Exploring Gaia Theory: Artificial Life on a Planetary Scale

Keith Downing
The Norwegian University of Science and Technology
Trondheim, Norway
keithd@idi.ntnu.no

Abstract

Gaia theory, the view that the biota can both affect their environment and do so in a manner that benefits life in general, is an extremely controversial interpretation of the complex relationships between the biota and biosphere. Since individual Gaian phenomena can span spatial scales from cellular to planetary, they evade thorough analysis and empirical validation. Consequently, a good deal of Gaian thinking revolves around an abstract computer model, Daisyworld [24]. However, this model fails to properly account for natural selection's role in Gaian emergence. Although we propose an alternate scheme that offers some improvement - one based on evolutionary computation and individual-based simulation - the field remains wide open for investigations from the alife perspective. This paper reviews both models along with a few natural Gaian phenomena before generalizing a set of common primitive features and emergent properties from the real and artificial examples. These shared characteristics will hopefully provide a backbone for a much-desired “Gaia-logic” and assist other alife researchers in the search for additional Gaian models.

Introduction

In the 1960’s, James Lovelock, a NASA atmospheric chemist, analyzed infrared spectrometer readings of the Martian atmosphere to assess the probability of life on Mars. He found an atmosphere very near chemical equilibrium, a telltale sign of a dead planet [14, 15]. Since Earth’s atmosphere is very far from equilibrium, Lovelock argued that the biota are the key to maintaining this dissipative, low-entropy state. At the time, the idea that living organisms could affect large-scale environmental change was highly controversial, but considerable evidence of life’s influence, particularly on geochemistry, has persuaded many earth scientists to accept the biota as a driving force of planetary change.

However, Lovelock and Lynn Margulis [16] felt that the biota had an even stronger role: they could not only affect the planet, but could do so in a manner that was beneficial for life. In short, the biota indirectly regulate planetary conditions within a window of survival that is largely defined by their own physiologies. Many Gaians expand this definition of the basic Gaia theory to include all situations in which the biota modify the environment to the benefit of life itself.

This radical viewpoint has evoked cries of “teleology” and “pop ecology” from a host of renowned scientists, but putting aside ancient prejudices and stale dogma, one sees a variety of interesting examples where the biota appear to play a major role in making the planet more liveable. These include the regulation of local climate by algae [4, 17], the control of global temperatures by photosynthetic organisms [26], the maintenance of relatively constant marine salinity [8] and nitrogen-phosphorus (N:P) ratios [12, 18, 23] by aquatic biota, and the emergence of efficient recycling loops among diverse microbial species [23, 25].

As evidence of these phenomena accumulate, many natural scientists have accepted Gaia’s essence: life begets life. However, many Neo-Darwinians remain skeptical, since the evolutionary origins of ecosystem-level homeostatic loops with biotic components are difficult to envision, and are in fact counter to the competitive, survival-of-the-fittest views of natural selection. Gaian interactions involve the coordination of many biological, chemical and physical activities, as illustrated by the networks of diverse microbes involved in the global chemical cycles. Reconciling the emergence of coordinated, multi-species, distributed controllers with Neo-Darwinian evolution is no simple task, even when coordinated strategies are clearly the best for all organisms.

The problem is greed: populations evolve in directions that garner the highest fitness for their individual members, and as countless game-theoretic analyses and alife simulations indicate, when greedy individual behaviors yield higher payoffs than cooperation, global coordination is unstable or never even emerges.

Consequently, one of the key challenges to Gaia sci-
entists is to show the compatibility of Gaia theory and individual-level natural selection. Artificial life research can greatly assist this effort through simulations of environmental and evolutionary dynamics that produce emergent Gaian phenomena. A handful of these systems already exist, but none has convincingly shown the inevitability of Gaian behavior on planets that support life. In short, nobody has exposed an underlying “Gaia-logic” that could apply to Earth and other actual planets or possible worlds.

This paper briefly describes two contemporary Gaian models: a) Daisyworld, the central Gaian metaphor since 1983 [24], and b) Guild, our own model that extends some of the key Daisyworld concepts to more closely address the issue of natural selection [6]. We then attempt a basic classification of the key components of Gaian systems, both natural and artificial, in hopes of a) forming the foundation for a “Gaia-logic”, and b) providing a starting point for other alife researchers to delve into this fascinating area.

**Proposed Gaian Phenomena**

Gaia scientists (a.k.a. Gaians) search for interesting examples of the bi-directional interactions between organisms and their environments. A few of the more popular instances indicate the nature and scope of postulated Gaian behavior.

