TOWARD A FUTURE FOR GAIA THEORY

An Editorial Comment

The three papers in this issue of *Climatic Change* (Kirchner, 2002; Kleidon, 2002; Lenton, 2002) are probably the most concentrated effort in recent years by several prominent theoreticians of the biosphere to set forth their views on the current status and future of Gaia theory. (Also see the forthcoming volume by M.I.T. Press of the proceedings from the Second Chapman Conference on the Gaia Hypothesis, Valencia, Spain, 2000.)

The three papers offer strikingly different renderings. Axel Kleidon asks whether life on global scales enhances itself by improving environmental conditions through its activities. His analysis suggests 'yes.' He further recommends that primary production measured in carbon units should be utilized as a 'metric' (my term) for Gaia theory.

In contrast, Timothy Lenton focuses not as much on environmental parameters but on whether a global system with life, compared to a sterile planet, will be more resistant to change and also more resilient in its rapidity of response to change. Lenton concludes, tentatively at least, that the Gaia system does enhance regulation and that this regulation will tend to accumulate over time.

The message in the third paper, by James Kirchner, runs counter to both Kleidon and Lenton. Kirchner uses evolutionary arguments to show why we should expect Gaia neither to be more stably regulated than an abiotic system nor produce an enhanced environment for life.

Overall, I am most in agreement with Kirchner. As I will emphasize, the dynamics of evolutionary adaptation have far too often been neglected by Gaia theorists. In this essay I will concentrate first on the arguments advanced by Kleidon and Lenton, looking both at their shortfalls and positive offerings. Eventually I will try to use ideas from all three papers to sketch out what I see as tasks for the future of Gaia theory, which involves the ongoing search for general principles of the biosphere.

1. Primary Productivity as a Metric

Kleidon proposes that the metric for Gaia – a means to measure Gaia-ness – should be gross primary productivity (GPP). Therefore a test for a positive Gaia would look for cases where $\text{GPP}(E_B) > \text{GPP}(E_A)$, in which (E_B) are environmental conditions in a biotic world and (E_A) are the environmental conditions in an abiotic

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world. Kleidon eventually concludes that ‘life has a strong tendency to affect its environment in a way that enhances the overall benefit’.

How does he reach this judgment? Basically by way of two examples: (1) terrestrial rainfall would be less without terrestrial life, and (2) life enhances the number of turns in the chemical cycles. But is this sample too limited to warrant his conclusion?

If someone tells you ‘all trees are green’ and then shows you an oak tree and a maple tree as examples, you wouldn’t want to even start to think they were right until they showed you examples from many more species. Such is basically Kleidon’s logical weakness.

One can easily find counter examples in which life is detrimental to the environment. It is well established that in most regions marine life severely depletes the global surface ocean of many key nutrients, among them phosphate and nitrate. Today’s marine productivity would be significantly higher under the chemical conditions of an abiotic ocean, where, with respect to current surface inventories, global phosphate and nitrate would be higher by about tenfold. This ocean situation is an example of a general Gaia principle that Toby Tyrell, speaking at the aforementioned Chapman Conference termed ‘biotic plunder’, which is exactly opposite of Kleidon’s conclusion. For ocean surface nitrate and phosphate, $\mathrm{GPP}(E_A) > \mathrm{GPP}(E_B)$, a situation that falls under Kleidon’s ‘antigaia’ null hypothesis.

We should also consider carbon dioxide. Regarding this important atmospheric constituent, it is almost certain that today’s life would be more productive under what scientists compute as higher abiotic levels of CO_2. The longterm, biologically influenced steady state of carbon dioxide is lowered by the ‘biotic enhancement of weathering’ (Schwartzman and Volk, 1989; Schwartzman, 1999), and it is also well established that most plants (particularly those with the C3 pathway) would do better under higher CO_2 levels.

These counter examples indicate that Kleidon’s conclusion that ‘life has a strong tendency to affect its environment in a way that enhances the overall benefit’ is not warranted. If the complex changes that life works upon the environment enhances the environment in fifty percent of the cases but are detrimental in the other fifty percent then it will not be too difficult to find supporting examples for either side. From a few conforming examples drawn from the wealth of interactions within the biosphere it will never be possible to convincingly demonstrate anything truly general about Gaia.

