More than meets the eye

Earth's real biodiversity is invisible, whether we like it or not.

Sean Nee

The world has creatures that 'breathe' iron and uranium, using these elements in the same way as we use oxygen. Others thrive in the equivalents of hot sulphuric acid or floor stripper, and others again live in solid rock. In terms of biomass, the single most abundant form of life on Earth is ocean-sediment-dwelling bacteria and, numerically, the most abundant life-forms in the ocean are viruses. We are still at the very beginning of a golden age of biodiversity discovery, driven largely by the advances in molecular biology and a new open-mindedness about where life might be found. But for this golden age to be as widely appreciated as it should, our view of the natural world must change — as radically as did our view of the cosmos when we began looking at it with technologies that allowed us to see more than can be seen with the naked eye.

For all of the marvels in biodiversity's new bestiary are invisible. As many pundits have pointed out (usually in the restricted context of bacterial diversity), by any criterion — biomass or numbers of individuals — life on Earth is microscopic. It is the new generation of explorers of this 'invisible' world who are transforming our world-view beyond recognition. Yet a six-article Insight special on biodiversity in this journal in May 2000 scarcely mentioned anything that could not be seen unaided.

This is not to say that the papers were not a fair reflection of what biodiversity science is at the moment — that is, firmly fixated on the visible world. And I am not suggesting that senior commentators on biodiversity, such as Robert M. May and Edward O. Wilson, have been blind to the invisible. But it is now time for biologists — by whom I mean people who think of themselves as biologists, zoologists, botanists and ecologists — to cease presenting to their students and the public a perspective of life on Earth that is so biased towards the visible. This will not be easy. The first part of the challenge is accepting that the contribution of visible life to biodiversity is very small indeed.

Types of diversity

Phylogenetic diversity. The old 'five kingdoms' view of the relationships between organisms gave prominence to macroscopic creatures, with three of the kingdoms being animals, plants and fungi. But even under this classification, the invisible world asserts itself. The phylogenetic rank just below kingdom is phylum, and 40% of animal phyla are all or partly microscopic (numerically, four out of five animals are microscopic nematodes). But a new view of life's interrelationships has emerged from molecular data, in particular from the DNA sequences of genes that encode important RNA molecules found in all organisms. On the tree of life (see opposite) based on analyses of this 'small-subunit ribosomal RNA' (ssRNA), visible life consists of barely noticeable twigs. This should not be surprising — invisible life had at least three billion years to diversify and explore evolutionary space before the 'visibles' arrived.

Mr Spock – unemotional role model.

The branch lengths in this figure are informative about diversity in terms of degree of divergence, and not just in the RNA genes used to construct the tree. Creatures that are distantly related according to their RNA genes are genetically divergent in many other respects. Consider the microsporidia, classically placed as a long branch at the 'base' of the Eukarya, one of the three main domains of life. These are remarkable intracellular parasites; their spores are wrapped in what is essentially a flexible hypodermic needle, and they infect a cell by piercing it and injecting themselves. In humans they cause diarrhoea. They are almost certainly misplaced in this tree as a result of a well-known artefact called 'long branch attraction', whereby very long branches get grouped together. Microsporidia are now thought to be highly divergent fungi — highly divergent indeed!

Metabolic diversity. Life requires energy. Visible life exploits only one of the many possible metabolisms to get energy, taking electrons from organic carbon compounds and giving them to oxygen — breathing oxygen with which to burn food. This is mainly how animals and plants fuel themselves, although plants, of course, use light to manufacture their own food. In comparison, the invisible microbial world has a far greater metabolic repertoire. As I have mentioned, there are creatures that 'breathe' metals, using them as electron acceptors; others use metals as electron donors — they 'burn' metals. A quarter of a century ago it was predicted, on energetic grounds, that a creature should exist that burns ammonia with nitrite for energy (who says biology is not a predictive science?). Such bacteria were recently discovered[1].

