

Gaia Circular



The Gaia Circular is produced by the 'Gaia: Earth Systems Science' specialist group of the Geological Society of London. It is not intended as a formal peer reviewed journal, rather as an outlet for more informal articles on any aspect of Earth Systems Science. Indeed this edition even contains fiction, with a short story exploring ideas about possible futures for energy production in the context of climate change.

A long standing perceived problem with Gaian approaches to the Earth has been the question of how such a system could be compatible with biological ideas on evolution. In this issue two articles (both co-authored by Tim Lenton at UEA) reflect on aspects of this problem. In one Williams and Lenton provide a non-technical review of some of their recent work using an evolutionary computer model called 'Flask'; while in the other article Betts and Lenton consider the possible role of 'sequential selection' in the early history of a planet with life. One of the fascinating aspects of Gaian ideas is that they have attracted interest from a wider range of disciplines than just Science. This is illustrated by the essays in a recent book on Gaian ideas edited by the philosopher Mary Midgley – these essays range from science, such as microbial ecology and climatology, to the social sciences and theology. In a thoughtful review of this book Jane Fisher considers how a scientist should respond to such a wide range of ideas, many of which are very different from the styles of thinking typical of science.

I would be very interested to hear from anyone with potential articles (or ideas for articles) for future issues of the circular. As this issue shows there are many ways of thinking and writing about the Earth System, from fully referenced academic essays to scientifically inspired fiction. Please contact me at the address below if you have ideas for future issues.

David M Wilkinson

*Biological and Earth Sciences
Liverpool John Moores University
Byrom Street,
Liverpool
L3 3AF UK*

Email D.M.Wilkinson@ljmu.ac.uk



Front cover picture:

Rock, life and atmosphere in the Dolomites in northern Italy. All three are key players in the functioning of Gaia.
Photo ©David Wilkinson

Gaia was founded in February 1998 to promote an integrated understanding of the Earth System through research and education. In 2001 Gaia decided to continue its activities as a newly formed specialist group on Earth System Science within the Geological Society of London.

Editor:

David Wilkinson, Biological and Earth Sciences, Liverpool John Moores University, Byrom Street, Liverpool L3 3AF, UK.
Email
D.M.Wilkinson@ljmu.ac.uk

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Background image: Winter sunrise, Yosemite Valley USA. Photo: Dave Wilkinson

The Gaia circular is published by The Geological Society Publishing House, Unit 7, Brassmill Enterprise Centre, Brassmill Lane, Bath BA1 3JN
Tel: 01225 445046 Fax: 01225 442836

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Second chances for Lucky Gaia:

Richard Dawkins famously suggested that “Anti-Gaia” is just as likely as Gaia, and would mean planetary extinction. Here, **Richard Betts** and **Tim Lenton** argue that the presence of life (with its capacity for death and evolution) enables a planet to explore different feedback systems in sequence, loading the dice in favour of the emergence of self-regulation.



Charles Darwin, presiding over the Cafe at the Natural History Museum in London. How to reconcile a Gaian approach with natural selection has been a long-running problem in Earth Systems Science. *Photo Dave Wilkinson.*

The Gaia theory proposes that life and its physical and chemical environment on Earth form a self-regulating system that maintains a habitable state (Lenton, 1998; Lovelock, 1988; Lovelock & Margulis, 1974). However, since the properties of planets cannot evolve through natural selection within a competing population (Dawkins, 1983; Doolittle, 1981), how can regulatory behaviour arise at a planetary scale? Here we suggest that a cruder form of selection for regulation is able to operate on a series of systems over time, rather than on a population of systems co-existing at the same time.

Life exerts numerous influences on the physical and chemical environment through its role in biogeochemical cycles, the hydrological cycle and the planetary radiation budget (Steffen *et al.*, 2004). Biotic responses to changes in environmental conditions may therefore exert feedbacks on the environment. Such feedbacks may either dampen the initial perturbation (negative feedbacks) or enhance them (positive feedbacks). A planetary-scale life-environment system is likely to feature a large number of feedback mechanisms, both negative and positive, and clearly a key characteristic of the planet would be whether the net effect of its feedback mechanisms is to stabilise habitable conditions (regulation) or to destabilise them (anti-regulation). Some evidence suggests that the current Earth System is self-regulating, and a number of mechanisms have been proposed (Lenton, 1998). However, explaining the emergence of overall regulatory behaviour has remained a difficulty.

Although the many variants of the Daisyworld model (Watson & Lovelock, 1983) have demonstrated that, in principle, regulatory feedbacks can emerge from a system containing natural selection, this model relies on a



a hypothesis of sequential selection

direct connection between the selection of traits at the individual level and their planetary consequences (Lenton, 1998; Lenton & Wilkinson, 2003). In a cold climate, dark daisies warm their local environment and promote their own growth, and the aggregate effect of many dark daisies is an overall warming of the planet. If an individual dark daisy warmed the rest of the planet as much as it warmed its own local environment, light daisies would not be out-competed by dark daisies and regulation would break down.

In contrast, a number of regulatory mechanisms proposed for the real Earth involve the effects of organisms on the environment which are spread evenly across the globe and which therefore cannot be selected for on the basis of these global environmental consequences. For example, the temperature-dependent enhancement of rock weathering by vascular plants, mycorrhizal fungi, lichens, and soil bacteria may regulate surface temperature by modifying the concentration of the greenhouse gas carbon dioxide (Schwartzman & Volk, 1989). Since CO₂ is well mixed in the atmosphere, an individual organism cannot preferentially modify the “greenhouse” forcing of its own local climate through enhanced rock weathering. Hence temperature regulation by rock weathering cannot evolve directly by natural selection (Lenton, 1998). So, while *Daisyworld* demonstrates in principle that Gaia and natural selection are compatible, it does not provide an explanation for the emergence of regulatory mechanisms that do not involve feedbacks on selection (Lenton, 1998).

If a planetary-scale feedback mechanism cannot have been naturally selected for, then the key process must be a by-product of selection at a much lower level (e.g. the gene) based on other factors. It has been argued, therefore, that the overall regulatory or anti-regulatory character of a life-bearing planet must also be a by-product, and if the Earth is self-regulatory then this is simply good fortune. An anti-regulatory system could equally have emerged and driven itself to extinction (Dawkins, 1983). Taking this argument further, the anthropic principle has been invoked to “explain” our existence on a self-regulating planet (Watson, 1999). In contrast, we argue that the emergence of feedback mechanisms as by-products of natural selection does not imply that the ultimate emergence of planetary-scale regulation is purely a matter of chance. We suggest that, in the long-term, there should be a bias towards the ultimate emergence of a regulatory system.