Algae are a major focus of Gaians, since they appear to be key components in homeostatic loops that control temperature over small and large spatiotemporal scales. A small-scale effect involves algae and dimethylsulfide (DMS). Algae release DMSP, a DMS precursor, into the atmosphere. Through various chemical reactions, DMSP leads to DMS and to sulphate aerosols, which serve as condensation nuclei for cloud formation, and clouds reduce temperature via shading [4]. In nutrient-rich waters, temperature normally has a positive influence on algae growth. So a decrease in algae density reduces DMSP emissions, causing fewer clouds to form, leading to increased local irradiation and temperature, thus promoting algae growth. Algal density and local temperature are therefore mutually regulated by their Gaian bond.

A more recent twist on the algae-DMS theory exploits the positive relationship between cloud cover and wind to argue that when algal density becomes too great, the increased DMS and cloud cover leads to higher winds, which then blow the algae to areas of less nutrient competition [7]. The presence of airborne algae supports this theory, but the quantitative significance of this phenomena is highly speculative.

On a larger spatiotemporal scale, algae photosynthesis (like that of land plants) takes up CO2 to build carbon-based biomass. Although most of this carbon is quickly returned to the oceans and atmosphere via the respiration processes of algae or higher organisms, a small percentage is not immediately recycled and sinks to the ocean depths, where it is eventually respired by microorganisms but where mixing rates are extremely low and currents move very slowly. Hence, the released CO2 may not return to surface waters for several centuries, often via equatorial outgassing. Thus, the net effect of the marine food chain is atmospheric CO2 reduction over large timescales, with algae as the biota-biosphere interface [21, 26]. Reductions in atmospheric CO2 will then lead to temperature decreases via a weakened greenhouse effect, and the lower temperature will inhibit plankton growth, thus reducing CO2 consumption. Once again, the plankton appear to be pivotal links in a homeostatic network.

A particularly intriguing Gaian possibility is the invariance of the nitrogen:phosphorous (N:P) ratio in marine environments at a value near 6.7, the “Redfield ratio” (1958). With few exceptions, Redfield ratios are found both in water concentrations and in the biomass of algae and zooplankton in all the world’s oceans. The big question is whether the biota have adapted their internal concentrations to the biosphere, or whether they have caused global changes in N:P ratios to suit their needs for the magical 6.7, which may represent some physiological optimum. As [23] points out, if the biota are passively adapting to the oceanic concentrations, then why don’t other chemical elements have matching ratios in marine organisms and waters? He argues that negative feedbacks between populations of nitrogen-fixing and denitrifying bacteria could lead to emergent control of the Redfield ratio. Furthermore, [12] uses difference-equations for these 2 populations within coupled atmospheric-oceanic compartment models to show that these regulatory loops actually do produce water-column N:P ratios near 6.7 - thus indicating that, indeed, local biotic mechanisms can lead to emergent chemical regulation.

In these and other proposed Gaian phenomena, many of the individual links (e.g., DMS to cloud cover) in the feedback loops have been confirmed to some qualitative degree, and in several cases, the relationship in a link becomes the focus of hundreds of life-science research papers (e.g. the algae-CO2-climate connection). But putting all the links together into a loop and then proving the quantitative significance of the myriad interactions across various spatiotemporal scales is a gargantuan task. This complex intertwining of many “biogeochemical” [21] factors can quickly overwhelm the naïve computer modeller.
Models of Gaia

Fortunately, one need not master all the biogeochemical vagaries to do Gaia research. To wit, [24] used a brilliantly simple computer model, Daisyworld, to thwart many of the major attacks upon Gaia theory. The fact that Daisyworld remains the centerpiece of the Gaian movement after 17 years illustrates both a) the difficulty of incorporating any real natural data into a convincing Gaian model, and b) the need of Gaian researchers for a set of basic principles (i.e. a Gaia-logic) to explain a wide variety of Gaian phenomena. Daisyworld has filled that need for a long time, but its shortcomings are becoming more evident as further natural data accumulates and the required scope of Gaia-logic expands.

Daisyworld

Watson and Lovelock’s classic Daisyworld model [15, 24] has served as Gaia theory’s prototype for over a decade. Hence, understanding Daisyworld is a key prerequisite to understanding Gaia theory. Since most proposed Gaian phenomena are very complex, involving geophysical factors and population dynamics spread over an entire planet, operational computer models of Gaian activity are scarce. Daisyworld is the notable exception, since it illustrates the emergence of distributed planetary temperature regulation via an extremely simple differential-equation model of two competing species. Unfortunately, Daisyworld has done little to reinforce the tenuous connection between Gaia and evolution.