Visible life can use one inorganic energy source — light — to manufacture organic compounds, but invisible life can also exploit chemical energy. Chemical energy almost certainly fuelled the first creatures that lived on Earth, and microbes that exploit a large variety of such sources provide the basis for the rich communities that thrive in the pitch darkness around hydrothermal vents on the sea floor — which were unknown to us until a quarter of a century ago.

The major biogeochemical cycles on which we depend were in place three billion years ago, long before the appearance of visible life, and are today maintained by the 'invisibles' and their vast range of metabolisms. The persistence of life on Earth depends on the endless recycling of essential elements such as sulphur, iron and nitrogen through their various forms. Thanks to macroscopic life, ecosystems are more productive and nutrient cycling is more rapid; animals and plants are good at churning things up. But the 'visibles' have introduced no qualitatively new features to global ecology.

Environmental diversity. Our awareness of the astonishing range of environments in which microbial life can thrive continues to expand. The superheated, pressurized environment of an autoclave, used for sterilization at 120 °C, would be ideal for the growth of 'strain 121', an 'iron-breathing' creature from a hydrothermal vent, which survives at even 130 °C. The greatest extremes of acidity, alkalinity, salinity and so on are not so extreme as to preclude invisible life. The Dead Sea is very much alive — it just doesn't contain fish.

Although representatives of the bacteria and archaea are the most famous extremophiles, microbial eukaryotes that occupy this stage are now also being discovered. Life in the Rio Tinto (river of fire) in Spain — which is metal-contaminated and as acidic as your stomach — is dominated by an extremely diverse array of them. A combination of the same molecular techniques used to study bacterial diversity in nature, as well as a willingness to look for them in supposedly inhospitable places, is revolutionizing our understanding of eukaryotic diversity, just as it is doing for bacterial diversity.

Morphological diversity. Visible life wins hands down in this category, although the invisible world puts up a good show with diatoms. Colours, noise, outlandish behaviour, emotion and consciousness — these must count for a lot. But none of it is really necessary for life on Earth, unlike the activities of invisible organisms, which terraformed the planet for visible organisms, creating and maintaining the atmosphere and nutrient cycles on which we depend.

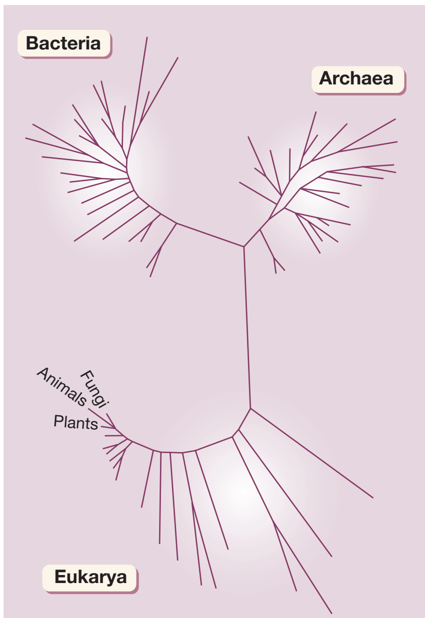
Even the oxygen content of the atmosphere depends entirely on the invisible world of phytoplankton. Although roughly half of the planet's oxygen is produced by terrestrial plants, this is mostly used up in terrestrial respiration. The primary reason why the oxygen content of the atmosphere does not dwindle to zero is because of the rain of dead and dying oceanic microbes from the surface waters to the ocean floor. Buried in the sediments, the oxygen they produced is not used up in their decomposition, resulting in a net gain of oxygen by the atmosphere and oceans. It is a measure of how recently we have really started to get to grips with the microbial world that the most abundant constituent of the plankton, *Prochlorococcus*, was discovered less than 20 years ago. For emotional reasons, we attach great significance to the morphological dimension of diversity — biologists are largely attracted to the subject in the first place by this emotion.