Consider the case of an overall anti-regulatory system emerging as a by-product of evolution. Such a system may be termed “Anti-Gaia” (Dawkins, 1983). Previous arguments (Dawkins, 1983) have suggested that this must cause extinction of the biota resulting in a dead

planet. However, in the case of Earth, we note that the physical and chemical environment is extremely heterogeneous. For example, local extremes of land surface temperature range from -89°C to 58°C , and local water availability ranges from zero to saturation. Some regions will therefore be closer to the limits of habitability than others. In a system driving itself away from optimum conditions, global-scale changes would lead to conditions becoming extreme in some locations before others. Extinction of life would not occur instantaneously across the globe, beginning earlier in some regions, while life in other regions continued. With life becoming sparse, the strength of the anti-regulatory mechanisms would diminish. Ultimately, a point could be reached where some life still existed, but in a state too sparse to exert a significant impact on the global environment. At this point, “Anti-Gaia” would have driven itself out of existence. However, with life still persisting, albeit very sparsely, the planet itself is not dead.

Unless the planet had moved to a new stable equilibrium state, this removal of anti-regulatory processes would allow conditions to return towards those under which life previously evolved. As long as the planet remained habitable, the positive feedback inherent in reproduction would encourage the life in refugia to spread. Evolution would be unlikely to take the same pathway as that previously followed, so it would be possible for the biota to evolve properties different to those of the previous system. These could be either regulatory or anti-regulatory. If new anti-regulatory properties evolved, life would again approach extinction, “re-setting” the system and allowing evolution to explore yet another pathway. This would continue, either until regulation emerged or until the planet became subject to an extreme external forcing which left no refuges for life. Therefore, even if regulation can only emerge as a fortuitous by-product of evolution by natural selection, the biota could have a number of opportunities to evolve regulatory properties. Once emerged, a regulatory system would by its very nature be more likely to persist.

We note that continued evolution could ultimately result in the loss of the properties associated with regulation, so the regulatory system could merely be transitory. Nevertheless, the above mechanism increases the probability of a planet developing regulatory properties for some part of its history.

We contrast this with a planet whose physical and chemical environment is not affected by life. Abiotic feedback processes could also produce either regulation or anti-regulation (Holland, 1984), and if the feedbacks were anti-regulatory then the environment could be driven into a state unsuitable for life. However, in contrast to the biotic feedbacks that are removed when life becomes sparse, abiotic anti-regulatory feedback



The Fly Agaric, the familiar fungus of illustrated children's book (despite its hallucinogenic properties!). This is a mycorrhizal species which forms symbiotic relationships with plants. Such mycorrhizal associations may help regulate carbon dioxide levels in the Earth's atmosphere, through their enhancement of rock weathering. *Photo Dave Wilkinson.*

mechanisms would remain, rather than destroy themselves. Thus there is no opportunity to re-set the system. Furthermore, without evolution there is no mechanism for the generation of new, possibly regulatory properties.

This mechanism is similar to that previously proposed for the automated "learning" of stabilising behaviour by a mechanical system (Ashby, 1952). Instead of requiring conscious intervention or natural selection within a population of competing systems, self-regulation of a system can emerge through a mechanism that is effectively "trial and error". The presence of evolving life on a planet provides the system with two properties which are crucial to such a mechanism; (i) the capacity for death (and hence an ability to reset the system) and (ii) the capacity for change and hence the chance for new properties to emerge. A third crucial property, removal of one system whilst retaining the capacity for emergence of a new system, is provided by the inevitable heterogeneity of environmental conditions and hence the provision of refugia.

Such a mechanism was hinted at by the late, great Bill Hamilton, who in the context of Gaia sought "a principle concerning to why system-stabilising outcomes...are more likely than system-de-stabilising outcomes" (Hamilton, 1997). He wrote: "I am hesitant myself as to whether when this set of principles is discovered it is going to involve n.s. {natural selection} in a big way or something else. I suspect one will be able to refer to n.s. but it won't be quite the idea as we normally think of it – vaguely I imagine that 'learning' through *repetitions over time alone* in a sufficiently complex system has to be shown able to replace the currently understood (and I am sure much more powerful) 'learning' through repetitions over both time and space, which is n.s. as we know it" (Hamilton, 1997).



In conclusion, it has previously been argued that the presence of regulatory feedbacks on Earth could be pure good fortune (Doolittle, 1981; Watson, 1999), and we agree that this would be the case if the regulatory feedbacks were purely abiotic. However, the presence of life, with its capacity for death and mutation, endows a planet with special properties that increase the probability of regulation emerging. Evolving life introduces a mechanism for selection amongst a sequence of biotas, through which anti-regulatory outcomes can be eliminated and the eventual emergence of regulation becomes more probable. We therefore suggest that planets bearing life, including the Earth, could "evolve" self-regulatory properties through a process of sequential selection.

Richard A. Betts is Manager Climate Impacts at the Met Office Hadley Centre, Fitzroy Road, Exeter EX1 3PB, UK (e-mail: richard.betts@metoffice.gov.uk).

Tim M. Lenton is Professor of Earth Systems Science in the School of Environmental Sciences, University of East Anglia, Norwich NR4 7TJ, UK (e-mail: t.lenton@uea.ac.uk).

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Earthy Realism: the meaning of Gaia



Jane Fisher reviews a new collection of Gaian inspired essays edited by Mary Midgley.



Susan Canney (secretary of the 'Gaia; Earth systems Science' specialist group) speaking at the official launch of 'Earthy Realism' in the Geological Society library in early October 2007. Photo courtesy Susan Canney.

It is difficult to know to whom exactly this book is addressed. It will certainly not be read by enough of those who need to read it. *Earthy Realism* has echoes of the wave of books in the 1980s about the meeting of Eastern mysticism and Western sciences, but deals with the subject in a more technical and science-based way. Professional ecologists, geographers and biologists ought to be aware of the arguments presented here, and policy-makers at scales from international to local should be compelled to take in these messages, but it also should be required reading for those 'woolly-hatted woolly-brained lentil stirrers' who seek

personal growth through 'green consumerism'. From an initial glance at the chapter headings I feared that many chapters would be concerned with 'fluffy', new-age notions, without due consideration of the scientific, economic and social challenges. I was wrong. As a scientist and active environmental campaigner, I found the contributions linking the influence of our relationship and perception of the Earth with current global environmental issues especially interesting, topical and relevant. Midgley's introduction focuses on the premise that if we are to understand the current global problems faced by our

planet, we need to bring together the opposing facets of Gaia – both the ‘scientific’ and the ‘spiritual’, and argues that we should not be afraid of the benefits brought to our understanding of Gaia in doing so.

The chapter by Wilkinson discusses a theory at the heart of the original Gaia hypothesis; the role of microbes. Since microbes are central to the biogeochemical cycles which form Gaian processes, it is essential to question their importance to nature conservation and their likelihood of becoming extinct. Wilkinson raises the question as to whether such microbes are indeed ubiquitous and able to re-colonise should they become locally extinct. The loss of host-specific microbes with the extinction of larger organisms is an interesting point and invokes the question as to whether the ecosystem role of such species can be replaced by others in the environment. While re-colonisation will, theoretically, prevent local microbial extinction from hindering Gaian processes, he highlights that this is an important question, which scientific research has yet to answer.

