

THE GAIA HYPOTHESIS: CAN IT BE TESTED?

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Abstract. The Gaia hypothesis' central theme is that biological processes homeostatically maintain, on a planetary scale, geochemical and climatic conditions favorable for life. A number of distinct hypotheses have been proposed, spanning a range from the self-evident to the highly speculative. The self-evident forms of Gaia reiterate the well-documented fact that biological processes are critical to biogeochemical cycles, adding the straightforward (though important) point that the coupling

between biotic and physical processes should create feedback loops. The speculative forms of Gaia assert that biological processes regulate the physical environment, keeping Earth's climate and surface geochemistry stable and favorable for life. As metaphors, these versions of Gaia are intriguing, untestable, and, if taken literally as a basis for research, potentially misleading. As hypotheses, they are ill-defined, unparsimonious, and unfalsifiable.

INTRODUCTION

"Geology is a particularly alluring field for premature attempts at the explanation of imperfectly understood data." (J. D. Dana)

"Geology has to choose between the rashness of using imperfect evidence or the sterility of uncorrelated, unexplained facts." (J. W. Gregory)

(quoted by Van Houten [1961, p. 89])

It has been clear for some time that biological processes are crucial factors in the Earth's surface geochemistry. When Huxley [1877] wrote his textbook in physical geography, he could describe the role of green plants in limiting atmospheric CO₂ concentrations as a matter of established fact. By the time Hutchinson [1954] reviewed the biogeochemistry of the terrestrial atmosphere, he could add CH₄, N₂, NH₃, NH₄⁺, N₂O, NO₂, H₂, SO₄²⁻, and formaldehyde to the list of biogenic or biologically controlled atmospheric substances. Harvey [1957] devoted two chapters to biological influences on oceanic chemistry. Since the 1950s, efforts on two fronts (unraveling contemporary biogeochemical cycles and tracing the geophysical, geochemical, and biological evolution of paleoclimate) have produced an explosion of new insights too vast to adequately document here; reviews can be found by Holland [1978, 1984], Schopf [1983], and others. Following Berger *et al.* [1984] we can list among the most

important and widely recognized biologically mediated processes photosynthesis; aerobic and anaerobic metabolism; denitrification; nitrogen fixation; bacterial sulfate reduction and iron oxidation; mineral dissolution by CO₂-enriched groundwater; sedimentation of organic carbon, carbonates, silicates, phosphates, and other materials; and changes in surface albedo produced by growth and decay of vegetation. These processes create important feedback loops linking natural selection and evolution within the biota and biologically induced changes in the physical environment [Cloud, 1968; Schneider and Londer, 1984]. Perhaps because the study of these linkages is inherently interdisciplinary, they have not received the emphasis that their importance in geochemical and geophysical processes would seem to demand.

A persistent undercurrent in some related work is the observation that the physical environment seems remarkably well suited to the needs of terrestrial life [e.g., Henderson, 1913] and that this fact might even reflect organisms manipulating their environment to meet their needs [e.g., Redfield, 1958]. The most recent, comprehensive, and controversial form of this idea is Lovelock and Margulis' Gaia hypothesis, which states [Lovelock and Watson, 1982, p. 795] that "the climate and the chemical composition of the Earth's surface are kept in homeostasis at an optimum by and for the biosphere" (see also Margulis and Lovelock [1974], Lovelock and Margulis [1974a, b] and Lovelock [1979a, 1986b, 1988]). In this view the biota and the physical environment are so tightly

coupled that they can be considered a single vast organism [Lovelock, 1986a, b, 1988] called Gaia (after the Greek goddess of the Earth), and the atmosphere can be considered to be [Lovelock, 1979b, p. 716] “like the fur of a cat and the shell of a snail, not living but made by living cells so as to protect them against an unfavorable environment.”

The Gaia hypothesis has received a great deal of public attention. I can only speculate why: it is a hypothesis of great generality and vast scope; it has been presented in nontechnical language; it addresses matters of both academic and practical concern; it suggests a colorful metaphor that many find intriguing; and its semantic and conceptual plasticity allow it to be virtually all things to all people. Two groups that immediately embraced Gaia were environmentalists and, paradoxically, industrialists. The former argued that harming any part of the planetary “organism” could have far-reaching consequences, while the latter argued that Gaia’s capacity for homeostasis made pollution control unnecessary [Schneider, 1987].

If verified, the Gaia hypothesis would represent a revolution in biogeochemistry, for it represents a fundamentally different view of the role of life on Earth. Some have spontaneously embraced it as obvious, and many have spontaneously dismissed it as bizarre. Others, representing a diverse array of specialties, have wondered how the hypothesis could be empirically tested; this question was the focus of the recent AGU Chapman Conference.

My primary purpose here is not to catalogue and weigh the evidence for and against the Gaia hypothesis. Instead, I want to address a more basic issue: Is the Gaia hypothesis a scientifically testable proposition at all? This approach may disappoint those who would prefer an introduction to the relevant biogeochemical and paleoclimatic theory and data. Nevertheless, the first question to ask of a theory is not whether it is true or false, but what it means and whether it can be tested.

I suspect that much of the ongoing debate surrounding Gaia has arisen because different parties defined the hypothesis in different ways, assumed that their interpretations of the hypothesis were scientifically meaningful and empirically testable, and then proceeded to argue over the data. My premise is that much of the debate over Gaia does not result from the ambiguity of the geologic record or the gaps in our current understanding of global biogeochemical cycles, but instead derives from a lack of clarity concerning what the Gaia hypothesis means and how (or whether) it can be tested.

A TAXONOMY OF GAIA HYPOTHESES

Defining the Gaia hypothesis is difficult. So many logically distinct theories have been put forth under the single banner of “the Gaia hypothesis” that compressing

them all into a single coherent statement would be at best unwise and at worst impossible. Instead, I have tried to compile a taxonomy of the central themes of different statements of the Gaia hypothesis in order to state each precisely and to clarify the distinctions between them.

Coevolutionary Gaia

The biota influences its abiotic environment, and the environment in turn influences the evolution of the biota by Darwinian processes. Watson and Lovelock [1983, p. 284] state,

The biota have effected profound changes on the environment of the surface of the earth. At the same time, that environment has imposed constraints on the biota, so that life and the environment may be considered as two parts of a coupled system . . . perturbations of one will affect the other and this may in turn feed back on the original change. The feedback may tend either to enhance or to diminish the initial perturbation, depending on whether its sign is positive or negative.

