical basis for understanding self-regulation. With this work, Lovelock began to refer to Gaia as a theory, in which self-regulation is understood as a property of the whole system of life tightly coupled to its environment. This replaced the original suggestion that regulation is "by and for the biota" (which was often interpreted as teleological although never intended as such). The term "homeostasis," which referred to regulation around a fixed set point, was also revised. More appropriate is Margulis's suggestion of "homeorrhesis," which describes regulation around an evolving point.

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Bibliography

Charlson R.J., Lovelock J.E., Andreae M.O., and Warren S.G. (1987). Oceanic phytoplankton, atmospheric sulphur, cloud albedo and climate. *Nature* **326**, 655–661. [This is a much-cited paper, proposing both a mechanism of climatic cooling due to phytoplankton and more speculatively a resulting, regulatory feedback.]

Lenton T.M. (1998). Gaia and natural selection. *Nature* **394**, 439–447. [This is a review, synthesis, and attempt to reconcile Lovelock's and Darwin's theories, introducing a hierarchy of types of environmental feedback and exploring their implications at levels from the individual to the global.]

Lenton T.M. and Watson A.J. (2000). Redfield revisited: 1. Regulation of nitrate, phosphate and oxygen in the ocean. *Global Biogeochemical Cycles* **14**, 225–248. [This reports on recent modeling work showing how feedbacks involving marine organisms regulate the proportions of nutrients in the ocean.]

Lenton T.M. and Watson A.J. (2000). Redfield revisited: 2. What regulates the oxygen content of the atmosphere? *Global Biogeochemical Cycles* **14**, 249–268. [This reports on tests existing proposals for oxygen regulation and introduces a new and more effective mechanism involving forests and fire.]

Lovelock J.E. (1979). *Gaia—A New Look at Life on Earth*, 148 pp. Oxford, UK: Oxford University Press. [This is the classic exposition of the Gaia hypothesis, an inspiring blend of science and poetry, born out of the frustration of censorship from scientific journals.]

Lovelock J.E. (1988). *The Ages of Gaia—A Biography of Our Living Earth*, 255 pp. Oxford, UK: Oxford University Press. [At the beginning of the twenty-first century, this is the definitive scientific exposition of the Gaia theory, a thorough response to the criticisms triggered by the original hypothesis, seeking consistency with natural selection, and replete with suggested and, to a lesser degree, tested regulatory mechanisms.]

Lovelock J.E. (1991). *Gaia—The Practical Science of Planetary Medicine*, 192 pp. London, UK: Gaia Books. [This is an accessible and well-illustrated introduction to the subject for the general reader.]

Schellnhuber H.J. (1999). "Earth system" analysis and the second Copernican revolution. *Nature* **402**, C19–C23. [This is a lively introduction, looking to the future of Earth system analysis and its use to help guide humanity along a sustainable path.]

Schneider S.H. and Boston P.J., eds. (1991). *Scientists on Gaia*, 433 pp. London, UK: MIT Press. [This is a collection of edited scientific and philosophical papers from the 1988 Chapman Conference on the Gaia hypothesis, covering a broad spectrum of views on the subject.]

Watson A.J. and Lovelock J.E. (1983). Biological homeostasis of the global environment: the parable of Daisyworld. *Tellus* **35B**, 284–289. [This paper gives the equations, mathematical analysis, and an interesting variant of the Daisyworld model.]

Biographical Sketch

Tim Lenton is a British citizen, who gained a first class honors degree (BA) in Natural Sciences from Cambridge University in 1994 and a PhD in Environmental Sciences from the University of East Anglia in 1998. He joined the Center for Ecology and Hydrology in Edinburgh in 1998 as an Earth system modeler. He has worked with James Lovelock on the development of the Gaia theory since 1994 and collaborated with Bill Hamilton. Current research topics include the response of the Earth system to human-induced global change; the regulation of climate and the carbon cycle over different time scales; the mechanisms regulating nutrient cycles and atmospheric oxygen; the role of evolution and feedback in generating environmental regulation, and; the lifespan of the biosphere. Tim is Research and Education Coordinator for The Gaia Society, a Director of Gaia Charity, and a member of the organizing committee for the Second Chapman Conference on the Gaia Hypothesis. He publishes and lectures widely and has provided research input to the BBC series "Essential Guide to Weather" and appeared in VPRO (Dutch) program on "Life in the Clouds," Discovery Channel program on "Something in the Air," and NHK (Japanese) series "Planet of Ocean."