Reviews

The Gaia hypothesis: A fruitful fallacy?

F. Baerlocher

Dept. of Biology, Mount Allison University, Sackville, New Brunswick (Canada EOA 3CO)

Summary. In 1968, Lovelock proposed that the Earth's biosphere, atmosphere, oceans, and soils form a single living organism, which he called Gaia after the Greek Earth goddess. This entity constitutes a feedback system which supposedly seeks an optimal physical and chemical environment for life on Earth. Most scientists accept a weaker version of the hypothesis, that life has had a tremendous impact on the physical environment. They reject the strong version on the basis that planetary self-regulation would need foresight and planning by living organisms, which is incompatible with natural selection. Lovelock subsequently proposed a simple computer model, called Daisyworld, which shows that, under certain conditions, feedback systems without foresight can stabilize external inputs. The main value of the Gaia hypothesis lies in its holistic perspective, which is needed to avoid environmentally undesirable, cumulative effects of small decisions.

Key words. Gaia; superorganism; Daisyworld; balance of nature; protection of nature; pollution.

Introduction

James Lovelock is an ingenious scientist and inventor. His contributions include the electron capture detector, which has revolutionized environmental analysis. He has been a Fellow of the prestigious Royal Society since 1974. In the 1960s, he was a consultant to a team at the Jet Propulsion Laboratories in Pasadena, whose task it was to develop techniques to detect life on Mars and other planets[19, 20]. The prevailing assumptions were that, if life existed, it would have much the same characteristics as on Earth. Consequently, one proposed series of experiments involved the use of an automated microbiological sampler to collect and test Martian soil for the presence of fungi and bacteria. Lovelock soon became disenchanted with this parochial approach. He found a more general definition of life in the writings of physicists[31]. From their point of view, living organisms are open systems, able to decrease their internal entropy or disorder by taking in substances and/or free energy from the environment and subsequently releasing them in a degraded form. At first sight, this definition seems rather vague and impractical, since it includes hurricanes, flames, and many other abiotic phenomena. Nevertheless, it provided Lovelock with a useful starting point. It suggested that there is a boundary between the place where energy is being exploited (e.g., an organism) and its surroundings, where waste products of lower energy should accumulate. Lovelock further assumed that life would have to use fluid media – liquids or gases – as conveyor-belts for raw materials and waste products. The activity of living organisms would therefore likely spill over into the atmosphere and/or oceans and change their composition. Since Mars has no oceans, Martian life would have to use the atmosphere as exchange medium. Discovery of life should therefore be possible through analysis of a planet's atmosphere. An advantage of this approach is that it is site-independent. A conventional space probe, on the other hand, might by chance collect samples where life happens to be absent. Even on Earth, such techniques are unlikely to discover much evidence for life if landfall occurred near the poles, or in certain deserts.

Lovelock elaborated these lines of thought with Dian Hitchcock and applied them to the Earth[11, 18]. How could knowledge of the Earth's atmosphere provide evidence for life? They pointed out that its chemical composition is far removed from chemical equilibria. To mention one example: it contains methane as well as oxygen. When exposed to sunlight, the two gases react and form carbon dioxide and water. The rate of this reaction is such that at least 1000 million tons of methane per year have to be introduced into the air to maintain the present concentration. There are no known chemical or physical processes that could explain such fluxes.

A chemical analysis of atmospheres, done quite easily by infrared telescopy, could thus give clues to the occurrence of life on planets. Since it was already known that the Martian atmosphere consisted mostly of carbon dioxide, without any of the more 'exotic' constituents found on Earth, Lovelock[18, 19] concluded that Mars was probably lifeless. This was confirmed in 1975, when two Voyager space probes failed to find any signs of life with conventional microbiological techniques[20].

In 1966, Lovelock received an invitation by Shell Research to investigate possible global consequences of air pollution. To him, there was an obvious connection with his previous project: in both cases, the atmosphere was treated as an extension of the biosphere. The effect of toxins on the human body depends on its ability to metabolize or secrete them. Similarly, waste products of fossil fuels presumably have different effects in biologically controlled and in lifeless atmospheres. In the presence of life, the kinds and concentrations of the pollutants might be influenced by newly developed properties of living organisms.