Homeostatic Gaia

The biota influences the abiotic world in a way that is stabilizing. The dominant linkages between the biota and the physical world are negative feedback loops.

Lovelock and Margulis [1974a, p. 93]

From the fossil record it can be deduced that stable optimal conditions for the biosphere have prevailed for thousands of millions of years. We believe that these properties of the terrestrial atmosphere are best interpreted as evidence of homeostasis on a planetary scale maintained by life on the surface.

Lovelock and Margulis [1974b, p. 3]

The notion of the biosphere as an active adaptive control system able to maintain the earth in homeostasis we are calling the “Gaia” Hypothesis.

Lovelock [1988, p. 13]

Through Gaia theory, I see the Earth and the life it bears as a system, a system that has the capacity to regulate the temperature and the composition of the Earth’s surface and to keep it comfortable for living organisms.

Geophysiological Gaia

The biosphere can be compared with a single immense organism which, like other organisms, may exhibit both homeostatic and unstable behavior.

Lovelock [1986b, pp. 12 and 19]

Gaia theory suggests that we inhabit and are part of a quasi-living entity that has the capacity for global homeostasis. This is the basis for geophysiology . . . a

systems approach to Earth science. It is the essential theoretical basis for the putative profession of planetary medicine.

Lovelock [1988, p. 13]

Gaia theory predicts that the climate and chemical composition of the Earth are kept in homeostasis for long periods until some internal contradiction or external force causes a jump to a new stable state.

Optimizing Gaia

The biota manipulates its physical environment in ways that create biologically favorable conditions.

Lovelock and Margulis [1974a, p. 93]

We argue that it is unlikely that chance alone accounts for the fact that temperature, pH and the presence of compounds of nutrient elements have been, for immense periods of time, just those optimal for surface life. Rather we present the "Gaia hypothesis" the idea that energy is expended by the biota to actively maintain these optima.

Lovelock and Watson [1982, p. 795]

The Gaia hypothesis . . . postulates that the climate and chemical composition of the Earth's surface are kept in homeostasis at an optimum by and for the biosphere.

Lovelock [1988, p. 8]

Planetary life must be able to regulate its climate and chemical state . . . the greater part of our own environment on earth is always perfect and comfortable for life. The energy of sunlight is so well shared that regulation is, effectively, free of charge.

Lovelock [1979a, p. 127]

The most important property of Gaia is the tendency to optimize conditions for all terrestrial life.

Some may take issue with this taxonomy. This is not the only way to classify the Gaia hypotheses, or perhaps even the best. My point is simply that it needs to be done, because the single term "Gaia" has been used to refer both to observations that many find self-evident and to propositions that many find extremely speculative.

This wide range of possibilities, along with the engaging plasticity of the terminology, means that individuals can make of Gaia whatever they wish. The unsympathetic can ridicule the notion of global optimal control. The sympathetic can point out that the biota and the abiotic environment are obviously interrelated in any number of ways. The uncritical (particularly among the public and the press) can take data detailing these interrelationships and misinterpret them as scientific validation of their fanciful extrapolations of Gaia. And in scientific discourse a great

deal of unnecessary argument may result from a simple misunderstanding of which hypothesis is on the table at any given time.

The wide variety of Gaia hypotheses creates a risk of misinterpreting evidence for one version as somehow also proving another form of Gaia as well. For example, it has long been known that the atmosphere is in greater chemical disequilibrium than would be produced by extraterrestrial radiation alone [e.g., *Lewis and Randall*, 1923]. This is, as *Hutchinson* [1954], *Sillen* [1966], and others have noted, evidence that biological processes are important determinants of Earth's atmospheric chemistry. *Lovelock* [1965] and *Hitchcock and Lovelock* [1967] pointed out that spectroscopic data should detect chemical disequilibrium in the atmospheres of other planets if life is present. *Lovelock's* [1975] prediction that life would not be found on Mars was subsequently supported by data from the Viking program. Atmospheric chemical disequilibrium is not, however, evidence that the biota manipulates the atmosphere in any particular way or for any particular reason.

The many Gaia hypotheses make it easy to create false dichotomies. Rejecting one null hypothesis (e.g., that the biota has no effect on its physical environment) does not prove an alternative hypothesis (e.g., that the biota and the physical environment form a goal-seeking, homeostatic cybernetic control system) unless the two hypotheses are mutually exclusive and jointly exhaustive (which, in this example, they are not). Nonetheless, *Lovelock and Watson* [1982, p. 799] (see also *Lovelock* [1979a], *Lovelock and Margulis* [1974a, b], and *Margulis and Lovelock* [1974]) propose that "a test for Gaia is to consider what would happen if life were now deleted from the Earth." This is, of course, a test for life, not a test for Gaia. A test for Gaia should look for evidence that a lifeless Earth would be different in the way that Gaia says a lifeless Earth should be different (that it should be less homeostatic, for example), not just different somehow. Many arguments for Gaia are based on rejecting the hypothesis that biotic processes are completely irrelevant to the physical environment; this hypothesis has already been rejected by many investigators for quite some time.

In order to proceed I must briefly summarize some relevant epistemology and scientific methodology. These points are familiar to many researchers, but it will aid the present discussion if they are stated explicitly.

HYPOTHESES: TRUE, FALSE, AND UNTESTABLE

The day-to-day business of science consists of testing hypotheses, but some hypotheses cannot be tested. Some hypotheses are untestable in practice, though the practical impossibility of performing an exact test is not crucial if surrogate tests can be devised. For example, one may hope

that a full-scale test of the nuclear winter hypothesis will never be carried out, but some of its basic mechanisms can be observed at other scales, such as in large forest fires. Other hypotheses (for example, the "hypothesis" that in 4000 B.C. a devious god assembled the geological record in a way that gives the impression that the Earth is much older) are untestable in principle; these can obstruct the progress of science. In this paper, unless otherwise noted, the terms "testable" and "untestable" will refer to testability in principle.

