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Review

# A geophysiologist's thoughts on geoengineering

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The Earth is now recognized as a self-regulating system that includes a reactive biosphere; the system maintains a long-term steady-state climate and surface chemical composition favourable for life. We are perturbing the steady state by changing the land surface from mainly forests to farm land and by adding greenhouse gases and aerosol pollutants to the air. We appear to have exceeded the natural capacity to counter our perturbation and consequently the system is changing to a new and as yet unknown but probably adverse state. I suggest here that we regard the Earth as a physiological system and consider amelioration techniques, geoengineering, as comparable to nineteenth century medicine.

**Keywords: Gaia theory; planetary medicine; amelioration**

## 1. Introduction

If geoengineering is defined as purposeful human activity that significantly alters the state of the Earth, we became geoengineers soon after our species started using fire, for cooking, land clearance and smelting bronze and iron. There was nothing unnatural in this; other organisms have been massively changing the Earth since life began 3.5 Gyr ago. Without oxygen from photosynthesizers, there would be no fires. Morton (2007) in his remarkable book *Eating the Sun* describes the crucial role of these organisms in shaping the evolution of the Earth and its climate.

Organisms change their world locally for purely personal selfish reasons; if the advantage conferred by the 'engineering' is sufficiently favourable, it allows them and their environment to expand until dominant on a planetary scale.

Our use of fires as a biocide to clear land of natural forests and replace them with farmland was our second act of geoengineering; together these acts have led the Earth to evolve to its current state. As a consequence, most of us are now urban and our environment is an artefact of engineering. During this long engineering apprenticeship, we changed the Earth, but until quite recently, like the photosynthesizers, we were unaware that we were doing it, still less the adverse consequences.

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It might seem that the fourth assessment report of the IPCC (2007) by over 1000 of the world's most able climate scientists would provide us with most of what we need to know to ameliorate adverse climate change. Unfortunately, it does not; the conclusions so far are tentative and preliminary. The gaps that exist in our knowledge about the state of the oceans, the cryosphere and even the clouds and aerosols of the atmosphere make prediction unreal. The response of the biosphere to climate and compositional change is even less well understood; most of all, we are ignorant about the Earth as a self-regulating system and only just beginning to recognize that many separate but connected subsystems exist that can exert positive and negative feedback on a global scale. It was not until 2001 that the Amsterdam Declaration stated as follows: the Earth system is a self-regulating system comprising the atmosphere, oceans and surface rocks and all of the organisms, including humans. Earth system science is acknowledged, but like a new book that one day we will read, it stays on the shelf. Consequently, the climate models of the IPCC are still based on atmospheric physics and the programs of their models do not yet include the code needed for a self-regulating Earth. Land and ocean surface changes are touched on but mainly from the viewpoint of their passive effect on the atmosphere. Even Lenton's (2006) review of climate change to the end of the millennium still appears to view the climate as mainly determined by geophysics. This concentration on atmospheric physics is a natural consequence of the evolution of climate science from weather forecasting, but most of all this is because there has been neither the time nor the resources to do more. We may soon need to try geoengineering because careful observation and measurement show that climate is changing faster than forecast by the gloomiest of the IPCC models (Rahmsdorf *et al.* 2007).

## 2. Geoengineering techniques

Physical means of amelioration, such as changing the planetary albedo, are the subject of other papers of this theme issue and I thought it would be useful here to describe physiological methods for geoengineering. These include tree planting, the fertilization of ocean algal ecosystems with iron, the direct synthesis of food from inorganic raw materials and the production of biofuels. I will also briefly describe the idea that oceans be fertilized to encourage algal growth by mixing into the surface waters the nutrient-rich water from below the thermocline.

Tree planting would seem to be a sensible way to remove $CO_2$ naturally from the air, at least for the time it takes for the tree to reach maturity. But in practice the clearance of forests for farm land and biofuels is now proceeding so rapidly that there is little chance that tree planting could keep pace. Forest clearance has direct climate consequences through water cycling and atmospheric albedo change and is also responsible for much of the $CO_2$ emissions. Agriculture in total has climatic effects comparable to those caused by fossil fuel combustion. For this reason, it would seem better to pay the inhabitants of forested regions to preserve their trees than plant new trees on cleared ground. The charity Cool Earth exists to gather funds for this objective. It is insufficiently appreciated that an ecosystem is an evolved entity comprising a huge range of species from micro-organisms, nematodes, invertebrates, small and large plants, animals and trees. While ecosystems have the capacity to evolve with climate change, plantations can only die.