The Earth as an organism

His studies eventually convinced Lovelock that the Earth's atmosphere is actively maintained and regulated by life on the surface. He concluded that this is due to the activity of a single entity containing "the entire range of living matter on Earth, from whales to viruses and from oaks to algae."[19] This superorganism "is capable of manipulating the Earth's atmosphere to suit its overall needs and endowed with faculties and powers far beyond those of its constituent parts." The author William Golding suggested the name 'Gaia' (after the Greek Earth goddess also known as Ge). Gaia was defined as "a complex entity involving the Earth's biosphere, atmosphere, oceans, and soil; the totality constituting a feedback or cybernetic system which seeks an optimal physical and chemical environment for life on this planet."[19]

Lovelock considers the continued existence of living organisms throughout the last 3–4,000 million years as a compelling argument for the existence of Gaia. It implies that the climate must have been relatively constant ('comfortable for life'). This is somewhat surprising, since over the same period the sun's output of energy has increased by about 30%. One might therefore expect that the oceans would at one time have been frozen solid. Geological evidence indicates that this was not the case. Conventional theories attribute the relatively high temperature of the young Earth to much higher carbon dioxide and ammonia concentrations in the early atmosphere (a prehistoric greenhouse effect[13]). Lovelock thinks that this explanation is insufficient and that active control by the biota was required to keep the environment at a comfortable temperature.

As another argument for the existence of Gaia, Lovelock mentions the composition of the atmosphere, which is far removed from chemical equilibrium. In his view[19], the atmosphere is not simply a by-product of life processes but a biological construction, "not living, but like a cat's fur, a bird's feathers, or the paper of a wasp's nest, an extension of a living system designed to maintain a chosen environment."

Lovelock presented his hypothesis at a conference about the origins of life in 1968, and published a first report in 1972[17]. Most scientists ignored it or criticized it as teleological. A notable exception was Lynn Margulis, a biologist from Boston, who subsequently coauthored several papers with Lovelock[21,22,37].

The Gaia hypothesis received its greatest support from environmental activists and gurus of the New Age wave. An important factor were the impressions and descriptions of astronauts who for the first time were able to see the Earth as a whole. The beautiful pictures of our blue and green planet, with curling wisps of clouds and brilliant white caps of polar ice have become a powerful symbol of the ecological movement.

The basic idea of Lovelock's hypothesis is sound: atmosphere, biosphere and oceans are indeed closely linked and can be interpreted as a cybernetic system. We ignore these connections at our own peril. It is also true that life processes can often lead to homeostasis, i.e., relatively constant conditions.

Similarly, most people would sympathize with Lovelock's motives. He writes: "The Gaia hypothesis is for those who like to walk or simply stand and stare, to wonder about the Earth and the life it bears, and to speculate about the consequences of our own presence here. It is an alternative to that pessimistic view which sees nature as a primitive force to be subdued and conquered."[19]

Lovelock summarized his conclusions in his book, *A New Look at Life on Earth*. To a biologist exposed to modern evolutionary theory, it is a curious book indeed. It does appear obvious that he takes the superorganism concept literally, though in all fairness, he states that the book was written primarily to stimulate and to entertain, and he repeatedly makes the proviso 'if Gaia exists'. Nevertheless, one cannot escape the impression that Lovelock was either ignorant of modern evolutionary theory or was deliberately pulling the reader's leg. A few examples suffice to illustrate this.

It is generally accepted today that the early atmosphere was reducing and oxygen free. As a result of newly evolving photosynthesis, oxygen gradually accumulated. This gas must have been extremely poisonous for early organisms, and Lovelock justifiably calls the start of oxygen release the worst incidence of atmospheric pollution this planet has ever experienced. Many organisms learned to detoxify oxygen and eventually used it for respiration. Other bacteria could not adapt and were driven into the anaerobic underground: sediments of lakes, oceans and wetlands. Many millions of years later, a new habitat became available to them: the anaerobic guts of most animals, where they enjoy a truly privileged existence with constant conditions and continuous influx of food. Lovelock[19] suggests that "it may well be that large mammals including ourselves serve mainly to provide them with their anaerobic environment." Apparently, Gaia had not forgotten her anaerobic children from the dawn of life's history and offered them, somewhat belatedly, a replacement for the loss of an entire planet.