Nevertheless I do support Kleidon’s concept that we need to quantify a degree of Gaia-ness by way of a ‘metric’, such as his primary productivity. A metric or set of metrics is sorely needed if Gaia theory is to move beyond verbal bantering and selected examples of this or that effect. Some time ago Schneider (1986) saw the lack of an agreement on a metric as a problem for the Gaia hypothesis. Too little has been done to address the issue Schneider raised. I applaud Kleidon for trying to make progress here.

2. The Question of Self-Regulation

I also salute Lenton for coming to grips with a term that is often bandied about by Gaia theorists without adequate definition. The term is 'self-regulation'. The problem is that it is difficult to know what self-regulation as a special Gaia property could possibly mean, because how can the Earth – biotic or abiotic – not be self-regulating?

To his credit, Lenton admits that plain old abiotic chemistry is also self-regulating. The existence of a chemical steady-state by itself is no example of how Gaia is special, because abiotic chemical systems with input and output flows usually also produce steady states. Are not the atmospheres of Venus and Mars self-regulated? On Earth, to be sure, life participates in the creation of chemical states and influences the rates of chemical transformations. But the existence of relatively steady states by themselves should not tempt us to talk about a special Gaia.

Does life, however, contribute an ingredient to the self-regulation that would be intriguing and thus lead to a theory of Gaia? Lenton points to two possibilities, called by traditional ecologists 'resistance' and 'resilience'. Does life make the chemical system of Gaia more resistant to changes? Does life make the system more resilient to changes in that the return is quicker to some steady state (not necessarily the original state) following an external perturbation?

Lenton tentatively concludes 'yes' to both questions. His evidence is more extensive than Kleidon's in that Lenton offers more examples. Yet, like the situation with Kleidon, how can we be sure that Lenton is not giving more weight to evidence that fits his pre-selected conclusions? It is gratifying that he does offer counter examples. And the complexity of the Earth system, as he acknowledges, makes it difficult to even address the issues of resistance and resilience on a global scale.

I cannot tell whether Lenton (or Kleidon for that matter) is correct or not. Lenton does suggest a crucial role for models and it seems to me that it is to models that we must ultimately turn for possible generalizations.

For example, the increased rates of chemical fluxes created by life in the environment imply shorter turnover times of elements in reservoirs of ocean, air, and soil. Shorter turnover times generally mean more rapid returns to steady conditions following perturbations. Thus it seems probable that Lenton may correctly generalize when he cites various models, say of Earth's oxygen, that show faster recovery times with life.

But we need to do better. In Gaia theory, the traditional model has been Daisyworld. This served its purpose long ago to introduce the idea of life creating stability in the face of external change to the environment. But in my opinion Daisyworld is no longer acceptable. It is too far removed from the real world.

Most problematic is that Daisyworld is not a model of chemical flows. If anything, Gaia theory is going to be a theory about Earth's chemistry, because the chemical constituents of the air, water, and soil that surround organisms are what the organisms primarily affect. Such a theory requires an understanding of chemical flows and life's effects on those flows. Furthermore, with chemical flows we typically have situations in which the local effects are not the same as the global effects. For example, consider the biotic enhancement of weathering. Life's activities on a local scale that preserve soil or attack elements in soil minerals to gain nutrients such as phosphorus have the effect of decreasing carbon dioxide on the global scale. This is unlike the Daisyworld situation in which the black daisies, for instance, by warming themselves also warm the planet.

What we need are models that look at chemical flows with and without life in a generalized manner and that examine the consequences of life on the resistance and resilience of their environments. Lenton has done a service by helping to point out a direction to go.

3. Costs, Benefits, and Evolution

Kirchner attacks much of the edifice of Gaia theory and I am in substantial agreement. I will not review his many trenchant points here except to emphasize a couple that stand out to me.