The evidence behind “Human-Caused Climate Change” is the focus of Betts’s chapter, and the evidence is summarised in a clear, succinct way, which is easily digestible for the non-scientist and invaluable for those of us who occasionally feel the need for an overview of the evidence when in debate with students or the public. I would have liked to have had the scale and rate of current climate changes placed in context of those experienced over the Quaternary, since proponents of the non-human caused climate change argument will often cite past global climate change. Betts raises the problem of the inability of humans to see their place in the wider globe, and concludes that we need be open to new ideas, such as alternative economics and that governments must use their power to bring about change. Betts identification of links between human-caused global climate change on the one hand and our current economic assumptions, resource dependency and demands on the other, makes a stark and logical argument.

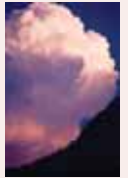
Several contributors concentrate on the role of human perception and the psychological separation of ourselves from the planet, and on the separation and reductionism within our studies of the sciences. These prevalent modes of consciousness are counter to the Gaian holistic appreciation of our interdependence on natural processes. Spallone’s chapter on “The Gaia effect: making the links” and Canney’s “Reconnecting a divided world” illustrate these gaps with examples from discourse with Indian, Philippine and Malayan nationals who instinctively recognise that many human health systems, and all agriculture and life support systems are inherently linked to the state of the environment. Midgley and Goodwin both relate ‘Gaian’ thought to a move towards a more holistic science, in contrast to the reductionist science that limits itself to “quantitative measures” of single



processes and the “mechanistic model of linear causality”, rather than the qualitative terms needed to describe complex systems such as Gaia, health and wellbeing. The pursuit of science can be related to disciplines normally seen as the opposite. “Science and art”, observes Gee, “both use the same observant curiosity...impelled by a desire to understand, both finding and recording pattern in what first seems random and chaotic”. While this may not describe our sciences, commonly studied and taught as disparate topics, it seems a just description of Gaian science, Ziman’s short but thought provoking chapter on this separation, or “pluralism”, leaps to our defence by reminding us that the Earth itself was controlled by solely physical processes for a billion years, long before the biological and associated bio-chemical process cycles began to influence it.

One of the original developers of the Gaia hypothesis, Lyn Margulis, stated that her Gaia “is no vague, quaint notion of a mother Earth” but is a science (Margulis, 1998, p.123). For many, the Gaia hypothesis anthropomorphised the globe and gave rise to the spiritual, Mother Earth belief. Harding’s chapter discusses the Gaia hypothesis within this context by describing the Earth as “her” and by arguing that increased appreciation of “her hills”, “her forests” and “her power” will help invoke a change in society leading to a reduction in our ecological footprints. Meanwhile, Brook argues that “we cannot save what we don’t love”. Primavesi also anthropomorphises the Earth by asking “Can Gaia forgive us?”. Such anthropomorphic sentiments do not sit well with my scientific outlook, and while such environmental appreciation is often beneficial to the individual, a force for improving mental and physical health for example, I fear that for most people this does not invoke the practical action needed to move themselves or society towards sustainable living. The environmental movement has long been circled by individuals who have searched for enhanced inner-connections with the Earth, but these notions have not led to reduced consumerism or carbon use, nor to enhanced pressure on governments for sustainable legislation. If our lack of spiritual appreciation of the Earth is the cause of the hysteresis in addressing current global environmental problems, then Harding is justified in promoting it, but I fear that on its own it will not lead to the practical action needed if we are to avoid pushing environmental change beyond the limits of Gaian buffering processes.

When asking “Can Gaia forgive us”, Primavesi states that “repentance”, which is part of the same process as “forgiveness”, will require “self-limitation” in order to reduce our ecological footprint. She also states that man’s activities seem to be leading to a rise in simple, ancient microbes, such as the Cyanobacteria, and describes this as “reverse evolution”, but here she falls foul of the human bias of noticing large organisms most. Bacteria are, and have always been, more important and more numerous than ‘higher’ organisms.



Resistance to develop solutions to global environmental problems are the subject of contributions from Turnbull and Mead, whose chapters on "...Why the Gaian world-view will struggle" and "The human psyche and the imminence of climate change" bring together the 'scientific' and 'spiritual or physiological' sides of Gaia. Both chapters discuss what it is in our inner psyche that prevents us from recognising and then acting on the urgent needs of our planet. This seems to be caused by two interrelated processes. The first: massive vested interest and economic ideology which, Turnbull argues, has permeated all we do and separates our actions from their impacts on the globe. The second process, proposed by Mead, appears to be mass denial, which is at least partly linked to the vested interest described in the Turnbull chapter. He succinctly argues that the scale of the disaster that will befall humanity and all natural systems, and our inability to see how to operate society in a sustainable way, stems from denial at the individual and government level. This denial is pervasive in society and most of us, including environmental scientists, geologists, ecologists or economists, will recognise these traits in ourselves or in other educated, environmentally-aware colleagues. Facing the global problems, Mead argues, means facing up to our guilt as to what we, especially in the developed world, have done to the poorest, future generations, and global ecosystems. Mead's succinct and well argued piece ends with the proposition that we need to "confront unwelcome truths without the fear of being destroyed by them" (quoted from Dr Rowan Williams, Archbishop of Canterbury).

The processes of denial of climate change, and our addiction to consumption and economic growth, is the theme of "Climate change and spiritual transformation" by David Midgley. He sees our vested interest, as discussed previously by Turnbull, as an addiction to massive fossil fuel use, and that requires a power shift in the existing modes of consciousness to reduce our close "symbiosis" with industrial technology. This dependence on technology and separation from the natural world leads me to question the additional separation in our personal relationships we, as a society, have begun to experience through the recent rise in internet-based communication. In his chapter, Cullinan states that the role in which humans play in the Gaian process will be governed by our human laws, and contrasts these with "Wild Laws", which are 'based on the laws of the universe'. Such include an awareness of the Gaian processes and the rights of all life. Cullinan describes the scale of the shift in collective thought required to implement these laws to be comparable to that required to appreciate Copernicus's discovery that the Earth orbits the sun. I wonder if it will be, in fact, a greater shift. In order to live under such "Wild Laws", change in our economic and social structures and in our daily lives will be required, and not just in our belief systems. Such a global change in our laws is required in order to develop and indeed enforce sustainable living, rather than a vain hope that a new-found appreciation of the wonders of Earth alone will instil action.

Cullinan describes this approach as a need to "roll up our sleeves" and "implement new governance systems".

What ever the answer to this, the authors of this book seem united in the assertions that we collectively fail to recognise our interdependence on the planet, to appreciate the spiritual pleasures of nature and, through processes of denial linked to our vested interest, we fail to act.