Departmental affiliations

A reflection of biologists' obsession with the visible world can be seen in the departmental affiliations of the explorers of the invisible world. With notable exceptions, these are rarely 'biology' or 'zoology'. Rather, more commonly, they are 'geology', 'biotechnology' or 'oceanography', and even 'civil engineering', 'planetary science' and 'astrobiology'. And astonishing new discoveries that challenge our views on the nature of life are more likely to be announced at a Geological Society meeting than a conference seemingly devoted to biodiversity.

Many of the explorers of the realm of the invisible are, of course, in departments of microbiology. To update our view of life on Earth, biologists need to overcome the gulf between microbiology and biology that first arose about 150 years ago, and which retains much of its original character. Charles Darwin voyaged the high seas, dining at the captain's table, before retiring to his country house to develop his various ideas. Louis Pasteur, on the other hand, was hired as a consultant to the alcohol industry and discovered organisms that can live without oxygen. He experimented with heat treatments to prolong product shelf-life and developed vaccines to prolong human life.

Darwin was a biologist, Pasteur a microbiologist. Microbiologists are employed by the wine and sewage industries; biologists go to wine tastings and discuss biodiversity and conservation in between using the bathroom. In the index to the standard microbiology textbook (*Brock Biology of Microorganisms*) you will find entries such as 'jock itch', 'sewage fungus' and 'Swiss cheese' — these are not the sorts of topics that turn on biology students. One challenge for biologists is to find ways of making sewage fungus palatable to our students and the general public.



Biodiversity through a molecular lens. This scheme is based on ssRNA gene-sequence data, and shows the relationships of organisms in the three main domains of life — Bacteria, Archaea and Eukarya (creatures with cell(s) like our own). Visible organisms are found among the plants, animals and fungi. Yet not only are these groups just twigs on the tree of life, but many of their members are invisible as well.

Microbiologists do not even give a 'biodiversity' label to their studies — they call them 'environmental microbiology'. A major journal publishing fundamental discoveries in this area is *Applied and Environmental Microbiology*. Most biologists interested in biodiversity would not even recognize that this is a highly important journal for them. And even when discoveries are published in the high-profile literature, as they frequently are, biodiversity enthusiasts are unlikely to register such titles as "An archaeal iron-oxidizing extreme acidophile important in acid mine drainage"[2] — which reports the discovery of creatures that are surely at least as astonishing as "Striped rabbits in Southeast Asia"[3]. If biologists want to keep up with this new golden age of biodiversity study, then there is no choice but to learn or relearn our basic chemistry, redox reactions in particular.

Emotional bias

We are sentimental about visible nature yet utterly self-centred about the invisible — simply happy with it if it is useful, such as bakers' yeast, or bent on its extermination if it is unpleasant or harmful (for example, a yeast infection). And, if it is not obviously important to us in one way or another, we do not even give it a thought. As May has said[4]: "As one moves down the size spectrum of organisms, from the romantic large mammals and birds, through non-descript small arthropods, on down to protozoan, bacterial and viral species, not only does concern for diversity and conservation fall away, it even changes sign."

As biologists, we must recognize this emotional bias and try to control it, like Mr Spock. Honesty to ourselves in considering what life is — and in presenting an honest picture to students and the public — demands it. Consider 'syntrophy'. This is the dominant ecological relationship in worlds without oxygen[5] — such as sediments and your gut — and is the phenomenon whereby the metabolic waste product of one species is the primary food or energy source of another (there are stricter definitions). The syntrophic networks that take in organic material provided by the oxygenated worlds and output the final waste products of carbon dioxide and water can be complex. But syntrophy is not mentioned in any major ecological textbook. Ecology students carry around inside their guts highly diverse ecologies, and this is simply never even mentioned. This neglect of the invisible world is no longer any more acceptable than, say, teaching astronomy but ignoring the existence of galaxies beyond the Milky Way, or teaching physics while refusing to discuss anything smaller than a pin head. ■

Sean Nee is in the Ashworth Laboratories, University of Edinburgh, West Mains Road, Edinburgh EH9 3JT, UK.
e-mail: sean.nee@ed.ac.uk

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