The minimal criteria of testability can be stated concisely. In order to be testable a hypothesis must be clear, and its terms must be unambiguous. It must be intelligible in terms of observable phenomena. And most importantly, it must generate predictions of two kinds: confirmatory predictions (phenomena that should be observed if the hypothesis is true and that would not be predicted by the existing body of accepted theory) and falsifying predictions (phenomena that should be observed if the hypothesis is false).

A hypothesis that is untestable is much less useful than one that is merely false. A false hypothesis, once known to be false, at least helps to restrict the sphere of possibilities. Untestable theories, on the other hand, are at best empty and at worst misleading, and in the minds of the unwary they can be entrancing. A few examples will suffice to make this point.

1. Ill-defined hypotheses are untestable because they can be endlessly reinterpreted to fit almost any data, but for the same reason they cannot contain specific empirical information; they exclude no possibilities.

2. Tautological hypotheses are untestable because they are true by definition, but as such, they contain no new information; their conclusions are entirely contained in their premises.

3. Unfalsifiable hypotheses are untestable because they make no falsifying predictions, but as such, they have no empirical content; confirmation of the hypothesis does not restrict the sphere of possibilities because the set of excluded data (data that would have been inconsistent with the hypothesis) is empty.

Note that hypotheses in each of these classes (which are not logically distinct, but are stated this way in the interests of simplicity) will usually show good agreement with experimental data. That is why they are misleading. One believes they fit the data so well because they capture the essence of the problem, when in fact they fit because they are independent of the empirical facts. For the same reason they are entrancing; one thinks it remarkable that the predictions are always confirmed. Attempts to test such theories are ultimately futile, not because they are doomed to failure, but because they are doomed to inevitable and inconsequential success.

Some criteria for judging the usefulness of hypotheses can also be stated. Some hypotheses, while testable and perhaps even correct, are simply not very useful. The more specific the confirmatory predictions derived from a hypothesis, and the more general the falsifying predictions, the more logical content the hypothesis contains [Popper, 1959, p. 113]. Hypotheses are useful to the degree that they are logically distinct from other theories; if a hypothesis simply restates widely accepted principles, or can be directly derived from them, a search for confirmatory data would be an inefficient use of scarce resources. Hypotheses are also useful in proportion to the phenomena that they alone can predict or explain and, perhaps more importantly, in inverse proportion to what they must assume. This is the well-known Law of Parsimony: if two hypotheses explain the same body of data equally well, prefer the theory that imposes the lightest burden of assumptions [Poincare, 1905, pp. 146 and 151]. While this principle cannot be precisely codified (and in a borderline case may reveal the choice among competing theories to be a matter of aesthetic taste), it remains a basic tenet of the scientific enterprise.

GAIA AS METAPHOR

Some have suggested that Gaia is simply a metaphor rather than a hypothesis. Metaphors are untestable, but they can nevertheless be scientifically useful; they can suggest new lines of analysis, such as the search for biogenic sources of cloud condensation nuclei [Charlson *et al.*, 1987]. Indeed, much of science, relying as it does on reasoning by analogy, is deeply metaphorical. As scientific metaphors go, Gaia is unusually colorful, rich, and evocative, and I hope that it will spur many interesting and fruitful speculations. But metaphors and hypotheses are two different things, and it is important not to confuse them.

Why is it misleading to treat a metaphor as an empirically testable proposition? As hypotheses, metaphors are ill-defined because they can be reinterpreted to explain almost any observed behavior; they fail to specify in what sense the metaphor is true. One can agree with Shakespeare that all the world is a stage, in some sense (e.g., its inhabitants can be viewed as playing out their roles), but it is not a stage in all senses (e.g., it is not made of flooring and does not have a row of footlights at its edge). There is, doubtless, some sense in which the biosphere can be considered as an organism [Lovelock, 1986a, b, 1988], but this analogy is not scientifically verifiable without some stipulation of how it does or does not apply. Proposals of specific ways in which the biosphere might act like a global organism (e.g., it might

exhibit homeostasis) are, of course, hypotheses and may be testable. The metaphor itself, however, is untestable. It has no empirical content beyond the data that suggest the specific ways in which it does or does not apply.

Boston [1989] has noted that Gaia can be interpreted as illustrating the principle of emergent properties, which holds that a complex system can have properties that would not be predicted from studies of its isolated components. As a cautionary note to those who view systems simplistically, this principle is well taken. As a hypothesis per se, however, it is ill-defined. Even simple abiotic systems can exhibit emergent properties; it is precisely which properties are predicted and which mechanisms create them that constitutes a hypothesis.

If Gaia is meant to be simply a metaphor or a restatement of the principle of emergent properties, it is puzzling that its proponents make so many references to the Gaia hypothesis, tests for Gaia, and proofs of Gaia [e.g., *Lovelock*, 1983, 1988; *Lovelock and Watson*, 1982; *Lovelock and Margulis*, 1974b; *Margulis and Lovelock*, 1974]. If Gaia is not intended as a scientific proposition, it is misleading to refer to it as if it were one.

COEVOLUTIONARY GAIA

The idea that the biota and the physical environment coevolve is not original or unique to Gaia. To my knowledge, it was first stated by *Spencer* [1844, p. 93], who held that the biogenic increase in atmospheric oxygen concentration made possible a "more perfect mental and bodily development" in the biota. While *Spencer's* account is simultaneously grander and cruder than the contemporary view, few would dispute its general premise; biotic processes shape the physical environment, which in turn guides biotic evolution. Indeed, the fact that the biotic and physical worlds are interrelated is by now so well documented [*Hutchinson*, 1954; *Berkner and Marshall*, 1964; *Cloud*, 1968; *Holland*, 1964, 1978, 1984; *Schneider and Londer*, 1984] that it would seem odd to call it a hypothesis at all. An observation that is so widely recognized lacks the tentative character of a true hypothesis.

Coevolutionary Gaia asserts not just that the biota and the physical environment are interrelated but also that this relationship is characterized by negative and positive feedback [*Lovelock and Watson*, 1982; *Watson and Lovelock*, 1983]. While the observation that interrelated system components exhibit feedback is useful for those unfamiliar with feedback processes, it also follows analytically from elementary theorems of systems analysis and has no specific empirical content. An empirical test is therefore unnecessary. If the biota and the physical world

are interrelated (that is, each has effects on the other), there are no other possibilities except that feedback, positive or negative, characterizes this relationship.