In the classic Daisyworld, two species of daisy, black and white, are grown on a simulated planet. Both species have the same preferred temperature, 22.5°C, at which their growth rates are maximal. The black variety have low albedo (i.e. reflectivity) and therefore create higher local temperatures than the ambient, whereas the white daisies and their high albedo create local temperatures below the ambient. The growth rates of the daisies are directly influenced by their local temperatures, which are a function of both the local albedo and the global temperature, which in turn depends upon solar intensity, the cumulative albedo of all daisies, and the albedo of the uncovered (by daisies) ground. This simple combination of two daisy types with the same optimal temperature leads to self-organized regulation of global temperature in the face of a slow but steady increase in solar input, similar to that from our own sun over the past 4.5 billion years.

Briefly, at low temperatures, black daisies proliferate due to their ability to raise local temperatures closer to 22.5°C. A globe nearly covered in low-albedo black daisies absorbs a high percentage of the incoming solar energy, thereby increasing global temperature to 22.5°C at a much faster rate than could the increasing solar input alone. Global temperature is then maintained near 22.5°C even as the solar input soars, due to the effect of the white daisies, whose high albedo enables them to create local temperatures near 22.5°C and outcompete the black daisies, whose local temperatures are too high. Eventually, however, the solar input is too great and even the white daisies succumb to heat death, at which point global temperatures rise unabated. However, across a wide range of solar inputs, one of the two daisy populations keeps the planetary temperature nearly constant, thus providing key evidence that simple local interactions among the biota can have global regulatory consequences. The invisible hands of teleology are unnecessary, and Gaia theory thereby takes a huge step away from the mysticism that was unduly attributed to it by a host of renowned Neo-Darwinian biologists.

However, Gaia theory is still very vulnerable on the evolutionary flanks, and Daisyworld provides only minor fortification. From the evolutionary standpoint, the main critique of Daisyworld is the lack of significant genetic diversity for color (i.e. albedo) and preferred temperature. [20] shows that if black and white daisies have preferred temperatures of 27.5°C and 17.5°C, respectively, then the regulatory range (of solar inputs) is reduced. He further claims that if preferred temperature were under genetic control, then cold-loving species would dominate under reduced solar input but quickly give way to heat-loving species as solar forcing increased. In short, the species whose combination of preferred temperature and albedo best matched the current solar trend would dominate. This “greedy” acceptance of the ambient conditions destroys the global regulatory behavior. The modified Daisyworld simulations of [19] verify Saunders’ claim.

The Guild System

Our Guild system [6] was designed to show the basic compatibility of Gaia theory and natural selection by simulating the evolutionary emergence of a diverse interacting set of species whose combined activity could control some aspect of the physical environment. We take a few steps beyond Daisyworld by a) including a wide range of diverse genotypes and b) incorporating a new metric for Gaian activity: nutrient recycling.

Biogeochemical Motivations Another intriguing example of life’s ability to create favorable conditions for more life involves the creation of efficient recycling pathways for poorly-supplied nutrients. As detailed in [23], the external supplies of critical elements such as carbon, nitrogen and phosphorus to terrestrial and
aquatic ecosystems are far below the amounts actually required by the biota. The deficit is filled by recycling processes wherein C, N and P atoms are shuttled among different compounds that are ingested and expelled by various organisms.

For example, carbon is taken up by photosynthesizing plants as CO₂ and used to build organic carbon compounds such as carbohydrates, which are then transferred to herbivores or detritus-consuming microorganisms, only to be returned to the atmosphere as carbon dioxide by respiration in plants, animals, bacteria and fungi. A small percentage of the carbon sinks out of aquatic and terrestrial ecosystems as organic detritus and the calcium-carbonate shells of buried microorganisms, returning millions (to hundreds of millions) of years later via geophysical processes such as volcanism, deep-sea thermal ventilation, and rock weathering [21]. In the case of weathering, the biota have been shown to significantly accelerate this key step of the carbon, nitrogen and phosphorus cycles [22], so many links of the circuit feel the biotic presence.

The net result of these recycling loops is that the biota annually consume 200 times more carbon, 500-1300 times more nitrogen, and 200 times more phosphorus than is supplied by external fluxes [21, 23]. These numbers represent the “cycling ratios” for the three elements (computed as the intra-biota transfer rate divided by the external flux). Without this amplification, Earth’s biota would be restricted to a fraction of their current total biomass; and without the biota, there would be no amplification.