At present, the air's oxygen content remains more or less constant at 21%. According to Lovelock, this value is optimal for life (if we ignore the anaerobic bacteria): a lower value would endanger the energy metabolism of most organisms, a higher value would drastically increase the likelihood of destructive fires. At an oxygen content of 25%, even damp wood burns readily, and rain forest would be as vulnerable to lightning as dry wood is today[37]. To Lovelock, the mere fact that oxygen content does remain constant, presupposes an active control. It is based on anaerobic bacteria. Their activity releases methane into the atmosphere, where it will be oxidized and thereby soak up oxygen. Lovelock estimates that without methane production in anaerobic sediments and animal guts, the oxygen content of the atmosphere would increase by about 1% every 12,000 years, having the devastating consequences mentioned earlier. The decision, whether or not buried organic matter is to be converted into methane, is made by Gaia[19]: "When there is too much oxygen in the air, some warning signal may be amplified". Bacteria working away in the sediments will then step up methane production "in the interest of the living planet."

The average salt content of the oceans is 3.5%. It is generally accepted that it has always remained fairly close to this level[13]. Every year rivers and streams introduce more salt into the oceans. This influx should lead to a doubling of the salt content within 12–100 million years. This doesn't appear to happen; geologists therefore assume that, on the average, an equal amount of salt will be removed[13,15]. Some of it crystallizes, sinks and will eventually be covered by sediments and thus withdrawn from circulation. Storms and tides carry salt inland; periodically, shallow areas dry up and leave salt deposits behind. Lovelock again perceives Gaia's hand behind these processes. He emphasized, quite rightly, that organisms play a role in the cycling of salt. Tiny algae and animals sink to the bottom after their death and carry salts (e.g., carbonates, silicates) with them. Corals form lagoons where water may evaporate more easily, leading to precipitation from the oversaturated salt solutions. But Lovelock goes beyond these commonsense observations. In his view, Gaia wants to prevent salt levels that might endanger life. Can the Great Barrier Reef really be interpreted as "a half-finished project for an evaporation lagoon", designed to keep the salt content of the oceans at a comfortable level?

Gaia and mainstream science

I think these examples give a fair impression of Lovelock's ideas and style. It is easy to see that he leaves himself wide open to attack by modern evolutionists[5,6]. He seems to imply that some species perform certain functions for no other reason than to benefit the biosphere or *life as a whole*. He does not offer any explanation how this could be achieved by natural selection, which an overwhelming majority of today's biologists consider to be the main driving force behind evolution. Natural selection is based on the fact that within each species some individuals leave more viable offspring than others. As a consequence, the genes of the successful individuals become more numerous in the next generation. There is no mechanism that would favour genes beneficial to the species, let alone the biosphere, as a whole, but detrimental to the individual or its offspring possessing them. Dawkins[4] therefore concluded that genes are basically "selfish". This was clear to Darwin, but later biologists did not always grasp this essential fact of evolution. It was forcefully restated in an influential and timely book by Williams[38]. Sentences such as "This property has been selected, because it ensures the survival of the species" at best indicate sloppy language; at worst they expose a fundamental misunderstanding of natural selection. Lovelock seems to have gone even further: he claims certain organisms perform functions for the benefit of life as a whole. What does this really mean? Organic pollution spells disaster for trout; it means paradise for sewage fungi. If we attribute to Gaia the most destabilizing event in the history of the planet – the switch from a reducing to an oxidizing atmosphere – how can we then attribute a stabilizing influence to that same Gaia?

According to the Gaia hypothesis, as presented by Lovelock in 1979, each species acts responsibly for the common good. Doolittle[6] compared this idea with a fictional community on the moon described by Lofting[16]. It was characterized by the absence of Darwinian competition among the flora and fauna. This was ensured by 'The Council', made up of members of both the Animal and Vegetable Kingdoms. Its main purpose was to regulate life on the moon in such a way that there should be no more warfare. Doolittle rightly asks which authority could possibly take the place of the Council on Earth to ensure a Gaian society.

The reaction by scientists from other fields was not much friendlier. The geochemist Holland wrote[13]: "I find the hypothesis intriguing and charming, but ultimately unsatisfactory. The geologic record seems much more in accord with the view that the organisms that are better able to compete have come to dominate.... We live on an Earth that is the best of all possible worlds only for those who are well adapted to its current state.... One curious aspect of Earth history is the continuity of life during the past 3.8 b.y. I believe that this continuity is a consequence of the relative dullness of Earth history...." In Holland's view, the two driving forces in the evolution of the atmosphere and oceans have been heat generation within the Earth and energy transfer from the sun to the Earth. He agrees, nevertheless, that the effects of the sun have been strongly modified by the biosphere.