In total, this book is worth reading. The connections made between human existence and the state of the world are profoundly important for us, those elsewhere, and future generations. The messages in this book are not new. They have been said before, but they should be stated and restated as often as feasibly possible, so that they are heard and understood by as many people as possible in all walks of life. Industrial globalisation and all its trappings are taking us to the very edge of the abyss. It is only through greater understanding that people; politicians, business leaders, and the public alike, can begin to learn what it is that is truly important for life on this earth. It seems obvious that the subject of this book will be new territory for them.

Jane Fisher is lecture in Ecology in the School of Biological and Earth Sciences at Liverpool John Moores University.

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Chair: Sir Crispin Tickell

Secretary: Dr Susan Canney
Email: susan.canney@zoology.oxford.ac.uk



Sunset on Green Mountain Ascension Island. Photo: Dave Wilkinson

The Moses plot:

Earth Systems fiction by Umoya Lister

Clerics, carbon and coffee at Charlie Darwin's cafe.

The descent to Ascension Island was a surprise. As the plane curved round to land into the teeth of the SE Trades, Joe could see the shimmering emerald of Green Mountain over the plump hydrogen-tank wings. Joe had heard about the Hooker-Darwin cloud forest, but the sight of its luxuriant canopy took his breath away. Half a century ago, Wilkinson, the Gaian ecologist, had predicted that random accidental plant escapes would build a new ecology on the ravaged peak. But lush reality went far past expectation. It was glorious.

At Wideawake airport he avoided the slow DNA-check line for citizens of poor nations like the US and UK. Thankfully, his Canadian passport spared him the search for illegal migrants. The terminal hall was dominated by a stunning and enormous Vulcan hanging from the ceiling, the bomber that had closed the Falklands airstrip and set in train the events that made possible the discovery of the Antarctic ozone hole. He boarded the glistening mag-lev to Georgetown and eventually made it to the cheap bed-and-breakfast, the best his New York 'paper of record' could afford for its



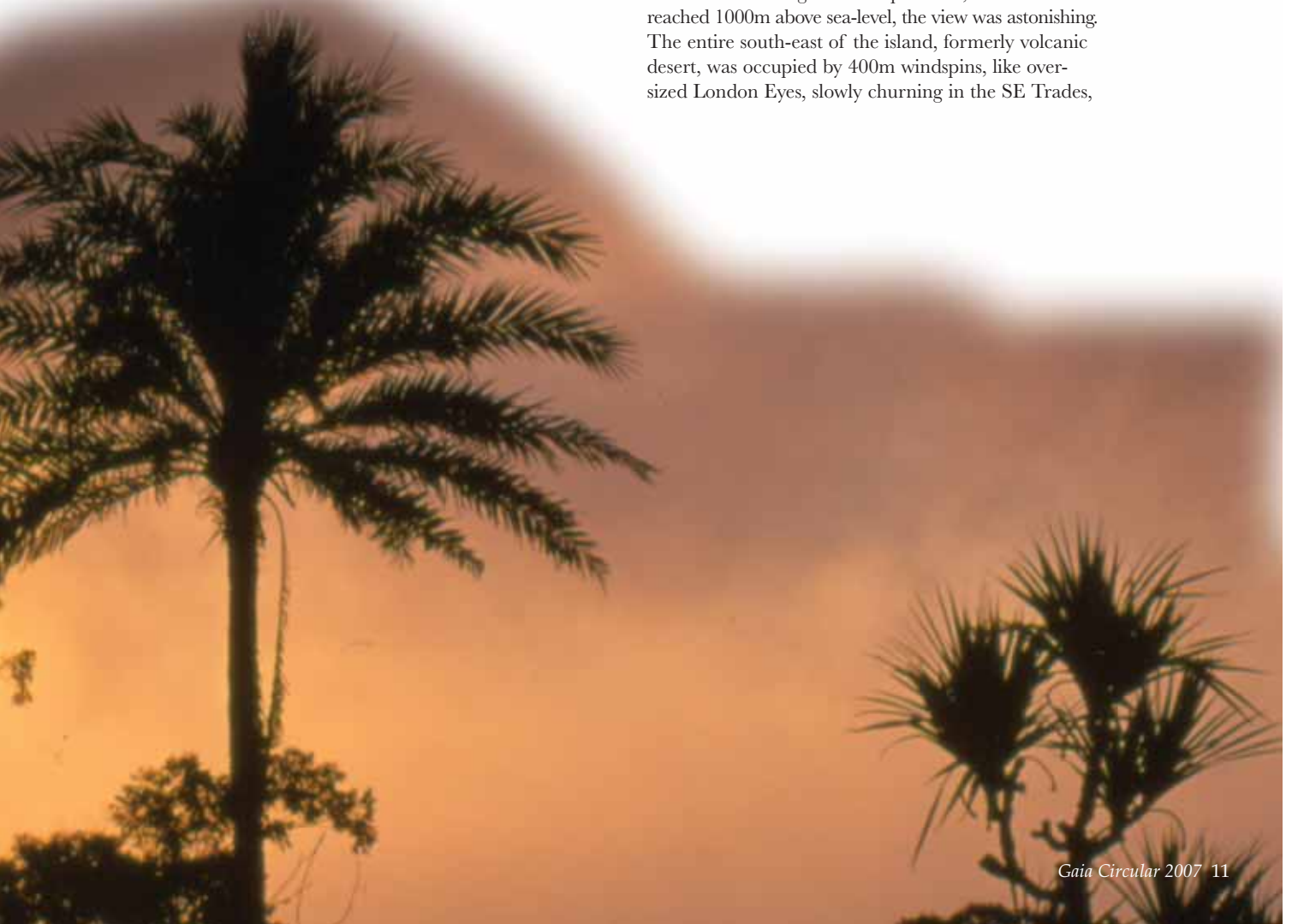
parting the Red Sea

sole remaining foreign correspondent. It was basic, down in the muggy capital rather than lofty Two Boats where the posh hotels looked out, but, like all things on Ascension, spotlessly clean. There was a slight hitch when the hotel gene scan machine realised his bank was in the US. Distrustful since the US debt default, it wanted pre-payment in hard Duchy of Normandy funds. Like some antique traveller, he had to walk next door to a branch of the St Helena Bank, which was willing to debit the New York account. For a sharp fee, they managed to produce paper money, still printed for tourist collectors. King William V's gentle, elderly portrait exuded confidence.

The meeting of the Organisation of Wind Exporting Countries began the next morning. All the super-rich OWECs were present – Falklandia, Fuegia, Kerguelen, Cabo Verde, South Georgia, Greenland, Iceland, Norway-Bouvet, New Zealand. There were TMH flags everywhere - Tasmania-Macquarrie-Heard had recently seceded from Australia and was attending OWEC for the first time. The whole show was hosted

this year by the six bailiwicks of the Atlantic Duchy isles: Tristan, St. Helena, Gough, Jersey and Guernsey as well as Ascension. They had invited the Chagos to join the Duchy, even though not a wind nation. The energy importing superpower customers had come too - both India and China. The impoverished supplicating 'burn-outs' had all sent delegates to plead for crumbs – not just the US, but also the Mid-East nations. Argentina was begging a loan from South Georgia, Fuegia and Falklandia. EuRussia still disputed Kerguelen's independence, and had boycotted the meeting, but unofficially sent a team. After all, OWEC bought most of its luxury fuel-cell cars from Germany. Britain, a cold little island living on herrings, potatoes, and Imperial-Nostalgia tourism from India, had recently been expelled from EuRussia for pinching hydrogen gas destined for France as it passed through the Bergen-Aberdeen-Dover-Paris pipeline. The UK was begging financial help from its former Wind Dominions. It was going to be a tough meeting.