Oceans cover over 70 per cent of the Earth's surface and are uninhabited by humans. In addition, most of the ocean surface waters carry only a sparse population of photosynthetic organisms, mainly because the mineral and other nutrients in the water below the thermocline do not readily mix with the warmer surface layer. Some essential nutrients such as iron are present in suboptimal abundance even where other nutrients are present and this led to the suggestion by John Martin in a lecture in 1991 that fertilization with the trace nutrient iron would allow algal blooms to develop that would cool the Earth by removing $CO_2$ (see Watson 1997).

Lovelock & Rapley (2007) suggested the use of a system of large pipes held vertically in the ocean surface to draw up cooler nutrient-rich water from just below the thermocline. The intention was to cool the surface directly, to encourage algal blooms that would serve to pump down $CO_2$ and also to emit gases such as DMS, volatile amines and isoprene (Nightingale & Liss 2003), which encourage cloud and aerosol formation. The pipes envisaged would be approximately 100 m in length and 10 m in diameter and held vertically in the surface waters and equipped with a one-way valve. Surface waves of average height 1 m would mix in 4 tons of cooler water per second.

Our intention was to stimulate interest and discussion in physiological techniques that would use the Earth system's energy and nutrient resources to reverse global heating. We do not know whether the proposed scheme would help restore the climate, but the idea of improving surface waters by mixing cooler nutrient-rich water from below has a long history; indeed, it is at present used by the US firm Atmocean Inc. to improve the quality of ocean pastures. The idea of ocean pipes for geoengineering was strongly resisted by the scientific community on the grounds that their use would release $CO_2$ from the lower waters to the atmosphere. We were aware of this drawback, but knowing that the low $CO_2$ levels during the glaciation were reached when the ocean was less stratified than now, we thought that algal growth following the mixing might take down more $CO_2$ than was released. The next step would be the experimental deployment of the pipes, observations and measurements.

Planting crops specifically for fuel, although sometimes an economic necessity, is a source, not a sink, for $CO_2$. Biofuels might be made green again if sufficient of the waste carbon from the plants could be permanently buried. Thus if any of the ocean fertilization schemes work, their value could be enhanced by harvesting the algae, extracting food and fuel and then burying the waste in the deep ocean as heavier-than-water pellets. This would remove a sizeable proportion of the carbon photosynthesized and place it as an insoluble residue on the ocean floor. The temperature of the deep ocean is close to 4°C and the residence time of water there is at least 1000 years. The buried carbon would effectively be out of circulation. It might be possible also to bury land-based agricultural waste at these deep ocean sites. This idea may be even more unpopular than the pipes. Critics rightly fear that waste buried in the ocean might be a source of nitrous oxide or other greenhouse gases, but again we may before long reach desperate times; so should we reject an experimental burial of carbon now?

Another amelioration technique is the direct synthesis of food from $CO_2$, nitrogen and trace minerals. When food was abundant, it seemed an otiose proposal, but not now since food prices are rising. Massive crop failure in future adverse climates would give food synthesis an immediately vital role.

The procedure for food synthesis would involve the production of a feed stock of sugars and amino acids from air and water as an industrial chemical operation, using either renewable or nuclear energy. This basic nutrient would be fed to tissue cultures of meat or vegetable cells and then harvested as food. Something similar to this kind of synthesized food already exists in a commercial form. It is a cultured mycoprotein product and supermarkets sell it under the brand name 'Quorn'.

Misplaced fear stops us from using nuclear energy, the most practical and available geoengineering procedure of all; we even ignore the use of high temperature nuclear reactors for the synthesis of food and liquid fuels directly from $CO_2$ and water.

## 3. Geophysiology

The Earth system is dynamically stable but with strong feedbacks. Its behaviour resembles more the physiology of a living organism than that of the equilibrium box models of the last century (Lovelock 1989). Broecker (1991) has shown by observation and models that even the wholly physical models of the Earth system are nonlinear, often because the properties of water set critical points during warming and cooling. These include the heat-driven circulation of the oceans. The phase change from ice to water is accompanied by an albedo change from 0.8 to 0.2 and this strongly affects climate (Budyko 1969). There are other purely physical feedbacks in the system: the ocean surface stratifies at 12–14°C, the rate of water evaporation from land surfaces becomes a problem for plants at temperatures above 22–25°C and atmospheric relative humidity has a large direct effect on the size and effective albedo of aerosols. In a simple energy balance model, Henderson-Sellers & McGuffie (2005) show the large climate discontinuity between the ice free and icy worlds and marked hysteresis.

