

Rebel organisms are newcomers that shake up the prevailing ecological order and can radically reshape the environment. Hywel Williams and Tim Lenton explain how this new concept can shed light on everything from how oxygen became so vital to life on Earth, to humanity's troubled relationship with fossil fuels.

In his 1944 book *What is life?* the physicist Erwin Schrödinger argued convincingly that one of life's distinguishing features is its ability to use energy to create order. To do this, organisms must export waste products to their environment.

James Lovelock noted this in the 1960s when considering how to detect life on Mars. He recognised the signature of life in the Earth's atmosphere, which is a long way from the chemical equilibrium it would approach in life's absence. The observation that organisms, Martian or otherwise, must inevitably change their physical environment became a cornerstone of Lovelock's Gaia hypothesis.

Looking at the Earth's history over very long timescales, it is clear that the evolution of new kinds of organism with different types of metabolism has transformed the biogeochemical cycles that support life on Earth.

The evolution of photosynthetic cyanobacteria, for example, led to radical changes in the biosphere during the Great Oxidation event around 2.4 billion years ago. Cyanobacteria proliferated widely using abundant water, carbon dioxide and sunlight for photosynthesis, but they polluted the

environment with a highly toxic by-product: oxygen. The Earth would never be the same again, and once-dominant anaerobic organisms were relegated to life at the fringes.

Cyanobacteria in the Archean are an example of what we call 'rebel species' – organisms with a newly evolved metabolism that disrupts the ecological balance established by incumbent species. In doing so, rebels often create a new ecological order that suits their preferences. Successful rebels can become dominant – today's rebel is tomorrow's reactionary old guard.

We first spotted rebel species in an unlikely environment: the computer. We were trying to understand how some fundamental properties of the biosphere emerged, specifically how nutrient recycling and environmental regulation could come about in a world populated by evolving micro-organisms. A key problem in Earth system science is that we have a sample size of only one – we have no other life-bearing planets with which to compare the Earth. So we have developed a computer model that simulates virtual biospheres in which to explore the interactions between life and its

# Rebels with a cause

environment. This model represents an evolving microbial ecosystem – after all, the Earth is overwhelmingly a microbial world.

Our model explicitly accounts for both the influence of the physical environment on growth and the influence of growth on the physical environment. For example, in the real world temperature affects the rate of photosynthesis, and metabolic waste products including greenhouse gases can alter temperature. This adds a new kind of feedback to the system.

Assuming that there is an optimum environment for any metabolic reaction – for example, human metabolic processes work best at around 37°C – our model organisms need their metabolic functions to suit prevailing conditions. Since prevailing conditions are in part controlled by biological activity, the model simulates co-evolution, by which the microbial community collectively alters the environment that in turn determines the natural selection pressures experienced by its future members.

Nutrient recycling loops readily emerge in our model, as they have on the Earth. Natural selection for advantageous feeding strategies creates communities that make efficient use of all available resources. The waste of one species often becomes food for another, and



Light micrograph of cyanobacteria filaments.

Shirley Summers / Science Photo Library

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cycling of scarce nutrients via such cross-feeding relationships lets the environment support a greater overall biomass. We have also looked at how environmental stabilisation can emerge from natural selection in a spatial version of the model. Community-level selection pressures weed out local communities that degrade their environment, while favouring those that improve their environment. The global result of this process is regulation of the environment against perturbations.

### Evolutionary regime change

Both nutrient recycling and environmental regulation can be disrupted by rebel species. In our model, this happens most often when there is some resource in the system that is not being fully exploited, perhaps a potential nutrient that no existing species has found a way to use. This creates a vacant niche for some lucky mutant to occupy. The first species to discover a way to use

an unexploited resource can grow rapidly using built-up stockpiles.

If this species has an environmental preference different to the evolved preferences of the established community, and if it also happens to move the environment towards its own optimum conditions, then we have a 'perfect storm' in evolutionary ecology: the new species grows rapidly, and in doing so, changes environmental conditions to suit its

own growth and harm the growth of others. This creates positive feedback between growth and environmental change that can lead to a dramatic shift in the state of the ecosystem, which may in turn cause widespread extinction of most or even all of the previous incumbents.

We call this process an 'evolutionary regime shift', where a rebel species causes the collapse of an established ecosystem and the formation of a new stable pattern of ecological order. Fortunately, our model predicts that large events such as these should be rare – the bigger the event, the less likely it is to occur. Rebels are no problem unless they can grow sufficiently to have an appreciable effect. In most cases, competition for resources with more established species prevents rebels from taking over.

There is a cautionary note to be sounded from our research, moving away from abstract models of microbes and into the all-too-real world of anthropogenic climate change. Human fossil-

fuel use has all the hallmarks of the disruptive rebel species we observe in our model: access to a previously unused resource leads to rapid growth, producing harmful environmental side effects. Fossil-fuel use has powered the Industrial Revolution, transformed agriculture and allowed a much greater human population to be supported. Humans now monopolise a far greater share of global productivity than any other species in Earth history.

The environmental changes related to fossil-fuel use are now beginning to be understood – climate change and ocean acidification are just two among many. What is clear is that, just like the rebels in our model system, humans are shifting the environment away from the conditions to which most existing species are adapted. We are already witnessing rates of extinction comparable to the largest mass extinction events in Earth history. What remains to be seen is how well life on Earth, including us humans, can adapt to rapid environmental change.

### MORE INFORMATION

Dr Hywel Williams is part of the Computational Biology Group, and Professor Tim Lenton is head of the Earth System Modelling Group, both at the University of East Anglia.  
Email: h.williams@uea.ac.uk or t.lenton@uea.ac.uk

### FURTHER READING

H.T.P. Williams & T. M. Lenton, (2007) The Flask model: Emergence of nutrient-recycling microbial ecosystems and their disruption by 'rebel' organisms. *Oikos*, 116 (7), 1087.

H.T.P. Williams & T. M. Lenton, (2008) Environmental regulation in a network of simulated microbial ecosystems. *Proceedings of the National Academy of Sciences, USA*. 105 (30), 10432.