Joe decided to take the gondola up Green Mountain. From the 140m high summit platform, built so it reached 1000m above sea-level, the view was astonishing. The entire south-east of the island, formerly volcanic desert, was occupied by 400m windspins, like oversized London Eyes, slowly churning in the SE Trades,



the steadiest winds in the world,” fresh but not frenzied”. In front of each wheel was a frail nylon net: enough to warn the few birds that strayed from the heavily protected coastal colonies. It was immense. If these mills were big, feeding on the world’s friendliest and steadiest winds, he suddenly longed to see the heroic engineering structures that for a hundred miles lined the barren, biologically dead summits of the 2000m high South Georgia ridge. Wind power goes up as the cube of the speed, and those mills ate the world’s most brutal gusts.

Here on gentle Ascension the scene was more kindly. Under the quiet wheels were hydroponic fields and, in the dry south of the island, solar photo-carpets, amid electrolyzers and hydrogen tanks. In the west of the island, he could see the clean, no-mess aluminium smelters. On the north-west coast, a ship disgorged garbage and fluids excavated from 20th century US landfills. The leachate fluid loaded the vats where bacteria extracted rare metals. Above them, methanogenic archaea, fed with hydrogen, helped the carbon along the path to methanol fuel. Each gram of carbon was counted and balanced elsewhere.

Offshore as far as he could see were immense square-rigged sail-barges, majestically tacking to and fro, parasails billowing above. Dotted like waterbeetles on the sea were the moor-point pulleys, where cables pulled by the automated ships turned the huge generators. In the still air between were twenty-acre solar barges. A vast Chinese hydrogen tanker and a small sodium carrier were filling up from a pontoon.

Further out to sea, high above the waves, he could see another enormous parasail. Underneath, the tractor unit of an empty watertanker was setting off for a new voyage. The squat tug was dwarfed by its tow: six empty bags like giant sea slugs, fabric kept afloat by air. In a few weeks, once each fabric water bag was filled with a million tons of water in the Amazon mouth, the tug would launch dozens of parasails and tack south round the curve of Brazil. After that it was plain sailing, south to the Uruguayan coast, then across the ocean to the Cape. From there it was north-east to the Gulf states where the old energy-hungry desalination plants had all been decommissioned as the oil ran out. When the wind changed, they came back, like the old East India ships. The Congo route was easier, but Brazil charged less for the water. The OWEC cartel held monopoly water-removal licences from both Brazil and the Congo. The wretchedly poor Mid-East states, desperate for water, were pleading for price cuts, but OWEC was not listening.

The sea was sparkling, so unlike the green-gunk Atlantic shores of North America. When atmospheric CO₂ rose decades before, the pH change and consequent extinction of carbonate-precipitating organisms had turned much of the world’s ocean surface to a smelly bloom of toxic cyanobacteria, especially where nitrates flowed out from overfertilised fields. Here it was different. Ammanox planctomycetes dealt with the nitrate, and in a great ring of barges around the island, carbonic anhydrase extracted CO₂ from seawater, reacting it with serpentinite dredged from the nearby mid-Atlantic ridge. The resulting magnesite and



siderite was exported worldwide as a building material. It was enough to turn the pH balance locally. There was even a bright new coral reef growing on sunk ships, seeded from corals in London Zoo’s aquarium. Ascension’s sea-turtles flourished. Fishing was superb.

He turned to look west, townside, and clumsily bumped into a woman. She looked at him, as if she were expecting him. “Hi, I’m Sara. From Somaliland. You must be the American?” They chatted about the environmental protests. The sinking of the sodium tanker in San Francisco harbour last month had been pretty embarrassing to OWEC. Moreover, hydrogen emissions were damaging the oxidative capacity of the global atmosphere. Someone had strung a big banner saying “Nuclear, not hydrogen”, now turned upside down, across a giant BH windwheel,

“Charlie’s” she whispered, “Eleven tomorrow morning”, and was gone. She’d obviously mistaken him for someone else. A journalist sniffs news: he’d be there. He walked down through luxuriant meadows, behind a well-known Chinese academic loudly discussing peak-uranium theory. Was Canada mined out? His Indian companion chuckled. “Don’t worry. We’re going to breeders.” They ambled on, discussing renting South African gold mines for nuclear waste perma-store, and the Zangbo/Brahamaputra hydro-power tunnel. A couple of mega-rich South Georgians were there too, in suits too obviously expensive to be tasteful, dripping gold, flaunting their ever-so exclusive Swiss watch-communicators. The sodium tanker had been one of theirs: nobody else was reckless enough to use old triple-hullers, and only the US was desperate enough to allow them to enter.

“Charlie’s” turned out to be a cafe of intrigue. Etched in the glass doors was a superb portrait of Darwin, the image mixed with the reflection of the lovely carbon-fibre wing of the soaring cathedral opposite. Inside, in one alcove, decor was after Fitzroy’s cabin on the *Beagle*. On the walls of another corner were pages of Darwin’s notebook and portraits of other visitors to the Atlantic Isles - Napoleon, Nelson, Wellington. In the Victorian century, Ascension had at times probably been the world’s biggest naval base, the nerve centre of the battle against slavery, often with a bigger fleet even than that guarding Britain. Memorabilia were everywhere. Jane Austen’s brother probably landed, on his final voyage. Had young Churchill and young Gandhi landed? Kipling? Trollope? Rutherford? Probably. More recently, Thatcher came, when for a brief moment Wideawake was the world’s busiest airport. After that, both Presidents Clinton visited, en route to see Mandela. The ghosts crowded the décor.

In one corner of the café a flamboyantly-dressed Texan oil importer haggled with two steely-eyed Ghanaian palm oil dealers in typically sober Presbyterian suits. They were refusing to cut their price – other oil-junkies like Saudi and Australia were desperate to buy also. The Texans had no bargaining cards. The cheerful waitress, a migrant worker from Africa, seemed to sense Joe’s need for quiet. She found him a table well away from them. Soon he was brought a mug of exquisite Zimbabwean eastern highland coffee.