In short, the coordination of biochemical processes across a diverse range of organisms enables life to thrive to a degree that dwarfs that of an uncoordinated, low-recycling environment. Furthermore, the abundance of critical nutrients adds stability to the environment, enabling the biota to endure periods of fluctuating external inputs. Once again, life begets life via its effects upon the environment.

If we classify organisms by the chemicals that they consume and produce (i.e., by their metabolisms), then each group constitutes a “biochemical guild” [23]. The formation of recycling loops is therefore dependent upon the emergence of the proper complement of biochemical guilds such that the waste products of one guild become the resources of another.

**Simulated Emergence of Recycling and Control**

Our Guild system combines abstract models of chemistry, biological growth and natural selection to simulate the emergence of both a) nutrient recycling networks, and b) the regulation of global chemical ratios. We borrow one key mechanism from Daisyworld: the ability of organisms to create local buffers against the global environment, where the combined buffering effects of many organisms can then exert an influence on the global situation. However, we avoid much of Daisyworld’s hard-wiring by providing a large genotype space, defined by a genetic-algorithm chromosome.

The simulations are seeded with a single species, so all additional genotypes must arise by mutation and crossover. Furthermore, the regulatory task is one involving the coordinated effort of a wide range of temporally co-existent genotypes; a single dominant species cannot do the job alone. Hence, it is the biotic community as a whole that regulates global conditions, and these heterogeneous communities emerge from a homogeneous seed population that is subjected to nothing more than competition for resources, reproduction (by splitting) of successful resource gatherers, and genetic operators. This emergence of coordinated group regulation via standard individual selection in a large genotype space significantly fortifies Lovelock and Watson’s rebuff of the Neo-Darwinians. In addition, our model illustrates the emergence of recycling networks. So both perspectives on Gaian activity: recycling and regulation, are commensurate with Neo-Darwinism.

The Guild system employs a standard genetic algorithm (GA) along with a simple model of chemical interactions. The environment consists of n nutrients/chemicals, N₁...Nₙ, with input and output fluxes Iᵦ and Oᵦ, respectively, and internal stores Eₖ for k = 1...n. An organism’s genome determines both the chemicals that it feeds on and those that it produces during metabolism; an organism cannot consume and produce the same chemical. Organisms reproduce by splitting; the genetic operators are mutation, during splitting, and crossover, via gene swaps between organisms. The growth, reproductive and genetic dynamics are intended to mirror those of bacteria, which are the basis of Earth’s primary biochemical guilds.

In addition, the organisms are assumed to be most active (i.e. have the highest feeding rates) when the relative fractions of the environmental chemicals, Eₖ, in the organism’s immediate vicinity are near a particular user-defined optimal ratio. By producing and consuming chemicals, the organisms can create local ratios that differ from the global values, thus providing a semi-protective buffer against their surroundings. For example, organisms that consume N₁ and produce N₂ will have, respectively, lower and higher local amounts than the global values. Conceptually, the preferred ratio is analogous to an ambient factor such as pH, whose value is dependent upon many different chemical concentrations. So individual growth is governed by both.
Figure 1: The evolution of cycling ratios (i.e., total inter-organism transfer / external flux) for 4 nutrients in a run of the Guild system. The gradual increase indicates the emergence of recycling in a community of biochemical guilds. Dashed vertical lines denote time points of extreme change in external input fluxes.

the availability of food resources and the degree of satisfaction with the resource ratios within one's buffer.

As shown in [6], a variety of Guild runs exhibit the emergence of both a) nutrient recycling (i.e. high cycling ratios), and b) control of the global nutrient ratios at levels near the optima. Control is particularly evident when the environmental input fluxes are drastically perturbed, and yet the biota maintain nearly optimal nutrient ratios.

Figures 1 and 2 shows the results of a typical Guild run in which the initial population of size 100 consists of a single phenotype that produces N1 and consumes N2. The environment is initially devoid of nutrients, with input fluxes of (20, 20, 20, 20) units/timestep for N1..N4, respectively, and output fluxes of 1% of the standing amounts, E_i, i = 1..4. At generation 400, the input fluxes change to (5, 10, 25, 50), and then to (50 25 10 5) at generation 600. The biota have optimal growth with ambient nutrient ratios (i.e. normalized E_i values) of (.4, .3, .2, .1).