Model systems that include, in addition to geophysics, an active and evolving biota self-regulate at physiologically favourable temperatures. Lovelock & Kump (1994) described a zero-dimensional model of a planet that self-regulated its climate; it had land surfaces occupied by plants and the ocean was a habitat for algae. This model system was normally in negative feedback with respect to temperature or $CO_2$ increase, but when subjected to a progressive increase of $CO_2$ or heat flux, regulation continued at first, but as the critical $CO_2$ abundance of 450 ppm, or heat input of $1450\ \mathrm{W\ m^{-2}}$, was approached, the sign of the feedback changed to positive and the system began to amplify and did not resist change. At the critical point, amplification rose steeply and precipitated a 6°C rise in temperature. Afterwards the system returned to negative feedback and continued to self-regulate at the higher temperature. As with the ice albedo feedback, there was marked hysteresis and reducing $CO_2$ abundance or heat flux did not immediately restore the state prior to the discontinuity.

The justifications for using this tiny zero-dimensional model to argue against the powerful forecasts of the giant global climate models are these. First, it is a model in which the biota and the geosphere play an active dynamic role, as in the model daisyworld (Watson & Lovelock 1983) from which it has descended. Second, it makes predictions that are more in accord with the Earth's history. It suggests that attempts at amelioration should take place before the critical point is reached. Unfortunately, when the large effect of unintentional cooling by short-lived pollution aerosols is taken into account, we may already be past this point and it would be unwise to assume that climate change can simply be reversed by reducing emissions or by geoengineering.

An engineer or physiologist looking at the IPCC forecasts for this century would find unconvincing their smooth and uninterrupted temperature rise until 2100, something expected of the equilibrium behaviour of a dead planet such as Mars. A glance at the Earth's recent history reveals a climate and atmospheric composition that fluctuates suddenly as would be expected of a dynamic system with positive feedback. The long-term history of the Earth suggests the existence of hot and cold stable states that geologists refer to as the greenhouses and the ice houses. In between are metastable periods such as the present interglacial. The best known hot house happened 55 Myr ago at the beginning of the Eocene period (Tripati & Elderfield 2005; Higgins & Schrag 2006). In that event, between one and two terratons of carbon dioxide were released into the air by a geological accident. Putting this much $CO_2$ in the air caused the temperature of the temperate and Arctic regions to rise by 8°C and of the tropics by 5°C and it took *ca* 200 000 years for conditions to return to their previous states. Soon we will have injected a comparable quantity of $CO_2$ and the Earth itself may release as much again when the ecosystems of the land and ocean are adversely affected by heat.

The rise in $CO_2$ 55 Myr ago is thought to have occurred more slowly than now; the injection of gaseous carbon compounds into the atmosphere might have taken place over a period of *ca* 10 000 years, instead of *ca* 200 years as we are now doing. The great rapidity with which we add carbon gases to the air could be as damaging as is the quantity. The rapidity of the pollution gives the Earth system little time to adjust and this is particularly important for the ocean ecosystems; the rapid accumulation of $CO_2$ in the surface water is making them too acidic for shell-forming organisms (The Royal Society 2005). This did not appear to happen during the Eocene event, perhaps because there was time for the more alkaline deep waters to mix in and neutralize the surface ocean. Despite the large difference in the injection times of $CO_2$, the change in the temperature of approximately 5°C globally may have occurred as rapidly 55 Myr ago as it may soon do now. The time it takes to move between the two system states is likely to be set by the properties of the system more than by the rate of addition of radiant heat or $CO_2$.

There are differences between the Earth 55 Myr ago and now. The Sun was 0.5 per cent cooler and there was no agriculture anywhere so that natural vegetation was free to regulate the climate. Another difference was that the world was not then experiencing global dimming—the 2–3°C of global cooling caused by the atmospheric aerosol of man-made pollution (Ramanathan *et al.* 2007). This haze covers much of the Northern Hemisphere and offsets global heating by reflecting sunlight and more importantly by nucleating clouds that reflect even more sunlight. The aerosol particles of the haze persist in the air for only a few weeks, whereas carbon dioxide persists for between 50 and 100 years. Any economic downturn that reduced fossil fuel use would reduce the aerosol density and intensify the heating and so would the rapid implementation of the Bali recommendation for cutting back fossil fuel use.