Sara arrived with a man chatting in Xhosa on his phone. “Two To Go!” he pronounced to the waitress. She whooped with a delight that surprised Joe, used as he was to plastic smiles. A few minutes later, the room emptied. The OWEC meeting was about to begin. At another table were a rabbi, two imams, and a Copt, all in deep conversation with the instantly-recognisable archbishop of Cape Town. The archbishop was roaring with laughter. He’d been to matins at the lovely old Hanoverian church, and was still incredulous at the discovery that it was built deep inside the cricket field. “A helmet behind the wicket is one thing, but a church! Proves ethics and competition can get along.” But in his laughter, he’d seen Sara and her friend come in, and he’d heard the order too. As the clerics rose to leave for the opening ceremony, all delivered broad smiles to her. In the door, the archbishop turned and quoted from Moses and the burning bush: ‘And yet it was not consumed’. He paused, and added “we too shall be renewable”.

The waitress exchanged a quick burst of Xhosa with the departing archbishop, gave Joe a refill and went to the kitchen. Sara leaned forward. “Operation Desmond. They’re the link. They all have the ears of their governments. Even the bishop here in Ascension is helping. Her diocese is part of the archbishop’s Cape Town province. The arrogant OWEC politicians haven’t a clue what we’re up to. We poor nations are standing up. Operation Desmond’s cover story is the new Afro-Arab train line. Tell your president the cover worked perfectly. Just six more hours. Then it’s *fait accompli*, too late for a World Court injunction - the Red Sea ceases to be international water.”

Joe still said nothing. It was good coffee. Sara continued. “We close Bab-el-Mandeb straits at the mouth of the Red Sea tonight. We’re putting a thin steel wall across the shallows under the new rail line, and in the deep channel the Afro-Arab-American waterwheels are winching up under the suspension bridge. The channel’s only a few hundred metres deep and a few kilometres wide. The flow’s several Amazons moving at one or even two metres a second – salty outflow turns the bottoms of the wheels one way, while above the ocean inflow pushes the wheeltops the other way. We generate electricity immediately. Djibouti and Somaliland will become the world’s aluminium capitals. Aden will make the hydrogen and sodium. There’ll be plenty of spare power for the trains in Ethiopia, Egypt, Kenya, and Saudi, even as far as Israel. But we’ll all share the revenue.”

Joe said nothing, though the genuine surprise must have showed on his face. Sara reassured him “We won’t forget you. We owe a lot to the US. We’re very grateful for your heavy engineering. South Africa and Israel couldn’t have done it on their own. US universities may be backward but no other poor nation has your old-fashioned skills.”

“How important is it?”

“Didn’t they brief you? It’s huge, really huge. Hydrogen’s price will halve. Poor people will have transport at last. OWEC will panic. Europe will scream about the Suez route being international, and OWEC will back them. They’ll be desperate to preserve their monopoly on cheap power, but we have

all the Red Sea states in our consortium. We’ll stonewall at the World Court. Anyway, we’ll build a ship-lock next year. Besides, from July to December nearly all China- North Atlantic shipping is by the Arctic nowadays.”

Suddenly a man rushed in. “Sara, he’s the wrong man. Washington’s agent was deported yesterday as an illegal immigrant.” Sara stared at him. It was time for Joe to speak. “Don’t worry. I won’t print. Just give me an exclusive when you’re ready.”

He kept his word. But he did phone his sister, whose hedge fund massively shorted OWEC shares on the Duchy’s stock market in Old Jersey. She bet everything on two minor stock exchanges that would benefit from cheap energy – the old markets in London and New York. They made millions. Joe, feeling guilty, bought serpentine waste heaps from Africa’s old asbestos, platinum and chrome mines, and started sequestering carbon in magnesite. Taking a trick from the coral-reef project, they captured the carbon from the air using carbonic anhydrase. His sister invested in oil plantations in Haiti, building up new soil carbon on ruined laterite desert. Between the new trees, they grew woody bushes. These were harvested, charcoaled, and dug in: within a few years the barren concrete had begun to develop thick new soils. Even OWEC, prodded by the archbishop, developed a conscience. As aluminium and hydrogen prices recovered in the global boom, they relented and began sponsoring a massive program of sequestration projects, regrowing tropical rainforest. Things snowballed. Soon they were precipitating ten billion tons of carbon a year.

Slowly the oceans degassed and the seas began to sparkle again. Ascension’s coral reef, that had delighted Joe so much, served as a nursery. DNA was extracted from dead corals and fish in museum collections around the world, recapturing hundreds of extinct species. The Bahamas, the Great Barrier Reef, Maldives, the Pacific Atolls – all were recolonised. Joe helped broker a deal with bankrupt Britain for the peaceful accession of Diego Garcia to the Duchy. That led to the reseeded of the most beautiful reefs of all, the Chagos corals. The abandoned US stealth bomber airfield provided a perfect base for the operation – soon it was making millions as a tourist paradise. Africa did not forget the US. In time, even America’s burned-out oil-junky economy recovered, fed with cheap clean energy and venture capital from Joe, Sara and their friends. Oh yes, she married him. It had been a good cup of coffee, Africa’s best.

“**Umoya Lister**” is the pseudonym of an atmospheric scientist who co-ordinates part of the European Union’s contribution to the global monitoring of atmospheric greenhouse gases and is involved in the UN WMO/IAEA Global Atmosphere Watch. Umoya is Xhosa for ‘air’ or ‘breath’.

Microbial

A new model for
the evolution of
environmental
regulation

Hywel T.P. Williams & Timothy M. Lenton

Earth System Modelling Group, School of Environmental Sciences,
University of East Anglia, Norwich NR4 7TJ UK
{h.williams,t.lenton}@uea.ac.uk



Gaia:

Whether free-living, aggregated in biofilms, or packaged into higher organisms, microbes are the most prevalent form of life on Earth. They make up more than half the biomass on Earth and occupy every conceivable niche in the biosphere. Their metabolic diversity and adaptability means that microbes can live where other life is impossible, in extreme environments such as deep-sea thermal vents, beneath the Arctic and Antarctic ice-caps, and even inside other organisms. Microbial life is heavily implicated in all the biogeochemical cycles, dwarfing the contribution of multicellular organisms — which in any case have microbes at the root of their metabolism. Mitochondria and chloroplasts, the main energy-producing organelles in animal and plant cells, both have evolutionary origins as once-free bacteria annexed into the greater whole. (Of course, the architect of this theory of endosymbiosis is none other than the co-founder of Gaia theory, Lynn Margulis.) Inside the body (but outside of the cell) the microbial gut flora of many higher species is an essential part of the metabolic processes of the host organism; cows could not digest cellulose without the incredible microbial diversity of the rumen [8], while humans rely on bacteria to digest various carbohydrates and lipids [9]. In short, Gaia's metabolism is microbial.

