The living Earth

James Lovelock

Imagine a science-based civilization far distant in the Galaxy that had built an interferometer of such resolving power that it could analyse the chemical composition of our atmosphere. Simply from this analysis, they could confidently conclude that Earth, alone among the planets of the Solar System, had a carbon-based life and an industrial civilization. They would have seen methane and oxygen coexisting in the upper atmosphere, and their chemists would have known that these gases are continually consumed and replaced. The odds of this happening by chance inorganic chemistry are very long indeed. Such persistent deep atmospheric disequilibrium reveals the low entropy characteristic of life. They would conclude that ours was a live planet — and the presence of CFCs in the atmosphere would suggest an industry unwise enough to have allowed their escape.

As part of NASA's planetary exploration team in 1965, thoughts such as these led me to propose atmospheric analysis for detecting life on Mars. I also wondered what could be keeping Earth's chemically unstable atmosphere constant and so appropriate for life, and what kept the climate tolerable despite a 30% increase in solar luminosity since the Earth formed. Together, these thoughts led me to the hypothesis that living organisms regulate the atmosphere in their own interest, and the novelist William Golding suggested Gaia as its name. Although the concept of a live Earth is ancient, Newton was the first scientist to compare the Earth to an animal or a vegetable. Hutton, Huxley and Vernadsky expressed similar views but, lacking quantitative evidence, these earlier ideas remained anecdotal. In 1925 Alfred Lotka conjectured that it would be easier to model the evolution of organisms and their material environment coupled as a single entity than either of them separately. Gaia had its origins in these earlier thoughts, from the evidence gathered by the biogeochemists Alfred Redfield and Evelyn Hutchinson and from the mind-wrenching top-down view provided by NASA.

Although welcomed by atmospheric scientists, Earth scientists were cautious. Biologists, especially Ford Doolittle and Richard Dawkins, argued strongly that global self-regulation could never have evolved, as the organism was the unit of selection, not the biosphere. In time I realized that they were right — but still I thought, something keeps the Earth habitable. In 1981 I composed a model of dark- and light-coloured plants that competed for growth on a planet in progressively increasing sunlight. My intention was not to make a blueprint for the Earth, but a model to show that Gaia is consistent with natural selection. This 'Daisyworld' regulated its temperature close to that fittest for plant growth and — unusually for an evolutionary model made from coupled differential equations — it was stable, insensitive to initial conditions and resistant to perturbation. Daisyworld is darwinian, but the evolution of the organisms and the evolution of temperature proceed as a single, coupled process. The model was much criticized, but so far has resisted falsification. It was easy to show that Daisyworld tolerates 'cheats' — daisies that grow but offer nothing towards self-regulation. Other critics claimed that daisies would adapt to changing temperature and therefore simply track temperature change, not regulate it. But the restraining function connecting growth with temperature is not negotiable; chemistry, not biology, sets its constants.

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Our planet in perspective: Gaia theory explains the constancy of our unstable atmosphere.

Gaia

Organisms and their environment evolve as a single, self-regulating system.

At this stage, the Gaia theory was missing plausible control mechanisms. The first discovered was a biological process that redressed the imbalance of the nutritious elements sulphur and iodine — these are abundant in the oceans, but deficient on the land surface. It was widely assumed that hydrogen sulphide and sea salt aerosol drifted from the ocean to the land. In 1971 I discovered that methyl iodide and dimethyl sulphide were ubiquitous in the Atlantic surface waters, and from my measurements Peter Liss calculated their fluxes in 1974. He argued that these biogenic gases were the main carriers of the natural elemental cycles of sulphur and iodine.

Then in 1982, the geochemists James Walker, P. B. Hayes and Jim Kasting suggested that the weathering of calcium silicate rock could regulate carbon dioxide and climate. Greater warmth leads to more rainfall and a faster removal of carbon dioxide from the atmosphere by rock weathering, which provides a negative feedback on temperature. This plausible mechanism is by itself too small to account for the observed rate of weathering. Organisms on the rocks and in the soil bring it to life as a Gaian mechanism; their growth varies with temperature and their presence amplifies the rate of weathering.

In 1986, there was the awesome discovery by Robert Charlson, James Lovelock, Meinrat Andreae and Steven Warren of a connection between biogenic dimethyl sulphide gas — the product of ocean algae — its oxidation in the atmosphere to form cloud condensation nuclei, and the subsequent effect of the clouds formed on climate. We wondered whether this could be a Gaian regulatory mechanism through the feedback between climate change and algal growth.

By the end of the 1980s there was sufficient evidence, models and mechanisms, to justify a provisional Gaia theory. Briefly, it states that organisms and their material environment evolve as a single coupled system, from which emerges the sustained self-regulation of climate and chemistry at a habitable state for whatever is the current biota.