HOMEOSTATIC GAIA

Gaia could be taken simply to mean that some of the interactions between the biota and the physical environment are stabilizing (i.e., characterized by negative feedback). If this is so, it is not surprising. Given that these feedback loops are numerous and that each must be either stabilizing or destabilizing, it is highly likely that some are stabilizing. Homeostatic Gaia can, however, be stated in two nontrivial versions: a weak form (the dominant interactions between the biotic and the abiotic worlds are stabilizing) and a somewhat stronger claim (these interactions make Earth's physical environment significantly more stable than it would have been without life).

Note that the simple fact of climatic homeostasis (to the extent that climatic and paleoclimatic data do or do not indicate stable conditions, a topic well beyond this paper's scope) is not at issue. Gaia concerns mechanisms through which homeostasis is thought to be maintained, not just the fact that it exists. Evidence of homeostasis is therefore not compelling evidence for Gaia; how can we tell whether the climate has been stable because of biotic processes or in spite of them?

The point has been made repeatedly (for example, by *Lovelock and Watson* [1982], *Lovelock* [1979a], and *Margulis and Lovelock* [1974]) that crude physical models of climate cannot explain why the Earth was warm enough to support life during the Precambrian, when the Sun is thought to have been approximately 25% dimmer than it is now [*Sagan and Mullen*, 1972; *Newman and Rood*, 1977]. This in itself is not a test of Gaia. The limitations of simple models (which assume that the Precambrian atmosphere had the same composition as at present, despite clear evidence for higher partial pressures of one or more greenhouse gases) do not necessarily imply that biological control mechanisms [e.g., *Lovelock and Whitfield*, 1982] are needed to resolve the "faint young Sun" paradox. The simplest solution to the paradox may be refined geophysical climate models, such as those of *Berner et al.* [1983] and *Walker et al.* [1981]. It is easy to speculate about hypothetical biological mechanisms that resolve the faint young Sun paradox and other incongruities in the climatic history of the Earth. The hard work lies in specifying a plausible, parsimonious, quantitatively realistic mechanism sufficient to dispose of the paradox and proposing and completing a test of that theory. One attempt to include quantitatively realistic biological

feedbacks in models of global temperature regulation [Volk, 1987] concluded that their effect would be small. A wide variety of hypothetical control mechanisms could be speculatively invoked to explain any given discrepancy between existing theory and data, but they should be testable against more than just the gaps they were selected to fill.

Lovelock and Margulis [1974a, pp. 100–101] and Margulis and Lovelock [1974, pp. 479–486] proposed a wide range of biological feedback mechanisms that might control the climate. Conspicuously absent from the bulk of the ensuing research, however, is any mention of processes that might destabilize the climate. For example, in a review of the role of oceanic phytoplankton in producing cloud condensation nuclei and altering the global radiation budget (the Gaian mechanism of climate regulation that has received the greatest attention to date), Charlson *et al.* [1987] note in passing that it is unclear whether the resulting feedback loop is stabilizing or destabilizing. They then discuss at length how stabilizing feedback might arise and how it might be instrumental in regulating climate; they do not address the possible origins and consequences of destabilizing feedback. Without knowing what biological mechanisms may undermine homeostasis, it is difficult to make a balanced assessment of the role of the biota.

Recently, ice core data have shown that variations in biogenic cloud condensation nuclei and carbon dioxide serve to amplify, not damp, the temperature excursions during glacial periods. Levels of nonmarine sulfate (a proxy for biogenic dimethyl sulfide, a precursor of cloud condensation nuclei [Charlson *et al.*, 1987]) are much higher during glacial periods than during interglacials [Legrand *et al.*, 1988]. Similarly, carbon dioxide levels are significantly higher during interglacials than glacials [Barnola *et al.*, 1987; Jouzel *et al.*, 1987]. These are the two most climatically influential biogenic compounds for which long-term records are available. Those records indicate that both of these biologically mediated feedback relationships are either (1) ineffective in offsetting nonbiological positive feedback processes controlling these compounds [Schwartz, 1988] or (2) actively destabilizing in their own right. Neither of these possibilities supports the notion of homeostasis through biological control of climate.

Lashof [1989] has estimated climatic and biogeochemical feedback responses to an anthropogenic greenhouse warming. Of the five biologically mediated feedbacks that he examines, only one (an increase in photosynthesis resulting from direct CO₂ fertilization) offsets the effects of an anthropogenic doubling of atmospheric CO₂. The other four biologically mediated processes (a decrease in vegetation albedo as the tree line moves north, an increase in plant respiration and metabolism of soil carbon, an increase in methanogenesis, and shifts in ocean biota

resulting in increased CO₂ release) would amplify the temperature rise expected from a greenhouse warming.

It is generally agreed that oxygen production by blue-green “algae” (recently reclassified as bacteria) changed the redox balance of the Precambrian atmosphere from reducing to oxidizing, in a demonstration of biological control that was clearly not homeostatic (and which virtually exterminated the microbes responsible for it). Lovelock [1979a, p. 31] and Lovelock and Margulis [1974b, p. 8] cite the fact that terrestrial life survived this event as evidence for Gaia’s resilient adaptation to change. If the most destabilizing biotic event in Earth’s history can be construed as evidence for Gaia, and the relative stability since then can also be cited as evidence for Gaia, one wonders what conceivable events could not be interpreted as supporting the Gaia hypothesis. If there are none, Gaia cannot be tested against the geologic record.

If Gaia stabilizes and Gaia destabilizes (since Gaia is a feedback system, those are the only two possibilities), is there any possible behavior that is not Gaian? Some might object that the biota’s destabilizing effect in the Precambrian indicates that Gaia had not fully matured, but such an objection is openly tautological; it defines Gaia in terms of homeostasis and then asserts that Gaia is homeostatic.

In the absence of clear evidence that biotic mechanisms do in fact stabilize the global environment, it seems wise to refrain from assuming that they ought to do so. It is wiser still, I think, to avoid the assumption that biotic mechanisms should be generally either stabilizing or destabilizing, or that the stability properties of these mechanisms are their most interesting or important features.

Before addressing the hypotheses that I have termed geophysiological Gaia and optimizing Gaia, I would like to pause here to comment on mathematical models of Gaia and whether they demonstrate biological homeostasis of the environment.