In recent years technological advances have led to a much greater understanding of the microbial world. We now understand (a little) how microbes metabolise, grow, and reproduce, and comprehend (a bit) how microbial genetics works, complete with lateral gene transfer that allows changes in cell DNA during the lifetime of the organism, a mechanism that seems quite alien compared to genetics in higher organisms. But our understanding of how microbial ecology interacts with the environment is one of the least understood, and most important, areas of current research. By virtue of their metabolic diversity, microbes are able to perform complex chemical transformations when multiple species collaborate. Artificially assembled microbial communities have been used to perform multi-step reactions for bioremediation of environmental pollutants (e.g., breaking down 3-chloroaniline [10]) and leaching of metal ores (e.g., copper [8]). The collaborative nature of these manufactured communities mimics (in spirit if not complexity) the

tight integration of naturally occurring microbial communities such as biofilms, in which many species form three-dimensional physical structures on surfaces that allow regulation of the microenvironment. Biofilms (also known as microbial mats) have been around for a very long time. Fossilised microbial mats called stromatolites have been found that are 3.5 billion years old [8]. This long history of environmental alteration suggests that understanding the dynamics of microbial ecosystems will be key to understanding Gaia. The question of how multiple microbial species can cooperate in biofilms to collectively improve their local environment, in apparent contravention of selfish Darwinian principles, has obvious parallels in the Gaia debate.

The fundamental question of how system-wide regulation can emerge from evolving lower-level components, be it at a global scale as with Gaia, or a smaller one as with ponds or biofilms, remains to be answered. It seems plausible that similar principles are at work at all scales, so if you can understand the microcosm, you at least have a chance of understanding the macrocosm. To this end, we have been developing a new mathematical model of microbial evolution [13,16]. The Flask model simulates a well-mixed flask of liquid in which is suspended a population of 'microbes'. Each microbe has genetic loci specifying traits for nutrient consumption/release and its interaction with the abiotic environment. Every microbe has a preferred abiotic environmental state in which its metabolic rate is maximised, while microbe growth alters the abiotic environment via cost-free by-products of metabolism. Microbes grow by converting consumed nutrients into biomass, and reproduce by splitting when a certain biomass threshold is reached. During each reproduction event, the parental genotype is inherited by the offspring individual with a low probability of mutation at each locus. Microbes interact with their shared environment, removing and adding materials during metabolism at a rate determined by the state of the environment. The ecological success of a microbe species is determined by its fit with the environment, in terms of nutrient supply and abiotic conditions. Successful species will grow and diversify, while unsuccessful species will starve and die off. Thus we have a highly abstracted, but versatile, mathematical model of microbial growth and evolution in a changing environment.

The Flask model is designed to address some of the key questions about the evolution of regulation. The original Daisyworld model showed that global regulation does not require top-down control or teleology [12]. Later variations of the model have since shown that in some circumstances natural selection is compatible with regulation, while in others it is not; broadly speaking regulation occurs when daisy albedo can adapt, but not with unconstrained adaptation of optimal growth temperature [17]. However, one key assumption of the Daisyworld model means that it represents a special case in evolutionary terms. In Daisyworld,

Image: Microbes play a major role in the earth System, but because of their size this is often not visually apparent to people. Exceptions are the microbial crusts which cover the surface in many deserts — as in this example from Utah in the USA. These crusts often contain filamentous cyanobacteria as an important structural element, along with larger organisms such as mosses and lichens. Photo Dave Wilkinson.

properties that confer local fitness also contribute to global regulation. If this assumption is relaxed, regulation does not emerge [13,17]. In the real world, it is conceivable that traits can arise which offer individual-level selective advantage but have a destabilising effect on the global environment. Most commonly, traits which alter the environment may be selectively neutral for individuals, because most biogeochemical cycles involve atmospheric and oceanic transports which have mixing rates sufficient to remove the local effects of environmental alteration. In many cases, environment-altering traits are simply by-products of other traits that are selected [11]. For example, mammals breathe out CO₂ when they respire, but this a simple consequence of respiration; having a respiring metabolism may be selected for, but expelling CO₂ as waste is not. The question for Gaia thus becomes, 'how can regulation arise from environment-altering traits of organisms that are selectively neutral or that are by-products of other selected traits?'. The by-product view of regulation avoids the problem of cheats that might destroy regulation, because by-products are not altruistically contributed to some collective regulatory enterprise. But other theoretical problems arise with the concept of by-product regulation, such as why we should expect to see any regulation if there is no adaptive mechanism to select for 'good' regulatory traits. It is possible that regulating negative feedbacks can emerge from the local interactions of organisms with their environment [4,7], but equally possible that destabilising positive feedbacks could appear [2,3].

In the Flask model, environment-altering traits may contribute to or oppose regulation and are selectively neutral at the individual level. In a single well-mixed flask, we observe the reliable emergence of nutrient recycling loops [1,16]. Microbes are constrained not to be able to consume a nutrient that they also release as waste, but it is common for one species to excrete a nutrient that another consumes. Although recycling loops may involve many different species, the simplest loop would involve just two species, where species 1 consumes A and releases B, and species 2 consumes B and releases A, as with (e.g.) oxygenic photosynthesisers and aerobic respirers in the real world. In the Flask model, the nutrient consumption of a microbe is scaled down if the nutrients it requires are limited, so it makes 'good evolutionary sense' to depend on as few nutrients as possible in order to reduce the risk of limitation. Given that populations grow exponentially in times of plenty, nutrient limitation is the normal state of the system, so selection pressure on consumption patterns is a powerful adaptive force. We commonly observe the evolution of single-nutrient consumers, which form ecosystems where nutrients are recycled many times before being lost to the system. The theoretical carrying capacity of the system would be reached when all supplied nutrients are consumed and efficiently recycled, so that the only loss of material is the unrecoverable 'heat loss' due to metabolic inefficiency. In practice the system typically adapts to operate close to this limit.



With single well-mixed flask ecosystems, we also observe a number of characteristic dynamics in the interaction between the population and the abiotic environment [16]. When abiotic preferences are allowed to evolve, the population loosely tracks the slowly changing abiotic environment, as individuals that are unsuited to current conditions are displaced by better-adapted competitors. When preferences are fixed, the population can drive the environment into inhospitable conditions to which it is unable to adapt, causing a fall in population sizes. In most cases this is a gradual process which is unlikely to drive the community completely extinct, because negative feedbacks on growth [4] reduce the size of 'harmful' populations as the environment worsens. However, there are circumstances where 'rebel' species can cause a rapid environmental change resulting in total extinction. Populations are typically converged around a shared preferred environmental state, either because this is enforced (with fixed preferences) or because of genetic convergence of the relevant traits (with evolvable preferences). This makes the population vulnerable to sudden environmental change. This can occur if a mutant appears that can exploit stocks of previously unutilised nutrients, allowing it to grow rapidly. Since abiotic environmental effects are by-products of growth, the rapidly expanding species will cause a large and sudden shift in the state of the abiotic environment away from the state to which the community is adapted. Any species which cannot adapt quickly enough – including the rebel species causing the problem – will go extinct. While diversity of environmental preferences might allow some species to survive, fixed or converged preferences mean that it is possible for the entire community to go extinct simultaneously in this way. (As an aside, this pattern of endogenously caused extinction is rather alarming when compared to a certain real-world species who are causing rapid environmental change by exploiting a previously unavailable energy source...).