It is sometimes assumed that the temperature of the sunlit surface of a planet is directly related to the albedo of the illuminated area. This assumption is not true for forested areas. The physiological temperature regulation of a tree normally keeps leaf temperature below ambient air temperature by evapotranspiration, the active process by which ground water is pumped to the leaves; the trees absorb the solar radiation but disperse the heat insensibly as the latent heat of water vapour. I have observed in the southern English summer that dark conifer tree leaves maintain a surface temperature more than 20°C cooler than an inert surface of the same colour.

## 4. Planetary medicine

What are the planetary health risks of geoengineering intervention? Nothing we do is likely to sterilize the Earth, but the consequences of planetary scale intervention could hugely affect humans. Putative geoengineers are in a position similar to that of physicians before the 1940s. The author physician Lewis Thomas (1983) remarkably described in his book, *The Youngest Science*, the practice of medicine before the Second World War. There were only five effective medicines available: morphine for pain, quinine for malaria, insulin for diabetes, digitalis for heart disease and aspirin for inflammation and very little was known of their mode of action. For almost all other ailments, there was nothing available but nostrums and comforting words. At that time, despite a well-founded science of physiology, we were still ignorant about the human body or the host–parasite relationship it had with other organisms. Wise physicians knew that letting nature take its course without intervention would often allow natural self-regulation to make the cure. They were not averse to claiming credit for their skill when this happened. I think the same may be true about planetary medicine; our ignorance of the Earth system is overwhelming and intensified by the tendency to favour model simulations over experiments, observation and measurement.

## 5. Ethics

Global heating would not have happened but for the rapid expansion in numbers and wealth of humanity. Had we heeded Malthus's warning and kept the human population to less than one billion, we would not now be facing a torrid future. Whether or not we go for Bali or use geoengineering, the planet is likely, massively and cruelly, to cull us, in the same merciless way that we have eliminated so many species by changing their environment into one where survival is difficult.

Before we start geoengineering we have to raise the following question: are we sufficiently talented to take on what might become the onerous permanent task of keeping the Earth in homeostasis? Consider what might happen if we start by using a stratospheric aerosol to ameliorate global heating; even if it succeeds, it would not be long before we face the additional problem of ocean acidification. This would need another medicine, and so on.

We could find ourselves enslaved in a Kafka-like world from which there is no escape. Rees (2003) in his book *The Final Century*, envisaged a similar but more technologically based fate brought on by our unbridled creativity. The alternative is the acceptance of a massive natural cull of humanity and a return to an Earth that freely regulates itself but in the hot state. Garrett Hardin (1968) foresaw consequences of this kind in his seminal essay 'The tragedy of the commons'.

Whatever we do is likely to lead to death on a scale that makes all previous wars, famines and disasters small. To continue business as usual will probably kill most of us during the century. Is there any reason to believe that fully implementing Bali, with sustainable development and the full use of renewable energy, would kill less? We have to consider seriously that, as with nineteenth century medicine, the best option is often kind words and pain killers but otherwise do nothing and let Nature take its course.

The usual response to such bitter realism is: then there is no hope for us, and we can do nothing to avoid our plight. This is far from true. We can adapt to climate change and this will allow us to make the best use of the refuge areas of the world that escape the worst heat and drought. We have to marshal our resources soon and if a safe form of geoengineering buys us a little time then we must use it. Parts of the world such as oceanic islands, the Arctic basin and oases on the continents will still be habitable in a hot world. We need to regard them as lifeboats and see that there are sufficient sources of food and energy to sustain us as a species. Physicians have the Hippocratic Oath; perhaps we need something similar for our practice of planetary medicine.

During the global heating of the early Eocene, there appears to have been no great extinction of species and this may have been because life had time to migrate to the cooler regions near the Arctic and Antarctic and remain there until the planet cooled again. This may happen again and humans, animals and plants are already migrating. Scandinavia and the oceanic parts of northern Europe such as the British Isles may be spared the worst of heat and drought that global heating brings. This puts a special responsibility upon us to stay civilized and give refuge to the unimaginably large influx of climate refugees.

Perhaps the saddest thing is that if we fail and humans become extinct, the Earth system, Gaia, will lose as much as or more than we do. In human civilization, the planet has a precious resource. We are not merely a disease; we are, through our intelligence and communication, the planetary equivalent of a nervous system. We should be the heart and mind of the Earth not its malady. Perhaps the greatest value of the Gaia concept lies in its metaphor of a living Earth, which reminds us that we are part of it and that our contract with Gaia is not about human rights alone, but includes human obligations.

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