First, he shows that biological effects are not necessarily stabilizing (thus countering Lenton's property of resistance). He considers anthropogenic global warming as an example, and provides a list of positive feedbacks that non-human forms of life exert on the environment, in which rising temperatures cause changes to these forms of life, creating further increases in carbon dioxide, other greenhouse gases, or temperature directly via albedo effects. There are negative feedbacks as well. So I conclude that, as stated above, the Earth system with life is complex and there has not yet been enough evidence that convinces me of anything special about the state of the system except for its interwoven complexity. I see nothing that is Gaia in terms of Gaia theory's 'classical' terminology of homeostasis or stability.

Second is the issue raised by Kirchner regarding the nexus of evolution and Gaia theory. Life alters the environment – this we all accept. We also accept that subsequent forms of life will adapt themselves via the process of evolution to that environment. Humans require the current high levels of oxygen in the air and would quickly suffocate in the atmosphere of three billion years ago. It looks as if the atmosphere is in a condition that benefits us, but that is only because our ancestors evolved to fit with high levels of oxygen.

This issue applies to creatures that change the environment and then themselves adapt to it. Kirchner picks up on the issue of rainforest vegetation and the increased local rainfall caused by transpiration, one of Kleidon's examples of a beneficial effect of life on the environment. All right – part of the rainforest's support is its own transpiration falling back as rain. But the rainforest vegetation has adapted and thus, in some sense at least, has evolved for these conditions. It did not create the conditions of high rainfall because it needed them to benefit, although it appears to benefit from those conditions. Kirchner points out that the semantics we use to interpret this and similar situations is crucial.

Let us go into the issue of transpiration more deeply, specifically to talk about costs and benefits on local and global scales. Did transpiration evolve to enhance rainfall? Certainly not. It evolved as a byproduct of plants opening their stomata to capture atmospheric CO_2 and also to bring up nutrients from the leaves. In other words, to some extent transpiration, as dispersion of water vapor up into the atmosphere, is a free product of some other necessity for plants. The effects of transpiration on rainfall are for free. The effects are from free byproducts.

Consider: If some plant developed xylem vessels specifically for the function of transpiring to increase rainfall, then a neighboring mutant plant without spending the energy to grow the xylem would reap the same benefits from the rainfall, grow better and soon out compete the xylem-producing plant. Plants do not produce xylem to increase rainfall, they produce xylem for internally beneficial reasons. Such reasoning is why we cannot expect there to be any life-enhancing properties on the Gaia scale, if it costs the organisms to produce such properties. The way I put it in an earlier writing, 'Gaia is (probably) built from free by-products, side effects' (Volk, 1998, p. 241).

I added the qualifier 'probably' because I admit that all the issues of evolutionary costs and benefits on different scales are not fully worked out. (See, for example, Klinger (1996) on the self-enhancing characteristics of bogs.) But at least I recognize the seriousness of the issues. Thus I have problems with statements such as that by Kleidon, in which he says that the tendency of life to enhance the environment, such as in his transpiration and rainfall example, 'can be understood as an emergent property of evolution since life-enhancing effects would be favored by natural selection'. (By the way, Kleidon cites a 1998 paper by Lenton at the end of this statement.) Not only have I not seen any proof of this assertion anywhere in the Gaia literature, but I completely disagree with it.

4. The Future of Gaia Theory

In my opinion, the subject of Gaia theory is the network of chemical relationships that comes into existence as a result of effects of living things on their environments and the evolution of those living things, with the resultant effect on the environment (closing the cycle). At the Valencia Chapman Conference, when I presented the concept that Gaia is built from a network of byproducts, Dick Holland of Harvard University rose during the question period. He asked whether in my view Gaia theory is now equivalent to figuring out the global biogeochemical cycles.

In some sense, yes. The truth about the Earth will in the end be the same truth no matter what framework of inquiry we use. We are trying to discern the operations of the biosphere. There is not a Gaia truth different from some other truth. There is only understanding for each fact we seek to uncover, regarding, for example, the biotic enhancement of weathering, the evolution of transpiration, the state of ocean surface nutrients impacted by the activities of plankton.