Schneider and Londer[30] similarly find it valid and worth stressing that the world is massively modified by living organisms. They in fact talk about co-evolution of life and climate, indicating an interdependence between the two, but do not acknowledge a primacy of life.

Lovelock's response: Daisyworld

Lovelock[19] was aware of some of the dangers in writing for a wider public. In his preface he writes that there are "sentences which may read as if infected with the twin blights of anthropomorphism and teleology." Maybe he can be compared to a intrepid but naive explorer, who has strayed from the safe paths of his own competence and jargon, unwittingly tramples over hallowed ground, and is attacked by outraged natives. In his most recent book[20], he describes his reaction to Doolittle's review as "shock and incoherent disbelief." But then he accepted that his presentation could indeed be taken to imply that Gaia was a teleological concept, requiring foresight, planning and cooperation by the biota. He went back to one of his original assertions: that life appears to have a stabilizing influence on the climate. How could the biota achieve this without cooperative planning? To answer this, he collaborated with Watson on a computer model[36]. In its simplest form it consists of a planet, colonized by two kinds of daisies. One is dark; consequently, ground covered with it reflects less light than bare ground. The other daisy is light, and reflects more strongly than the bare ground. Black daisies will be warmer than white ones, and tend to be favoured by cooler temperatures; conversely, higher numbers of black daisies tend to warm the planet. The opposite is true for white daisies. Both species have a peaked growth curve. Daisies and the temperature are a closely coupled system, changes in one component will affect the other and this in turn feeds back on the original change. At the lowest temperature that allows growth of daisies, the feedback is positive; we therefore have a relatively rapid rise in temperature. As it increases, white daisies become more common. They exert a negative feedback, therefore additional heat input (simulating the behaviour of the sun through the ages) will now have an increasingly lesser effect on planet temperature. At the point where no more daisies survive, the temperature will once again increase rapidly. The planet Daisyworld therefore goes through an intermediate region where its temperature remains relatively stable despite increased input of heat. The daisies can therefore be said to stabilize the planet's temperature without foresight or cooperation (this of course ignores the rapid rise when black daisies first colonize the planet, which is really a destabilizing effect due to the biota).

This model is indeed free of "the teleological stain", and in his most recent book[20], Lovelock presents his view of the history of the Earth's climate. He still believes that life was primarily responsible for the relatively benign conditions over the last eons, but has toned down his rhetoric. He includes a fascinating proposal of how Mars could be made to bear life by receiving our surplus CFCs (chlorofluorocarbons). His scenario is still highly speculative, but cannot be rejected outright on purely logical grounds. The question that remains is: does this model really capture the essence of interactions between organisms and their environment?

It seems reasonable enough to assume that living organisms will sometimes, maybe usually, enter into feedback relationships with environmental factors. It does not necessarily follow that the feedback is always positive at the lower end of the factor and negative at the higher end, which seems to be necessary to achieve the stabilizing effect observed in Daisyworld. Let us assume, for example, that beyond the white daisies, we had another group of 'superblack' daisies. This would lead to a steep increase in temperature, followed by another period of comparative stability. It may therefore be more realistic to say that biota can modify gradual changes of environmental factors. Periods of stasis might be punctuated by rapid change. Of course, this corresponds to the concept of evolution proposed by Eldredge and Gould[8], and which Lovelock quotes with apparent approval. A similar point was made by Dubos[7] who reviewed Lovelock's early work favourably, but felt that Lovelock rather overemphasized homeostasis, and neglected the "creative aspects of evolution"; a case in point again being the release of oxygen into the atmosphere. It proved enormously destructive for the biota of that time, but was the foundation of the subsequent flowering of new phyla. Thus, instead of Gaia, which stands for "power of support", "unshakable foundation", "stability"[35] it might have been more appropriate to compare Earth to the indissoluble triad of the Hindu gods Siva (destroyer), Brahma (creator) and Vishnu (preserver)[10]. All activity reflects their interactions and "creation and destruction are like two sides of a coin". This idea is again borrowed from Gould[10], who used it to describe the effect of an as yet hypothetical companion star to the sun, that might be involved with periodic mass extinctions. In his more recent book, Lovelock does put more emphasis on the destructive side of Gaia. But he would surely object to the possibility put forward in Gould's essay[10] that "no internal dynamic drives life forward. If environments did not change, evolution might well grind to a virtual halt". Thus, from the simple model of Daisyworld, we might conclude that interactive systems teeter between homeostasis and disruption. It is of course a great distance from Daisyworld to the complexity of natural systems with its myriad of interacting species. More factors mean more potential feedbacks, and there is always the possibility that any one of them profoundly changes the outcome. The net effect cannot, as system analysts like to say, be predicted by "hand waving." Thus, there is no a priori reason why the biosphere should necessarily keep conditions suitable for life. Even in Lovelock's simple Daisyworld, a new species might increase temperature above the tolerance levels of any kind of species, and thereby wipe out all life. This is especially likely when there are delays in the feedback mechanisms. A species might activate a process that will take a long time to become effective, but, through sheer inertia, proceeds in the same direction long after the initiator has died out. Many people believe that today this possibility is greater than ever.