Like life, Gaia is an emergent phenomenon, comprehensible intuitively, but difficult or impossible to analyse by reduction — not surprisingly it is often misunderstood. A simple automatic mechanism, like a thermostatically controlled oven, requires a sensor to measure the difference between the ambient temperature and the set point of regulation, and an amplifier to magnify this difference and apply it as negative feedback to oppose unwanted change. Living systems rarely work in this simple way; they require positive as well as negative feedback for homeostasis, and a restraining function replaces the simple manual set point. This function allows regulation within a physiologically acceptable range, instead of at a single set value. Andrew Watson and other critics have assumed that to be Gaian, a planet must regulate near perfectly — but physiological systems may perform no better than is needed. No one doubts that humans are in thermostasis, yet our core temperatures range from 35 to 40 °C and our extremities from 5 to 45 °C. This may appear imprecise, but it serves us well. For the past ten million years the Earth's average surface temperature has covered a similar range between 11 and 16 °C. This is not evidence of incompetent regulation — it is sufficient to sustain the Earth system. The occasional failure of the Earth to regulate efficiently — as in the present interglacial — resembles the physiological condition of a fever where positive feedback dominates.

Gaia theory does not contradict darwinism, rather it extends it to include evolutionary biology and evolutionary geology as a single science. In Gaia theory, organisms change their material environment as well as adapt to it. Selection favours the improvers, and the expansion of favourable traits extends local improvement and can make it global. Inevitably there will be extinctions and losers, winners may gain in the short term, but the only long-term beneficiary is life itself. Its persistence for over three billion years in spite of numerous catastrophes, internal or external, lends support to the theory. I have never intended the powerful metaphor 'the living Earth' more seriously than the metaphor of 'the selfish gene'. I have used it, along with my neologism geophysiology, to draw attention to the similarity between Gaian and physiological regulation.

I was pleased when Stephen Schneider persuaded the distinguished American Geophysical Union to devote their 1988 Chapman Conference to Gaia, but disappointed when too many of those who attended argued against the discarded Gaia hypothesis of the 1970s, seemingly unaware that the theory had been revised. I suspected that few would take Gaia seriously until eminent scientists approved it publicly. In 1995 I started dialogues with John Maynard Smith and William Hamilton. Both of them were prepared to discuss Gaia as a scientific topic , but neither of them saw how planetary self-regulation could evolve through natural selection. Even so, Maynard Smith gave unstinted support to my colleague Tim Lenton when he wrote a seminal article in *Nature*. Hamilton wondered, in a joint paper with Lenton, if the need of organisms to disperse was the link that connected ocean algae with climate. In a 1999 television programme, Hamilton said: "Just as the observations of Copernicus needed a Newton to explain them, we need another Newton to explain how darwinian evolution leads to a habitable planet."

Then the ice began to melt. In 2001, at a conference in Amsterdam — at which four principal global change research programmes were represented — more than a thousand delegates signed a declaration that started with the statement: "The Earth System behaves as a single, self-regulating system comprised of physical, chemical, biological and human components."

Gaia theory is fruitful and makes successful or useful predictions (see Table 1). More than this, it enlightens our view of Earth system science and the environment. Importantly, as Lynn Margulis has insisted, it draws our attention to the microorganisms, which are the biological infrastructure of the Earth. Microorganisms filled the whole biosphere for the greater part of life's history and they are still vital for effective planetary regulation.

Table 1 Some predictions from Gaia

Prediction (year)	*Test and result*
Mars lifeless from atmospheric evidence (1968).	Viking Mission (1977). Strong confirmation.
That elements are transferred from the ocean to the land by biogenic gases (1971).	Dimethyl sulphide, dimethyl selenide and methyl iodide found (1973, 2000).
Climate regulation through biologically enhanced rock weathering (1981).	Microorganisms found greatly to increase the rate of rock weathering.
That Gaia is aged (1982).	Generally accepted.
Climate regulation through cloud albedo control linked to algal gas emissions (1987).	Still under test.
Archaean atmospheric chemistry dominated by methane (1988).	Still under test but tending to be accepted.
Oxygen has not varied from 21 ± 5% for the past 200 million years (1989).	Still under test.
Boreal forests regulate their regional climate in a Daisyworld manner (1988).	Now part of global climate modelling.
Biodiversity is a necessary part of planetary self-regulation (1992).	Tested by models, but not yet in the field.
That the current interglacial is an example of system failure in a physiological sense (1996).	Still controversial.

A major achievement of Gaia has been the change in style of Earth system models. Climatologists, notably Peter Cox, Richard Betts and John Schellnhuber and colleagues, now include a responsive biota in their models of future climates, and their contributions have added realism to the predictions of the 2001 Intergovernmental Panel on Climate Change third assessment report.

As the Earth ages, the Sun's heat ineluctably intensifies; in approximately one billion years the Earth will pass the limit of climatic stability and irreversibly return to inorganic chemistry. Moreover, as it grows older the Earth system weakens, and before long a large planetesimal impact may throw our planet prematurely into its final hot, dry state. A few thermophiles in oasis ecosystems might survive, but we could never recapture the abundant life and lush environment we now enjoy. The Earth system is elderly and we should treat it with respect and care.

Gaia theory reconciles current thinking in evolutionary biology with that in evolutionary geology. It extends, not contradicts, Darwin's vision, just as relativity enhances, not denies, Newtonian physics. The theory is provisional, but provides an intellectual habitat where understanding of the Earth can evolve and grow. Perhaps its greatest value lies in its metaphor of a living Earth, which reminds us that we are part of it and that human rights are constrained by the needs of our planetary partners. ■

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