In another sense, however, I also had to answer no. As a field of science develops, there are ways of asking questions that might help us blaze quicker paths to the truths. What initially made Lovelock's ideas so exciting, in the early books, was the potential of a common explanatory principle behind many aspects of biosphere chemistry. Could there be a basic reason involving life's presumed homeostatic actions common to global temperature, atmospheric oxygen, the carbon cycle, and ocean salinity? Could many mysteries of the biosphere have a single who-done-it?

Lovelock's initial conclusions, in my judgment, did not pan out. But many of us continued forth, at least inspired by Lovelock's emphasis on feedback loops and his knack for asking big questions. I was inspired by Lovelock's early writings to move into issues about the effects of life on a global scale that led to technical work I would not otherwise have accomplished. But for me at that point Gaia became more of a name for a scientific program. Gaia became a way of thinking, a mantra to be mindful of the biggest scale. But then what do we have if Gaia theory is a way of generating hypotheses and not a specific hypothesis about the way the biosphere works?

More strongly than ever, I think we must disregard many of the ideas of what I will call traditional Gaia theory. (Kirchner's current paper contains a good summary of the tradition.) But at the same time I do suggest that we also keep the essence of Lovelock's search. This essence is the possibility for general principles that apply across many specific instances of the biosphere. We are not nearly at the end of our seeking. Perhaps there are some overarching principles we are currently missing. What could they be? I think the papers by Kleidon, Lenton, and Kirchner are essential study for those seeking ideas about such biosphere-scale principles. I now offer my own summary of the future of Gaia theory.

Let us experiment with biosphere-scale metrics in the way that Kleidon proposes primary productivity as his choice. At least then we will have quantitative bases for comparing measurements on various states of Gaia, either from data or from models.

My own candidate for a metric is the 'cycling ratio'. The cycling ratio is defined, for any scale system of choice, as the ratio of the flux of any specific element into the photosynthesizers within the system relative to the flux of that element into the system across the boundaries. The cycling ratio measures the amplification of life by the totality of processes within the system compared to the case if photosynthesis were limited to the external supply of an essential element (Volk, 1998).

So let there be debates about metrics and trial balloons of different metrics. Schneider raised this issue of the need for a metric years ago (Schneider, 1986). This issue needs to be addressed if Gaia theory is going to move forward. With a metric or metrics we can seek out patterns. Then, finding patterns, we can ask about principles.

Furthermore, Gaia theory needs new models in the search for general biosphere principles. Particularly in his concept of resilience, Lenton might be on to a principle that can be demonstrated by a generic model, perhaps similar to Daisyworld in its 'toy' simplicity but concerned with chemical fluxes. Lenton thinks that the Earth with life is more resistant to change, although Kirchner, as we have seen, thinks otherwise. Models can help here. Readers searching for some new directions might look at the recent Gaia modeling by Downing and Zvirinsky (1999), who used genetic algorithms to 'evolve' chemical cycles.

Lastly, following the analysis of Kirchner, we need to cease talk about life benefiting the environment without being clear about what the costs are to the life forms that produce these supposed benefits (also see Volk, 1998, final chapter).

In general, life forms will not be able to send forth costly beneficial substances that become dispersed in the environment, because the benefits also support other organisms that do not carry the costs of production, mutants of the same species, for example, that benefit without contributing. In general, Gaia (whatever 'she' is) is likely built from environmental effects that are released as free byproducts from metabolic pathways evolved for direct benefit to the organism's internal milieu.

As admitted, all the issues about costs and benefits on different scales need to be worked out and surprises might await us as we analyze nature. But the scientists in Gaia theory need to stop making blanket statements that evolution will select life forms that benefit their environments.

What appear to be benefits are just chemical wastes put forth that inevitably influence the evolution of other creatures to use those wastes and also to adapt to the presence of the wastes as part of the chemical matrix that surrounds them. The biosphere's network changes as creatures evolve, probably creating a general trend toward a higher cycling ratio (or primary productivity) in evolutionary time, but not because environmental conditions have been improved. In general, I predict that the concept of Gaia will progress from Daisyworld into something we might call Wasteworld.

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