To address the key outstanding question of how (or if) we can reconcile global regulation with local adaptation, we have recently developed a spatial version of the Flask model, in which a number of flasks are connected in a ring topology [15]. Each flask is locally well-mixed as before, but in the new model we implement a slow rate of diffusive mixing between neighbouring flasks. This creates a simple scheme that gives properties of spatial structure and environmental heterogeneity, which we feel may be crucial to the appearance of environmental regulation. The liquid transferred between flasks carries with it materials and microbes. Material transfer (nutrients and abiotic factors) reduces any between-flask environment gradients. Microbe transfer between local populations carries genetic information that changes species composition and thus alters the nature of each community's collective interaction with its local environment. For simplicity, in the current version of the spatial model we impose universal fixed environmental preferences on all microbes.

One obvious change that occurs when we move from the single well-mixed flask to the multi-flask



spatial system is a marked increase in robustness against extinction [15]. Endogeneously created extinctions are relatively frequent in the single-flask system, but are virtually eliminated in a similar spatial system. The main reason for this is that spatial structure creates environmental heterogeneity. If a rebel species appears that causes a local extinction, it is unlikely to spread quickly enough to cause a global extinction since the slow rate of between-flask mixing acts as a brake. By the time a destructive species reaches locations around the ring that are far from its origin, it is likely that the original denuded location will have been recolonised from a surviving neighbour population. This time lag afforded by spatial structure also increases the time available for other species to adapt to the environmental changes caused by a rebel species. These refugia-recolonisation dynamics form an additional mechanism for robustness that operates alongside the negative feedbacks on growth that already reduce the likelihood of endogeneously caused extinctions.

Robustness from spatial structure is not a new concept and has been observed in a variety of systems. Of more interest to Gaia researchers is the observation that once life becomes established in the spatial model, the environment is consistently regulated to habitable conditions, even in the face of severe external perturbations. To understand how this regulation occurs, we must first of all note that the increased metabolic throughput resulting from nutrient recycling means that the biota in the model are the main control on the abiotic environment, which at carrying capacity dominates over the external flux of abiotic factors. The second key observation is the existence of feedbacks on growth [4]. As previously noted, these feedbacks on growth often prevent a population from driving itself extinct — since the worsening environment reduces the size of the population causing the environment-degrading effect — but they also play a role in achieving system-wide regulation by creating a form of between-flask competition based on environmental factors.

When the abiotic environment is favourable, populations expand exponentially to reach carrying capacity and selection pressure on nutrient consumption patterns is the main adaptive force. Genes controlling environment-altering traits are not selected and are subject to genetic drift, while the abiotic environment also drifts in response to the stochastic forcing from the biota. However, when the environment drifts far enough from the optimum conditions for growth, metabolic rate is reduced, microbes begin to starve, and nutrients build up in the environment. The abiotic environment becomes the key factor limiting growth and traits affecting the environment are now subject to selection pressure. Each flask is locally well-mixed, so no microbe can gain selective advantage over its local competitors via its environmental alteration. However, the collective metabolic action of a local population on its environment can improve or degrade growing conditions, affecting the size of the population. Since the abiotic environment is limiting, any local population that improves its environment will grow

rapidly and expand to colonise neighbouring locations, while degrading populations starve and die out. Since the net environmental effect of a population has a genetic basis (in the genotypes of its constituent individuals) this between-flask competition creates a form of higher-level selection that acts on the collective environment-altering properties of local communities, leading to community species compositions that have overall improving environmental effects. Over time, the prevalence of environment-improving communities steers the global environment towards more hospitable conditions.

Invoking higher-level selection to explain Gaian global regulation may seem a bit like jumping from the frying pan into the fire, but the form of higher-level selection we infer is a restricted form and supported by careful analysis. In previous work we have conducted experiments using artificial selection to shape the properties of single-flask communities [14], but the situation here is quite different. Artificial selection imposes both the unit of selection and the method of transmission, both of which are emergent from system dynamics in the current scenario. No long term higher-level adaptation is implied; local populations are constantly shifting due to mutations and movement of microbes, so there is no steady population genotype in which selection might fix beneficial traits. There are no community ‘generations’ and the spread of ‘good’ communities is by differential proliferation rather than explicit reproduction. Transport by diffusive mixing means community reassembly is uncertain and thus the chance of reliable transmission is weak. These factors combine to make community-level inheritance a very noisy process. However, there is enough persistence in the local communities for selection based on collective environment-altering traits to provide a steering force that moves the system away from the harsh boundaries of the habitable region and towards the ‘green fields’ of the nutrient-limited regime, where the populations expand to carrying capacity. Once the system moves back into the nutrient-limited regime, traits affecting the environment become selectively neutral once again, until the system eventually drifts too far from the growth optimum and the cycle repeats.

An interesting question is what will happen when preferences for the optimal abiotic environment are allowed to mutate — will the population regulate or adapt? We have run the spatial model with evolvable preferences, and find that the ‘error’ between the abiotic environment and the mean population preference is consistently reduced. Long periods of stability occur in which environmental state remains at a fixed level, but it is hard in the evolvable-preference scenario to separate the contribution to stability of environmental regulation from that of organism adaptation. Our current formulation of the spatial model with fixed preferences can be argued to reflect the real world, where adaptation is ultimately constrained by the laws of physics and chemistry [3]. For example, any photosynthetic reaction has optimal conditions of temperature, light intensity, CO₂ supply, etc., in which its rate is

maximised. While there is some flexibility for metabolism to adapt to different environmental conditions, there remain hard thermodynamic constraints on any metabolic reaction (and on the space of possible metabolisms) that make a single optimal environment a reasonable working assumption.

The Flask model suggests a new mechanism by which environmental regulation can be reconciled with natural selection. The novel concept of multiple selection regimes operating at different levels and leading to the emergence of regulation will require further investigation backed by empirical evidence, but we feel that the model we propose is theoretically robust and widely applicable. In future work we will explore the possibility of regulation with adapting environmental preferences, hoping to understand our preliminary observation of 'regulatory epochs' of environmental stability. We are already extending the model to use a more accurate and complete chemical model than the current abstract formulation, with

the initial aim of developing a simple adaptive box model of Archaeal biogeochemistry. Another project is to develop adaptive modules based on the Flask scheme that can be used with existing Earth system models (e.g., the GENIE model [6]), where adaptation has traditionally been hard to incorporate. This challenging project promises significant pay-offs if successful, by linking evolutionary theory with well-modelled biogeochemical processes. A longer term goal is to compare the Flask model to real-life flasks containing real live microbes. This avenue is one of the most exciting areas for future research and is an arena where some of our Gaian hypotheses may be empirically tested.

Hywel Williams is a postdoctoral research assistant and **Tim Lenton** is a Professor both in the School of Environmental Sciences at the University of East Anglia.

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The Geological Society

Burlington House, Piccadilly
London W1J 0BG

Tel: +44 (0)20 7434 9944 (Office)

Fax: +44 (0)20 7439 8975

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