Figure 1 illustrates the gradual rise in cycling ratios as phenotypic diversity rises and the recycling loops form, while Figure 2 shows the approach of nutrient ratios to their biota-preferred values (dotted horizontal lines) and their persistence in the face of the two large disturbances at generations 400 and 600.

As a brief causal explanation, competition drives the initially homogeneous biota toward greater trophic diversity (i.e., diversity of consumed nutrients), and since each organism must produce at least one non-consumed chemical as waste, a diversity of outputs also emerges. This increasing biotic heterogeneity results in the fortuitous formation of recycling networks. When all of the pieces (i.e., guilds) of these networks fall into place, previously under-consumed (and thus accumulating) nutrients are taken into the food chain, fueling a population explosion and an increase in cycling ratios. The elevated nutrient transfer within the recycling network then facilitates further population growth within each guild. The high transfer fluxes between these large interconnected guilds dwarf the environmental input and output fluxes, thus reducing the biota's sensitivity to external perturbations.

Competition within and between this diverse collection of well-populated guilds results in a frequency-dependent selection that enables the guilds to effectively control global chemical ratios via their cumulative production and consumption. For example, consider a guild G that consumes nutrient N_k. The local environment of G will have a lower proportion of N_k than the global environment, so changes in the total biomass of G will decrease E_k and hence the global proportion of N_k. Now if the global ratio is near optimal, then any major increase in G's biomass will push the global ratio away from optimal and give a selective advantage to the members of other guilds, namely, those that produce N_k. This will then push E_k back up toward the optimal proportion. In short, any deviations from optimal (i.e. error) of the global ratios will create an environment that favors guilds that (fortuitously) decrease the error. Importantly, the selective advantage of these guilds stems not from their global influence, but from their ability to create pleasant lo-
nical environments for their own growth. Thus, the interplay between the guilds, orchestrated by standard natural selection, achieves and maintains a stable optimal nutrient ratio.

In summary, natural selection operating on a collection of diverse competing biochemical guilds leads to the emergence and stability of both a) a self-sustaining nutrient recycling network and b) a distributed controller. For an in-depth description of the Guild model, the parameter settings (such as mutation, crossover, metabolism and feeding rates) for particular test cases, and full details of simulation results, see [6].

Clearly, models of this simplicity cannot fully explain complex biogeochemical phenomena, but they can often illustrate the sufficiency of particular mechanisms for deriving similar patterns. This work shows that simple local interactions, under the scrutiny of natural selection, can lead to interesting cooperative arrangements. Since these particular cooperative results, efficient cycling networks and distributed global chemical regulation, are both viewed as fundamental examples of Gaia in action, our simulations lend support to the basic compatibility of Gaia and evolution. The Guild system’s use of a legitimately large genotype space and true evolutionary simulations makes a somewhat stronger argument for this compatibility than Daisyworld’s small set of hard-wired genotypes.

Unfortunately, the Guild model, like the original Daisyworld, side-steps the evolving-preferences issue [20], since all guilds are assumed to have the same constant preferred chemical ratios. When included in the Guild genomes, these preferences inhibit regulation, as individuals simply evolve preferences to the current conditions. These “regulatory parasites” are clearly a problem.

An improved chemistry model in the Guild system could help tackle the evolving-preferences dilemma. Given a set of chemical and energetic primitives, certain preferences of ambient chemicals and physical factors would arise to match the restrictions imposed by the set of metabolic possibilities. Hence, the constraints of chemical principles upon ambient preferences (and their ease or difficulty of change) would shed some light on the true range of freedom that organisms actually have in “breaking from the regulatory ranks”. This agrees with Williams [25], who contends that Gaia and the global chemical cycles can be best understood from the cellular level of enzymes, their production and regulation.

Characteristics of Gaian Processes

Williams’ focus on the cellular level motivates his contention that Gaia is a basic property of living systems. Thus, in great similarity to alife researchers’ mutual quest for a “bio-logic” [10], Williams and other Gaians have begun looking for a “Gaia-logic”. The two pursuits are intimately related, since both involve the emergence of distributed phenomena from local interactions, with adaptivity occurring on both lifetime and evolutionary time-scales. As the Guild system illustrates, the basic alife techniques can aid this search for Gaia-logic.

Our own vague conception of “Gaia-logic” spans many levels, from the metabolic activities of single cells to population and ecosystem dynamics, with natural selection playing a key role. Our search for a concrete theory begins with an analysis of several Gaian systems, both natural and artificial.

Although the sample space of theorized natural Gaian phenomena is rather small, and the space of Gaian computer models is even smaller, there are a few key features of the natural and artificial systems that appear to be vital components of Gaia. Alife models of Gaia will need to embody many of these characteristics, either as explicit primitive constraints or as emergent properties.