MODELS OF GAIA

An interesting outgrowth of the Gaia hypothesis has been a mathematical model demonstrating that homeostatic behavior can be achieved in a biotic system without any form of conscious control. The Daisyworld model [Watson and Lovelock, 1983; Lovelock, 1988], designed to be heuristic rather than realistic, describes a planet on which temperature is controlled by the albedo, which is determined by the color of the daisies growing on the surface. This model’s purpose is not to describe how the Earth’s temperature might actually have been regulated in the face of changing solar luminosity; instead, Daisyworld is intended to explore the consequences of strong coupling between the biota and the physical environment.

The theory behind Daisyworld can be outlined as follows. Biotic growth curves (as a function of environmental variables such as temperature) are characteristically peaked. If the variable of interest is a function of biotic populations, there is some range of changes in external conditions for which the effect of the induced shift in biotic populations offsets the imposed change (Figure 1).

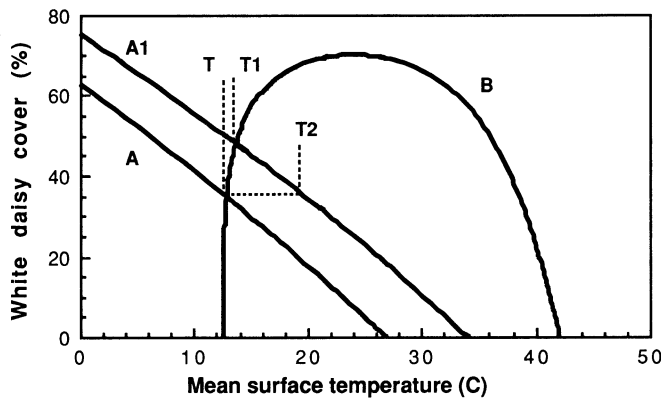


Figure 1. The effect of temperature on the population of daisies (B) and the effect of daisy cover on the mean temperature in the Daisyworld model (see text) for two values of solar luminosity (A and A1). This example assumes that only white daisies are present; increasing daisy cover raises albedo and lowers mean temperature. If solar luminosity increases from A to A1, the resulting temperature rise increases daisy cover and raises albedo, limiting the temperature rise from T to T1. If daisy cover did not respond to temperature, the shift in luminosity would result in a temperature increase to T2. Parameter values used are those of *Watson and Lovelock* [1983]. These curves differ from those of *Lovelock* [1986b, p. 15] because the latter are mislabeled. What *Lovelock* refers to as “daisy population” is actually β , one factor in the growth rate equation [*Watson and Lovelock*, 1983, equation (1)]. What *Lovelock* refers to as “mean temperature” is actually the temperature of the daisies. Mean temperature is a function of the daisy temperature, the temperature of bare ground, and the fractional daisy cover. The model is very stable because the selected parameters make daisy cover a nearly vertical function of temperature at the operating point T. Daisy cover shifts from zero to 45% in response to a temperature change of only 1°C.

This result is general and holds whether the daisies warm or cool the surface. Figure 2 shows the behavior of the model when both light and dark daisies are assumed to be present; the surface temperature is held nearly constant over wide excursions in solar luminosity.

It is easy to see how the result in Figure 2 is obtained. Black and white daisies are assumed to have exactly the same growth response to temperature, but black daisies are assumed to be 10°C warmer than white daisies in equivalent ambient conditions. Consequently, black daisies thrive in cooler ambient conditions, lower the albedo, and warm the surface, while the opposite is true of white daisies.

Watson and Lovelock's conclusion that “regardless of the directions of the feedbacks, the model always shows greater stability with daisies than it does without them”

[*Watson and Lovelock*, 1983, p. 288] (italics in the original) indicates a selectivity of emphasis. There is a range of luminosities for which the temperature/luminosity curve is flatter than it would have been without daisies, but there are also ranges where it is much steeper (as simple continuity between the endpoints requires). If the operating point is near either end of the stable range, small shifts in luminosity can have drastic consequences. Perturbations could also cause the system to suddenly jump from one path of the hysteresis loops to another. The sense in which such behavior indicates “greater stability” is unclear.

Likewise, the claim [*Lovelock*, 1988, p. 46] that “in no way is the stability of Daisyworld dependent on an idiosyncratic choice of initial values, or rate constants” needs to be qualified. Daisyworld exhibits stability near the optimal temperature for daisies because the black daisies, which warm the surface, thrive in cooler temperatures than the white daisies, which cool it. But what if, instead, the optimal temperature for black daisies were 15°C higher than that for white daisies? (A higher optimal temperature might explain why the black daisies evolved to be 10°C “warmer” in color while sharing the same environment as white daisies.) If this were true, black daisies would thrive in warmer temperatures and would tend to keep the surface warm (and vice versa for white daisies). The result is a tug-of-war between the two types of daisies. As Figure 3 illustrates, a Daisyworld regulated in this way is a hysteresis loop, where each value of solar luminosity gives two equilibrium temperatures (each representing complete extinction of one or the other type of daisies) that lie well outside the optimal temperatures for either species. Climatic perturbations would likely result in unstable transitions between the upper equilibrium, in which a too hot Daisyworld tries to keep itself too hot, and the lower equilibrium, in which a too cold Daisyworld tries to keep itself too cold.