The balance of nature

In the traditional view, the living world as we experience it is the outcome of opposing forces; the overall approximate balance we tend to see is the unplanned outcome of selfish organisms pursuing their own conflicting ends. Adam Smith believed in the supreme beneficence of natural order in economy [27]. By pursuing their own interests, everybody would attain their own best advantage but also the common good; each individual was led "by an invisible hand to promote an end which was not part of his intentions."

This apparent and usually temporary harmony is often exaggerated and transformed into a balance of nature. The poet Alexander Pope writes, "From nature's chain whatever link you strike, tenth or ten thousandth, breaks the chain alike." Would the ecosystem of Venice really collapse if we removed all its pigeons, or its rats? Elton [9] undoubtedly was closer to the truth when he wrote: "It is further suggested that if we knew enough about the ecological relations of the animals we could predict the effect of any interference, just as a clockmaker can work out the ultimate effect of the twirling of one wheel upon the rate of revolution of any of the others. At the same time it is assumed that an undisturbed natural community lives in a certain harmony, referred to as 'the balance of nature'.... The picture has the advantage of being an intelligible and apparently logical result of natural selection in producing the best possible world for each species. It has the disadvantage of being unture. 'The balance of nature' does not exist, and perhaps never has existed.... The simile of a clockwork mechanism is only true if we imagine that a large proportion of the cog-wheels have their own mainsprings, which do not unwind at a constant speed. There is also the difficulty that each wheel retains the right to arise and migrate and settle down in another clock, only to set up further trouble in its new home." Lovelock would probably agree; he attributes the longevity and strength of Gaia to "the informality of her constituent ecosystems and species" [20]. In other words, individual species, even ecosystems, are expendable. This, of course, puts his Gaia concept in marked contrast to real organisms, whose components are strongly integrated and generally irreplaceable.

The superorganism concept

When Lovelock first advanced the Gaia hypothesis, he was unaware that the very same idea of Earth as a superorganism had already been proposed in 1785 by the geologist James Hutton [20]. It has since periodically reappeared in various subfields of biology. Professional ecologists associate it primarily with the work of Clements [2]. He interpreted plant communities as superorganisms and equated their development with the life history of an individual plant. Tansley [34] in 1935, rejected the term 'organism'; and proposed instead 'ecosystem', defined as "the *whole system* (in the sense of physics), *including not only the organism complex, but also the whole complex of physical factors* forming what we call the environment of the biome – *the habitat factors in the widest sense*." This surely comes close to what Lovelock means, without the unfortunate connotations associated with the term superorganism.

Today, a weak form of the superorganism concept survives in systems ecolgy [26]. Most ecologists are doubtful about the Gaia hypothesis, but many believe that ecosystems have emergent properties. These are properties unique to a given level of biological organization that are wholly unpredictable from observations of the isolated components of that level [28]. Odum [23] tried to predict some emergent trends in developing ecosystems, apparently with mixed success.

The superorganism concept also dominated the literature on insect colonies from 1911 to 1950 [39], and has recently been applied to bacteria [33]. Its demise in the study of social insects is instructive. According to Wilson [39], it "exemplifies the way inspirational, holistic ideas in biology often give rise to experimental, reductionist approaches that supplant them. For the present generation, which is so devoted to the reductionist philosophy, the superorganism concept provided a very appealing mirage. It drew us to a point on the horizon. But, as we worked close, the mirage dissolved – for the moment at least – leaving us in the midst of unfamiliar terrain, the exploration of which came to demand our undivided attention." Wilson attributes the waning of the concept to the fact that it did not offer any new techniques, measurements, or even definitions to unravel the mysteries of social organization. He is unaware of any examples where the deliberate use of the idea led to new discoveries. This is really the crucial point of any hypothesis: does it lead to new experiments, predictions, observations?