Primitive Factors

The first basic mechanism is trivial: organisms must be affected by their physical environments. This is often modelled as relationships between ambient factors and growth rates. An apparent implicit assumption in Gaia theory is that these ambients should consist of something other than available food resources, such as temperature, pH, salinity, etc. The daisies in Daisyworld have optimal growth at 22.5° C, while the Guild organisms grow best at particular ratios of ambient chemicals (which serve as crude abstractions of pH). The forms of the functional relationships between ambients and growth can have significant effects upon the emergent ecosystem dynamics.

A second basic principle is frequency-dependent population growth. The standard situation involves negative frequency-dependent selection in a typical Malthusian manner: higher population density entails more competition for resources and lower overall fitness. However, since Gaia embodies the notion of organisms making the planet more liveable for each other, some positive relationships between population size and average fitness will often occur, but these are often more emergent phenomena than the negative connections, which are typically implicit in resource limited situations.

The third property is the inverse of the first: organisms must have some causal means of altering their physical environment. Normally, this influence occurs
Figure 3: Summary of the basic causal mechanisms involved in many proposed Gaian phenomena: 1) ambient effects upon growth rate, 2) frequency-dependent population growth, 3) direct biotic effects upon an environmental factor (BIEF), 4) BIEF effects (possibly indirect) upon ambient factors, 5) local selective advantage of the Gaian root, and 6) biotic production and consumption of resources.

only at the aggregate level. For example, one daisy in Daisyworid cannot exhibit a significant influence on the planetary temperature, but a large population can. Similarly, in Guild, one organism cannot change environmental chemical ratios by more than a miniscule amount, but the combination of all guilds constitutes a powerful force. In nature, a single plankton cannot produce enough DMSP to form a cloud, but many million plankton can.

Let us define the “Gaian root” as the substance or physical condition produced by an organism that has some causal effect upon the environment. In the three examples above, the Gaian roots are local albedo, local metabolic inputs and outputs, and DMSP, respectively.

The fourth characteristic is a set of causal links relating the biologically-influenced environmental factors that are directly influenced by the biota (call them BIEFs) to those ambients that govern biological growth rates. In some cases, the causal chain may be short or trivial (i.e. the BIEFs are the ambients), while others involve a complex environmental model. Daisyworid has a relatively short pathway from local albedo to aggregate global albedo to global temperature and back to local temperature (a function of the global temperature and local albedo), which then controls growth. In the plankton-DMS example, the chain involves DMSP, DMS, cloud formation, shading effects upon temperature and wind, etc. Finally, in Guild, the chain loops from local chemical fluxes to global chemical ratios to effective local ratios (a function of the global ratio and the local fluxes) to growth.

The fifth factor is local selective advantage. Since the global environmental effects of individual organisms are microscopic, if standard individual-based natural selection is to guide the evolution of Gaian phenomena, then the bases for these small environmental effects (i.e. the Gaian roots) must also produce some immediate local selective advantage. Otherwise, organisms that did not expend the energy to contribute to environmental change, i.e. “cheaters”, would have a selective advantage over the contributors.

For example, [3] estimates that the metabolic cost for plankton to produce DMSP (a dimethyl-sulphide precursor) exceeds the climatic benefit (accrued by the collective of millions of plankton) by 9 orders of magnitude. However, [13] find that internal DMSP concentrations are critical to preventing osmotic water loss in phytoplankton. So clearly, DMSP provides an immediate local selective advantage, while the wider influence is merely a pleasantly coincidental side-effect that connects phytoplankton to climate in a manner that gives little or no benefit to the individual organisms but can play a key role in the long-term stability of populations, communities and ecosystems.

In the DMSP example, the local mechanism relating DMSP to dehydration prevention is quite different from the factors that connect DMS to cloud formation and temperature change. The DMSP plays two different roles. However, in other situations the Gaian root will have a similar local and global role. The local buffering effects in both Daisyworld and Guild are typical examples. In the former, a daisy’s individual albedo allows it to experience a different temperature than the ambient, which is largely determined by the collective albedo of all daisies. Still, the Gaian root, albedo, functions similarly at the local and global levels. In Guild, an organism’s consumption and production have a strong influence upon the effective local chemical ratio, which often differs from the global ratio, but the mechanism is the same at both levels: production and consumption (either individual or net) govern chemical ratios. By allowing individual organisms to essentially bathe in a local environment that differs from the global, these buffering mechanisms allow the Gaian root to incur a local selective advantage while contributing a small piece to a more global influence. Without the local selective advantage, the global effect accrued by a small population of colonizing individuals would be so insignificant as to make genes for the Gaian root selectively neutral or deleterious.