What is most interesting about this “pathological” Daisyworld that I have described is that the available data suggest that the biotic feedbacks regulating climate actually work this way. As pointed out above, ice core analyses indicate that during glacial periods, biological processes produce less carbon dioxide and more cloud condensation nuclei. In other words, biological processes appear to make the planet colder when it is cold and warmer when it is warm. *Dickinson and Hanson* [1984] and *Hansen et al.* [1984] have estimated how Earth's vegetation patterns would shift in response to global temperature changes; they found that planetary vegetation albedo would shift in ways that exaggerate, rather than offset, the imposed temperature change. Of course, the Daisyworld model is heuristic and is not meant to imply that the Earth's temperature is actually regulated by changes in vegetation albedo. Nevertheless, to the extent that vegetation albedo actually does influence climate, the

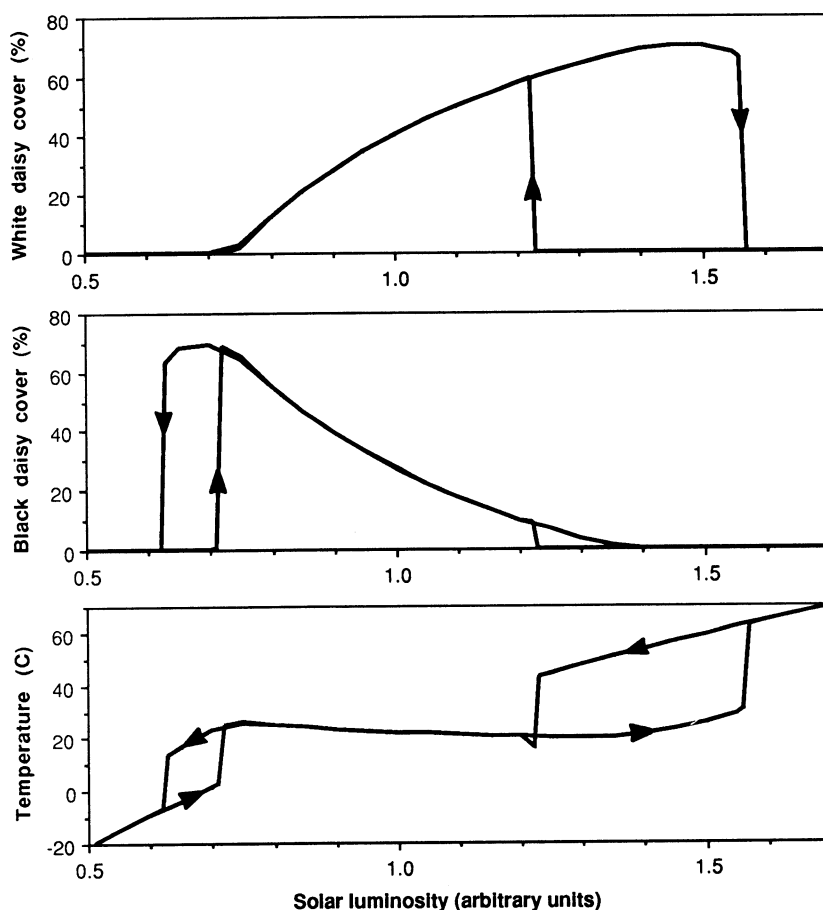


Figure 2. Mean surface temperature and daisy populations for the Daisyworld model incorporating both black and white daisies over a range of solar luminosity (adapted from *Watson and Lovelock* [1983]). *Watson and Lovelock* do not show the hysteresis loops that arise when solar luminosity decreases; they are shown here to illustrate the existence of multiple equilibria in some ranges of luminosity. Black daisies will be warmer than

the ambient temperature, and white daisies cooler, owing to their coloration; black daisies thrive in ambient temperatures around 15° to 25°C and warm the surface, while white daisies thrive in ambient temperatures around 20° to 30°C and cool the surface. As a result, over a wide range of solar luminosity the surface is maintained at temperatures favorable for one or both daisies.

available data indicate that it does so in the way that the pathological Daisyworld (instead of *Lovelock and Watson's* Daisyworld) says it should.

Do models such as Daisyworld constitute [*Lovelock*, 1983, p. 66] "a cybernetic proof of the Gaia hypothesis"? Of course, clever modelers can make a model do almost whatever they want, but the point I will try to make here is slightly more subtle. Models are often used to derive the consequences of hypotheses. When the model's components can be independently verified or have been derived from well-grounded mechanistic theory (as in climate modeling), the results can be particularly useful in comparing theory and observations. However, the results of heuristic models like Daisyworld cannot be directly tested against real world data. Consequently, the theory is tested, not by comparing model and real world behavior, but by comparing model results to the behavior predicted by the Gaia hypothesis. That kind of test will inevitably succeed (barring logical or mathematical errors) because it is not comparing a theory with data, but comparing a

theory (in words) with itself (in mathematical terms). Such models can be used to derive and illuminate the implications of the Gaia hypothesis, but not to establish its validity.

GEOPHYSIOLOGICAL GAIA

Lovelock [1986b, 1988] has recently proposed "geophysiology," the representation of the biosphere as a single organism, as a systems approach to Earth science. In this view the biosphere, like an organism, will generally maintain internal homeostasis in the face of changing external forces. Just as physiology addresses the functioning of whole organisms, geophysiology is intended to unify the constituent parts of the biosphere and the disciplines that address them. According to *Lovelock* [1988, preface], "specialties, like biogeochemistry, theoretical ecology, and evolutionary biology, all exist, but they have no more to offer the concerned environmental