In Gaia's case, the answer is probably a qualified yes. Lovelock [20] claims that his discoveries of the vital role of dimethyl sulfide in the sulfur cycle and of the universal occurrence of CFCs were inspired by his Gaia hypothesis. There is no denying that his publications rejuvenated research into global connections between the biota, atmosphere and oceans. Recently, Schwartzman and Volk [32] lent support to one of Lovelock's favourite hypotheses, that early life forms have been responsible for keeping our planet relatively cool and "comfortable for life". Without biotic weathering, the Earth might be up to 45 °C warmer than it is, making it uninhabitable for nearly all but the most primitive microbes. Schwartzman and Volk [32], however, take care to distance themselves from any teleological conclusions: "The Earth's earliest biota in this scenario did not optimize conditions for its existence, but was a critical factor in creating conditions for low-temperature life to emerge and thrive." Without this fortuitous temperature drop, life on Earth might well have been aborted at an early stage.

Gaia and protection of the environment

The Gaia concept of a world governed by powerful interactions that buffer it with various feedback loops is likely to look very attractive to polluting industries. It has therefore been claimed that Lovelock gives green light to environmental degradation. This is patently unfair; there can be no doubt that Lovelock cares very deeply about the environment. But again, his approach is highly original and iconoclastic. His concern is resolutely and uncompromisingly with nature as a whole, and not on how environmental changes might rebound on humans. Quite deliberately, he plays the role of a shop stewart for 'lower' forms of life. Not surprisingly, this often puts him at odds with orthodox environmentalist dogma; by and large, I think his ideas provide a timely corrective to the ideological blinders of many environmental activists.

One of his crucial points is that much of the current ecological movement is obsessed with human problems. It is indeed paradoxical to witness, for example, the effort and money devoted to document and avoid the most minute chance of a reduced life expectancy due to cancer when a new pesticide is introduced, and compare this with the relative indifference to its side-effects on innocent 'by-standers': it almost inevitably entails massive slaughter of non-target organisms in streams and soils. This is indeed, as Lovelock[20] puts it, "straining at the gnat while swallowing the camel."

It is also common to blame technology rather than ourselves; cities and industrial centres are seen as the epitome of what is 'bad' about modern societies. Many try to avoid the noise and dirt and flee to the countryside. It can be argued that this spreading out of the population does greater harm to nature than city living: it replaces one large, easily noticed and therefore controllable source of pollution with numerous small sources, where controls are often uneconomical, less noticeable and therefore thought unnecessary. Suburbanization blankets a much wider area and has a more insidious effect. It is wise to remember that acid rain became a problem when taller smokestacks were built and started to distribute emissions over long distances.

At the bottom, the major problem is one of overpopulation. Lovelock[19] quotes, with apparent sympathy, a statement by Garrett Hardin: "There is only one pollution.... people." The need to feed and house them, and their insatiable demand for material goods, are responsible for our wasteful and destructive use of the land. Growing populations are ultimately responsible for desertification of formerly fertile land and the cutting-down of tropical forests.

It is instructive to see how Lovelock evaluates some recent environmental concerns. In 1972, he demonstrated for the first time that CFCs were present in minute quantities throughout the global environment[19,20]. At the end of his report, he wrote what he now considers one of his greatest blunders: "The presence of these compounds constitutes no conceivable hazard." At that point, nothing was known about their ozone destroying capabilities. But even when this became known a few years later, Lovelock considered a thinner ozone layer a remote and hypothetical threat. The controversy soon escalated into an 'ozone war', with some activists demanding that ultraviolet radiation, like other carcinogens, should be reduced to zero. Lovelock remained unimpressed; he clearly recognized that UV has always been part of our natural environment, and he felt that its threat to life was vastly exaggerated. Today, he takes CFCs more seriously[20]. Because of their long atmospheric life times, their concentration has increased over 500% since his early measurements; more worrying than their cancer causing potential is the intensity with which they absorb infrared radiation[12]. They therefore contribute to the greenhouse effect, which has potentially much more far-reaching effects than increased UV radiation. Lovelock is now in favour of sharply curtailing CFC production.