Finally, Gaian phenomena involve the consumption and production of resources by the biota. Later Daisyworld extensions include resources, and they are also a key ingredient in Guild. Similarly, a reasonable sim-
ulation of the plankton-DMS connection will include algal nutrient supplies and DMSP release. This not only supports the emergence of one Gaian phenomena, nutrient recycling, but generally renders biological simulations more realistic.

Figure 3 summarizes these six primitive characteristics, many of which appear in natural and artificial systems that exhibit Gaian behavior. Although some of these primitives could also be emergent in particular simulations or real-world phenomena, they are generally taken as givens in Gaian discussions. A Gaia-logic will presumably build on factors such as these and proportional relationships between them such that emergent Gaian dynamics can be predicted from instantiations of these primitives in different biogeochemical contexts.

**Emergent Properties**

The hallmark emergent property of Gaian systems is biotic-abiotic feedback, with the emphasis being on negative feedback (i.e. homeostatic) circuits. Essentially, the biota, BIEFs and ambients are connected in a homeostatic loop such that perturbations to population density or the environment are regulated back toward their normal values. Thus, the biota participate in the regulation of factors such as climate via population density, and perhaps diversity. Furthermore, if the biota have optimal growth under particular ambient conditions, the indirect biotic influences often combine with natural selection to push the ambients toward those preferred values.

In many cases, the causal link from the biota to the ambients is indirect. For example, under a relatively cold climate regime, a homeostatic loop involving plants and global temperature might work as follows: an increase in temperature (the ambient) would lead to increased photosynthesis and plant growth, which would draw down more CO₂ from the atmosphere. This would reduce the absorption of the earth’s infrared heat by the atmosphere (the greenhouse effect) and thereby reduce temperature. Unfortunately, in a warm climate regime, the loop could become positive, leading to runaway warming: increasing the ambient temperature of a plant species that is already living near its optimal growth temperature would lead to reduced plant growth, reduced CO₂ draw-down (and increased CO₂ output to the atmosphere from organic decay), and hence, increased greenhouse warming.

The proportioned dominance of similar positive feedbacks at the end of glacial periods (along with the mere fact that the biota “permit” the large temperature swings of the glacial cycles) leads many to question the importance of homeostasis in Gaia theory. Furthermore, the central Gaian notion of the biota making the planet more favorable for life does not entail purely homeostatic connections to abiotic factors, since the explosive growth enabled by positive feedback is also important for the rapid colonization of environments following migrations, catastrophic environmental changes, etc. Hence, biotic-abiotic feedback loops in general, whether positive or negative, appear to be key emergent Gaian patterns.

In Daisyworld, the initial explosive growth of black daisies results from a simple positive feedback: during the cold period of low solar irradiance, black daisies reduce planetary albedo, which drives temperatures up toward the optimal, which increases the growth rate for daisies (black and white). Then, when the global temperature is near the optimum, the competition between the black and white daisies manifests homeostatic control over a wide range of solar fluxes. When the sun becomes too hot, positive feedback takes over again: the death of white daisies causes planetary albedo to drop, making the effects of solar luminance on temperature even greater, killing more daisies, etc. Incidentally, Lovelock [15] views many such drastic changes in environmental factors as signs of a once-present Gaian homeostasis that eventually succumbed to an uncontrollable ambient.

In Guild, any increase in a particular strategy can alter the global chemical ratio so as to favor a different strategy. Thus, the populations of different strategists/guilds are homeostatically controlled via their influence upon the environment. The biota becomes a robust distributed controller of itself and the environment via the forces of natural selection upon diverse biochemical guilds.

A second emergent property is Lenton’s [11] frequency-dependent selective feedback. He differentiates between the effects of population density upon growth versus selective advantage. The former is the second primitive factor above, while the latter is more emergent and specifically characteristic of Gaia: if a population of organisms can incur environmental change, then these alterations may raise or lower their selective advantage over other populations.

For example, in Daisyworld, the proliferation of dark daisies warms the planet, which increases the selective advantage of the light over the dark varieties. In Guild, if one metabolic strategy dominates the population, it will often decrease its own selective advantage by altering global chemical concentrations so as to favor other strategies, as detailed earlier.