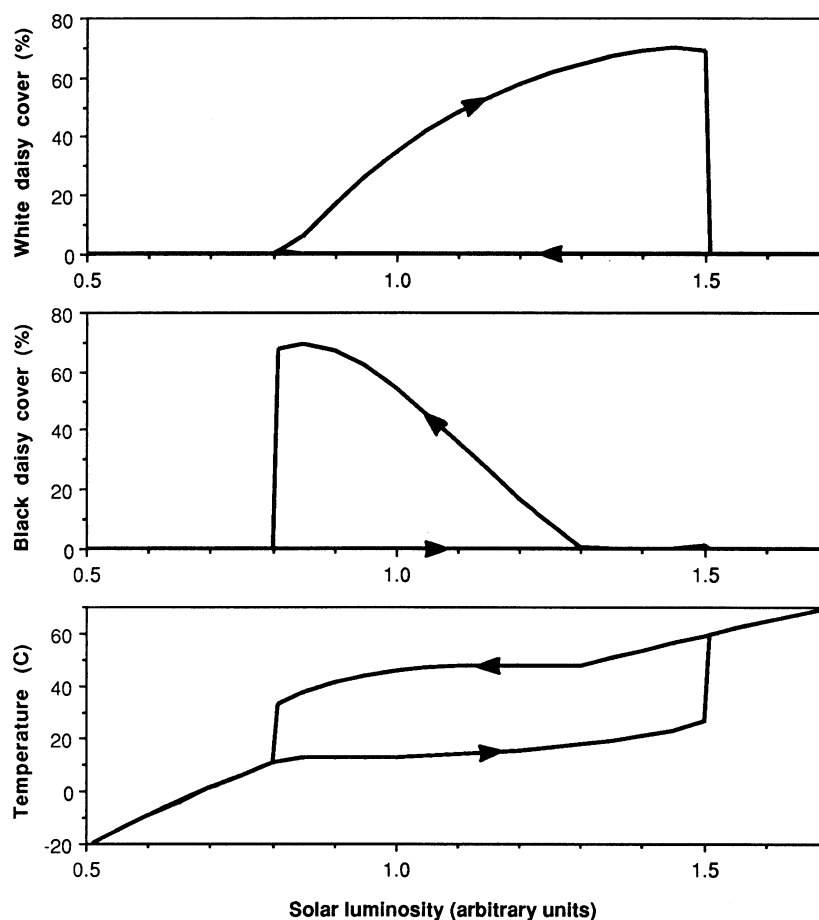


Figure 3. Daisyworld exhibiting “pathological” behavior as a result of fixing the optimal temperature of black daisies at 15°C above that of white daisies. Doing so reverses the bias implicit in *Watson and Lovelock’s* [1983] assumption that black daisies are 10°C “blacker” than white daisies. Note the existence of two

equilibria, both outside the ranges of ambient temperatures that are favorable for either daisy color (20°–30°C for white, and 30°–40°C for black). At either equilibrium, one of the daisy species is driven to extinction.

physician or the patient than could the analogous science of biochemistry or microbiology in the nineteenth century.”

Some systems level approach to Earth science is desperately needed, but should this be its basis? It may be misleading to use the same language we apply to organisms when discussing the biosphere as a planetary organism. To borrow a point from evolutionary biologist E. Mayr, there may be no such thing as a healthy herd of deer, but only a herd of healthy deer. Now, a herd (or a planet) may be said to be healthy, but not in the same sense that one of its members is healthy.

It is important to distinguish geophysiological Gaia from an Earth-as-organism metaphor. Consider, for comparison, the Earth-as-mechanism metaphor that underlies contemporary natural science. The success of this mechanistic framework has demonstrated the effectiveness of thinking about the natural world as if it were a machine (whether or not it actually is, in any sense, a mechanism). I would agree with the proponents of Gaia that it may be useful to attempt to speculate about the

natural world *as if it were* an organism. But the question of whether the Earth *actually is* an organism is neither scientifically meaningful nor scientifically answerable.

As a hypothesis, the biosphere/organism metaphor is, like all metaphors, ill-defined. In which senses is the Earth like an organism, and how can we tell how far to take the analogy? The vast diversity of living organisms, from men to microbes and plants to pachyderms, means that any conceivable phenomenon could be compared to some behavior of some organism. For example, geophysiology explains the sudden redox shift at the end of the Archean, a dramatic example of biological destabilization, in terms of puberty [Lovelock, 1988, p. 99]. Similarly, geophysiology reinterprets the ice core data (which suggest, as described above, that biological feedback reinforces the temperature shifts between glacial ages and interglacials, rather than homeostatically opposing them) in the following way [Lovelock, 1988, pp. 136 and 150]: “the glacial cool is the preferred state of Gaia, [and] the interglacials like the present one represent some temporary failure of regulation, a fevered state of the planet . . . [during glacials] cloud

cover and low carbon dioxide operated in synchrony as part of a geophysiological process to keep the Earth cool.”

Geophysiology can be endlessly reinterpreted, and for that reason it is unfalsifiable. Any conceivable behavior could be taken to be physiological, particularly if one defines the physiologically “preferred” state at will and if one considers physiological breakdown (e.g., “feverish” interglacials) to be evidence for physiological behavior. Geophysiology predicts [Lovelock, 1988, p. 13] “homeostasis for long periods until some internal contradiction or external force causes a jump to a new stable state.” But external forces and internal contradictions are always prevalent; any instability could (perhaps erroneously, since a balance of “internal contradictions” can be stabilizing) be attributed to any number of such causes. Moreover, given that stasis is defined as the absence of jumps, and jumps are defined as the absence of stasis, geophysiology seems to predict simply that the biosphere will exhibit homeostasis except when it does not. It is futile to try to falsify such a hypothesis, or to try to derive meaningful predictions from it.

To some, an endlessly interpretable theory is appealing because it can be used to explain virtually anything. But for the same reason it predicts nothing, and its explanations are empty. If any conceivable phenomena can be explained by geophysiology, then geophysiology says simply that “anything is possible.” The value of a scientific theory, by contrast, lies precisely in limiting the sphere of the possible, thereby allowing one to separate the plausible from the implausible.

If the purpose of geophysiology were simply to spur interesting speculations about the climatic history of the Earth, one might not object. But Lovelock [1986b, p. 12] (see also Lovelock [1988, pp. 152–182]) expressly advocates geophysiology as “the essential theoretical basis for the putative profession of planetary medicine” to cure Earth’s environmental ills. With no means of testing the underlying theory, how can one tell whether the cures it recommends are the planetary equivalent of penicillin or of bloodletting? The risk of creating iatrogenic global maladies through treatments that have no testable basis should not be underestimated. It is hard to see how geophysiology could help us to distinguish between “planetary medicine” and planetary malpractice.

OPTIMIZING GAIA

The most speculative version of the Gaia hypothesis holds that biotic control of the physical environment creates conditions that are favorable, or even optimal, for the biosphere. This hypothesis is ill-defined unless one can specify what constitutes favorable or optimal conditions. It can be demonstrated that for any set of conditions,

there is some “objective function” that those conditions optimize. Every conceivable environment can be “favorable,” if one has complete freedom to specify what it is favorable for.

What could possibly be optimal for the whole biosphere? One can define an optimal environment for a given organism in a number of ways. But what conditions are optimal, or even simply favorable, for a diverse collection of organisms that have conflicting requirements? One response is that current conditions are optimal, but this creates an obvious tautology by defining optimality in terms of prevalent conditions and then asserting that prevalent conditions (assumed to be maintained by biological control) are, in fact, optimal.

Stability and optimality (for the agent supplying the homeostasis) are mutually exclusive. The population of an organism that makes its environment more suitable for itself will grow, whereupon it dominates more of the environment and grows still further; this behavior is destabilizing. Stability is achieved by organisms “fouling their own nests” and thereby limiting their population growth.