Lovelock also parts company with the mainstream ecological movement when dealing with nuclear power[19,20]. He considers radiation a normal and inevitable fact of life, and finds it inconsistent that we do not look at cigarettes with the same fear now reserved for uranium. They are responsible for more deaths than thousands of Chernobyls. He emphasizes, though, that he is not enamoured of nuclear power, but his concern is that[20] "the hype about it, both for and against, diverts us from the real and serious problem of living in harmony with ourselves and the rest of the biota." Paralyzed by fear of a remote catastrophe, we do not realize that we are slowly sinking in quicksand.

What, then, are the major environmental problems in Lovelock's view? As answer, he often mentions the three deadly Cs: cars, cattle and chainsaws. Cars of course, contribute to the greenhouse effect with potentially disastrous global consequences; chainsaws cut down tropical forests for adsurdly wasteful beef farms. This leads to the irrevocable destruction of an enormous number of species[3,40]; we are just beginning to realize the tremendous importance of the tropical forests in global climate[29]. Lovelock[20] thinks, with some justification, that "Chain saws are an invention more evil than the hydrogen bomb."

The global role of these forests make a much more convincing case for their preservation than what he considers "feeble economic arguments." They are usually based on the concept of maximum sustainable yield; i.e., on the assumption that it makes economic sense that the harvesting rate not exceed the natural renewal rate of the resource. Unfortunately, this is not necessarily the case[1]. A recent example concerns the use of rainforests[25]. Three possibilities were compared: income from fruits and latex products, clear-cutting and selective cutting. Sustainable yield from fruits and latex was estimated at $ 422 per hectare. Clear-cutting would yield $ 1000 for one year only, and selective logging $ 310 every 20 years. In this case it seems obvious that the most sensible strategy would be to concentrate on the fruits and latex. If the choice were between clear-cutting and selective timber harvest, however, the rational choice would be for clear-cutting. Compared to sustainable logging, it would yield an excess income of $ 690 in the first year. Who would seriously consider giving up $ 690 now for the prospect of receiving $ 310 in 20 years? Humans prefer present use over future access; future value therefore tends to be discounted. One crucial reason is that unharvested resources represent capital providing no return. If the rate of real interest (prevailing rate less inflation) exceeds the maximum growth expected of a renewable resource, it is more economical to exhaust the resource as quickly as possible[1].

The principal danger of using economic arguments for nature protection is that it legitimizes this approach. What, if it should turn out, as it inevitably will, that it sometimes makes economic sense not to protect nature? How can one then credibly switch back to a protectionist stand? As Clark[1] suggests, corrective public intervention is indispensable and should take priority to slow down and stretch out the exploitation of the resource pool.

Another frequently heard argument for the preservation of rain forests is that some of their constituent species contain powerful, as yet unknown drugs[40]. Again, this is not a totally convincing argument. Drugs most profitable to the industry are often those effective against degenerative diseases of the developed world. How does one convince people living in South America of the benefits of such drugs? They often die too young to suffer from these diseases; if they did, they probably could not afford to buy the drugs. Some of this dilemma has been summed up in a trenchant cartoon by Scott Willis: a fat man in a huge car, with a license plate labelled 'Developed Countries' stops by a tree that is being chopped down by a poor Latin American peasant and yells: "Yo! Amigo! We need that tree to protect us from the greenhouse effect!"

It is the special merit of Lovelock's hypothesis that it forces us to view the whole system, whether or not we call it Gaia. Regardless of how valuable a reductionist approach is in science, it can be destructive when applied to nature protection. It all too easily leads to "the tyranny of small decisions"[14,24]. The pollution of a pristine lake is rarely the result of a conscious decision. It occurs instead through the accretion of thousands of small decisions: to add one more house or one more factory. Each individual step seems harmless enough; nevertheless, it puts us on a slippery slope. Inevitably, we will approach a state which we would have rejected, had we had a clear choice between it and the starting point.

In the introduction to his first Gaia book[19], Lovelock writes that he wishes to entertain and to stimulate, and in his second book[20], he quotes with apparent approval a comment by Vilfredo Pareto "Give me a fruitful error any time, full of seeds, bursting with its own corrections". There can be no doubt that he has achieved these objectives.