In general, a negative relationship between population density and selective advantage is important in Gaian systems such as Guild, where the emergence of diversity is a key prerequisite to Gaian control. In
Daisyworld, the relationship is present but not as vital, since any single type of daisy can control global temperature over a given interval of solar irradiance. Regardless, the concept of frequency-dependent selective feedback probably constitutes a key aspect of Gaian logic.

A third emergent property, recycling, is gaining increasing popularity as a fingerprint of Gaian dynamics [23, 25]. As discussed earlier, the ability of diverse species (often microorganisms) to coordinate their metabolic inputs and outputs such that few resources go to waste can provide both (a) a resource base that supports several orders of magnitude more biomass than do the external nutrient fluxes alone, and (b) considerable insurance against wild fluctuations in those exogenous flows.

These conditions support Gaian control, since (a) the populations become large enough that their aggregate environmental effects can be felt, and (b) as the competition for food abates, natural selection can begin to operate on characteristics other than those directly related to resource gathering, such as the side-effects of the Gaian root (e.g. dehydration prevention, local albedo or chemical-ratio alteration, etc.).

Discussion

Although the inclusion of several of the above 6 primitive features would appear to “hard-wire” feedback into the system, they function more as necessary than sufficient groups of mechanisms. Feedback formation depends not only on relationships between entities such as population densities, chemical concentrations, and ambient physical conditions, but the quantitative amounts of those entities as well. A model with a proper set of necessary mechanisms can be seeded with just the right amounts of each entity such that significant feedbacks “emerge” at time 0, but more interesting simulations begin with rather uninteresting combinations of entities that eventually self-organize and evolve into active causal loops.

In general, Gaia research has focused on uncovering these necessary mechanisms and showing that they fit into nice little causal circuits. The key issue now becomes one of emergence: given these primitive relationships, do the forces of nature actually drive systems toward biotic and environmental conditions that manifest powerful feedback states. Daisyworld and Guild indicate that under various conditions, they can, but additional field work and computer models are needed.

To date, few researchers have investigated Gaian issues. The EUZONE model [5] of the evolution of aquatic ecosystems is motivated by Gaian thinking and achieves the emergence of one species, vertically-migrating photosynthesizers, which creates a niche for another species, aerobic bottom-feeders, via its effects upon the chemical environment. However, environmental regulation does not arise in EUZONE.

The Guild system parallels research into the emergence of autocatalytic-sets [9], metabolic-systems [1] and hypercycles [2], except that we focus on (a) interaction pathways involving both organisms and chemicals, and (b) the self-organized regulation of the environment by the evolving biota. In general, a whole host of alife systems involve populations of genotypes that encode for feeding, mating and other strategies, but questions regarding recycling throughputs and whether or how the phenotypes regulate the surroundings are normally not addressed.

While Williams [25] claims that the basis of Gaia logic lies in the cells themselves, we feel that Gaia theory is not so easily reducible and must encompass many levels, from enzymes and cells to populations and ecosystems; and with Neo-Darwinian natural selection guiding the way, due to (not in spite of) the natural tendency of organisms to selfishly maximize their own fitness. Our alife perspective to the problem leads to the obvious question: could Gaia be a basic emergent phenomena in a wide variety of ecosystems? Since a good many of the biological influences on the environment are chemical, the alife spirit motivates a follow-up query: is Gaian emergence possible across a wide variety of biochemistries from carbon-based to silicon-based (in the sense of silicon being the key structural molecule in organic chains) to chemistries based on other periodic tables, to those involving strings, s-expressions, etc.?

Answers to these questions call for an approach similar to [9], wherein many sets of randomly generated primitive interactions are simulated, and the emergent patterns categorized. To wit, we are working on a Guild extension in which random chemistries are generated; they differ with respect to sanctioned reactions and their energy yields. Biota have genetically-determined metabolisms with energy-production capabilities determined by the chemistry. Different chemistries will presumably lead to different fitnesses for particular metabolisms, and hence to the evolution of different chemical-transfer networks at the ecosystem level. The frequency of emergent Gaian phenomena such as recycling and control across these possible biochemical worlds will hopefully shed some light on whether Gaia constitutes “order for free” [9] derived from a Gaia-logic whose generality encompasses more than “life as we know it” [10].

While many biologists deride Gaia theory, many others view it as a potentially revolutionary break-
through on par with Darwinism itself. This promise, along with the fact that a good deal of Gaian thinking is based on the rather trivial, yet enlightening, Daisy-world model, should be read as an open invitation to all natural-science modellers to join in the pursuit of Gaia-logic.

References