Consider the Daisyworld model in a world with only white daisies. At a stable point the daisies supply homeostasis because if the temperature rises, more daisies grow and the albedo increases. This implies that a higher temperature would be more suitable for white daisies, so the temperature at the stable point is cooler than optimal, and the daisies’ growth response prevents a warming that would be favorable for them. At the peak of the daisy growth curve, there is no homeostasis; if the temperature increases, daisies die, and the temperature increases still further, and more daisies die. The optimum is reached only in an unstable transition between a stable suboptimum and total extinction.

A common objection to Gaian optimization is that it is teleological; it would require some sort of foresight and planning [Doolittle, 1981]. It is important to note that one can form a mechanistic scenario for the evolution of favorable conditions without any “engineering,” just as ants and termites have evolved strategies for regulating the temperature of their nests without being told how to do it:

Lovelock and Margulis [1974a, p. 99]

Although the environmental control mechanisms are likely to be subtle and complex, we believe their evolution can be comprehended broadly in terms of Neodarwinian thought. . . . Analogous with the evolution of local environmental or internal control, in the evolution of atmospheric homeostasis those species of organisms that retain or alter conditions optimizing their fitness (i.e., proportion of offspring left to the subsequent generation) leave more of the same. In this way conditions are retained or altered to their benefit.

Margulis and Lovelock [1974, p. 486]

It is a recognized fact of biology that environments are regulated on a much more local scale . . . We merely suggest extrapolation of these ideas to the entire atmosphere-biosphere system.

Lovelock [1986b, p. 13]

Life and the environment evolve together as a single system so that not only does the species that leaves the most progeny tend to inherit the environment but also the environment that favors the most progeny is itself sustained.

The problem with these arguments is not that they are demonstrably wrong, but that they are radically unparsimonious and, given ordinary Darwinian removal of the unfit, they are unfalsifiable. For global control to arise by evolution, an organism's effects on "the entire atmosphere-biosphere system" would need to be significant enough to affect its own reproductive success. This is highly implausible, as *Doolittle* [1981] has pointed out: "It is difficult to accept that behaviors whose effects . . . will not be felt for thousands of generations can be selected for, especially when the first beneficiaries of those effects may be organisms which are not themselves responsible for them." Recently, *Lovelock* [1988, pp. 126–151] has emphasized Gaian mechanisms arising through behaviors that benefit organisms directly, in other than Gaian ways. But if the connection between individual reproductive advantage and Gaian altruism is only coincidental, we would expect Gaian and non-Gaian behavior to arise with equal probability. Darwin said it all much more straightforwardly: the environment and the biota are well matched because organisms that are poorly adapted will be underrepresented in the next generation's gene pool.

Given that the unfit are selected against, claims that Gaia creates a favorable environment are unfalsifiable. Whether or not Gaia optimizes, we would still observe that the Earth's organisms match its environment, because organisms that do not suit the environment do not thrive and will not be noticed. *Holland* [1984, p. 539] put it quite simply:

The geologic record seems much more in accord with the view that the organisms that are better able to compete have come to dominate, and that the Earth's near-surface environments and processes have accommodated themselves to the changes wrought by biological evolution . . . We live on an Earth that is the best of all possible worlds only for those who are well adapted to its current state.

When, at the recent AGU Chapman Conference on the Gaia hypothesis, I raised an objection to Gaia, arguing that the Earth's physical environment was obviously not

favorable for penguins, I was met with the response that Arctic animals are eccentric, exotic, fringe species. That, of course, is exactly the point; on a much colder Earth, penguins (and latter-day mastodons, perhaps) would be more prominent, and scientists would peer out from their fur coats to observe that the environment seemed ideally suited to their needs.

CONCLUSIONS

The proponents of the Gaia hypothesis have made three valuable contributions. First, they have reiterated the point originally made by those investigating biogeochemical cycles, namely that biological agents play a vital role in creating the Earth's physical and chemical environment and that those interested in the surface chemistry and physics of the Earth cannot arbitrarily ignore biological processes. Second, they have suggested some mechanisms by which the biota may be particularly important in determining the Earth's climate. Third, they have created an engaging and colorful metaphor that some have used as a unifying theme and a motivator for research. In my view, however, this metaphor (if taken literally) is ultimately misleading and will needlessly color one's impressions of how the biota and the physical environment interact. Attempts to test this metaphor as a scientific proposition will be, in my opinion, ultimately futile.

Some have viewed Gaia as a daring but viable hypothesis. My view is that each of the different Gaia hypotheses is either daring or viable, but not both. Coevolutionary Gaia is testable but not daring; it simply recasts, in different language, the long-standing and widely accepted observation that biological processes and the physical environment influence one another. The claim that these interrelationships are generally, or even universally, stabilizing (homeostatic Gaia) may be testable and may well spur some interesting research into the feedback mechanisms controlling climate. The scanty data available to date, however, tend to refute the hypothesis itself. Geophysiological Gaia, by contrast, cannot be refuted by data, not because it is inescapably correct, but because it is ill-defined and can be reinterpreted to explain almost any imaginable phenomena. Optimizing Gaia is similarly ill-defined, and given simple Darwinian elimination of the unfit, it is both unparsimonious and unfalsifiable.

Gaia is crippled by its great generality; it searches for a simple capsule description of the role of life on Earth. The key fact, that the biota and the physical worlds are interconnected, was realized long ago. The day-to-day task of figuring out "how the world works" consists of documenting these interconnections and their consequences. There is a lot of difficult, important science to be

done here, and we should get on with it. An untestable belief that these relationships ought to have some general form or function may only blind us to what they actually are and actually do. What is "out there," what can be observed, measured, hypothesized, verified, and falsified, is biogeochemistry, natural selection, evolution, and so forth. Gaia may be a grand vision, but it is not the kind of vision that can be scientifically validated.

Some may object that to abandon the empirical search for Gaia is to forgo the chance of discovering a grand, ultimate truth. With *Poincare* [1905, p. 163] I would respond,

To those who feel that we are going too far in our limitations of the domain accessible to the scientist, I reply: These questions which we forbid you to investigate, and which you so regret, are not only insoluble, they are illusory and devoid of meaning.

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