1 Clark, C. W., Clear-cut economies, The Sciences *29* (1989) 16–19.
2 Clements, F. E., Nature and structure of the climax. J. Ecol. *26* (1916) 252–284.
3 Cohn, J. P., Gauging the biological impacts of the greenhouse effect. BioScience *39* (1989) 142–146.
4 Dawkins, R., The selfish gene. Oxford University Press, Oxford 1976.
5 Dawkins, R., The extended phenotype. Oxford University Press, Oxford 1982.
6 Doolittle, W. F., Is nature really motherly? CoEvol. Q. *29* (1981) 58–63.
7 Dubos, R., Gaia and creative evolution. Nature *282* (1979) 154–155.
8 Eldredge, N., and Gould, S. J., Punctuated equilibria: an alternative to phyletic gradualism, in: Models in Paleobiology, pp. 82–115. Ed. T. J. M. Schopf. Freeman, Cooper and Co., San Francisco 1972.
9 Elton, C., Animal ecology and evolution. Oxford University Press, Oxford 1930.
10 Gould, S. J., The Flamingo's Smile. W. W. Norton, New York 1987.
11 Hitchcock, D. R., and Lovelock, J. E., Life detection by atmospheric analysis. Icarus *7* (1967) 149–159.
12 Hively, W., How bleak is the outlook for ozone? Am. Sci. *77* (1989) 219–224.
13 Holland, H. D., The chemical evolution of the atmosphere and oceans. Princeton University Press, Princeton 1984.
14 Kahn, A. E., The tyranny of small decisions: market failures, imperfections, and the limits of economy. Kyklos *19* (1966) 23–47.
15 Kennett, J. P., Marine geology. Prentice-Hall, Englewood Cliffs, N.J. 1982.
16 Lofting, H., Doctor Dolittle in the Moon, J. P. Lippincott, New York 1928.
17 Lovelock, J. E., Gaia as seen through the atmosphere. Atmos. Envir. *6* (1972) 579–580.
18 Lovelock, J. E., Thermodynamics and the recognition of alien biospheres. Proc. R. Soc. B. *189* (1975) 167–181.
19 Lovelock, J. E., Gaia, A New Look at Life on Earth. Oxford University Press, Oxford 1979.
20 Lovelock, J. E., The ages of Gaia. Oxford University Press, Oxford 1988.
21 Lovelock, J. E., and Margulis, L., Atmospheric homeostasis by and for the biosphere: the Gaia hypothesis. Tellus (1974) *26*: 2–10.
22 Margulis, L., and Lovelock, J. E., Biological modulation of the Earth's atmosphere. Icarus *21* (1974) 471–489.
23 Odum, E. P., The strategy of ecosystem development. Science *164* (1969) 262–270.
24 Odum, W. E., Environmental degradation and the tyranny of small decisions. BioScience *32* (1982) 728–729.
25 Peters, C. M., Gentry, A. H., and Mendelsohn, R. O., Valuation of an Amazonian rainforest. Nature *339* (1989) 655–656.
26 Richardson, J. L., The organismic community: resilience of an embattled ecological concept. BioScience *30* (1980) 465–471.
27 Roll, E., A history of economic thought. Faber and Faber, London 1953.
28 Salt, G. W., A comment on the use of the term emergent properties. Am. Nat. *113* (1979) 145–148.
29 Schneider, H., Are we entering the greenhouse century? Sierra Club Books, San Francisco 1989.
30 Schneider, S. H., and Londer, R., The coevolution of climate and life. Sierra Club Books, San Francisco 1984.
31 Schroedinger, E., What is life? Cambridge University Press, Cambridge 1944.
32 Schwartzman, D. W., and Volk, T., Biotic enhancement of weathering and the habitability of Earth. Nature *340* (1989) 457–459.
33 Sonea, S., The global organism. The Sciences *28* (1988) 38–45.
34 Tansley, A. G., The use and abuse of vegetational concepts and terms. Ecology *42* (1935) 237–245.
35 Vernant, J.-P., Myth and thought among the Greeks. Routledge and Kegan Paul, London, 1983.
36 Watson, A. J., and Lovelock, J. E., Biological homeostasis of the global environment: the parable of Daisyworld. Tellus *35B* (1983) 284–289.
37 Watson, A., Lovelock, J. E., and Margulis, L., Methanogenesis, fires and the regulation of atmospheric oxygen. BioSystems *10* (1978) 293–298.
38 Williams, G. C., Adaptation and natural selection. Princeton University Press, Princeton 1966.
39 Wilson, E. O., The insect societies. Harvard University Press, Cambridge 1971.
40 Wilson, E. O., (Ed.), Biodiversity. National Academy Press, Washington, D.C. 1988.

0014-4754/90/030232-07$1.50 + 0.20/0