Fast-cooking the biosphere

The heat is on for many species: adapt to global warming or die. How are organisms and ecologies changing, and how much should we care?

In terms of climate change, we are some way up the Celsius scale already. The 1990s were the hottest decade in recorded history and some scientific models predict an average global temperature rise of up to 4 °C over the next hundred years, even if CO₂ emissions are reduced to Kyoto Protocol levels. Only a foolhardy biologist would make such long-term predictions for the state of the biosphere, but short-term predictions are depressing enough. It took climatologists 20 years to become convinced of the signature of global warming, and it has taken field biologists an extra decade to confirm some preliminary biological responses. Now the evidence is creeping up on us with a consistency that weather patterns cannot match.

The extent to which developed and developing nations are prepared to sacrifice financially to reduce their CO₂ output depends on how much various communities and economies rely on natural ecologies for their survival. Some economies may be able to adapt faster than humans can put a brake on climate change, but some, it appears, will die with their ecologies. Arguments for accepting a large part of climate change as merely another selection pressure exist, but the climate is changing so fast and biological responses can be so unpredictable, can we afford to take the risk?

Thomas Gale Moore, Senior Fellow of the Hoover Institution at Stanford University, CA, USA, addressed this question mainly from mankind's perspective in his paper 'Why Global Warming Would be Good for You' (Moore, 1995). While recognizing the problems for people in low-lying countries, he maintains the main argument, set out in his paper, that "Spending trillions of dollars on trying to slow global warming is much less effective than spending a small fraction of that on helping poor countries." The problem

is, however, that we know much more about how the physical environment is changing than about how biology is responding. Some people's future could be altered in profoundly negative ways by the biological effects of climate change.

Only eat oysters in months containing an 'r', so the saying goes; at warmer times of the year they might be bad. Such advice could soon be unnecessary. In a warming world, the summer months might wipe out some oyster populations completely, especially along the Atlantic seaboard of the USA. Global warming is just the latest insult to the ill-fated bivalves but it may be the one that tips the balance. Inna Sokolova, Assistant Professor of Biology at the University of North Carolina (Charlotte, NC, USA), argues that as ambient coastal water temperatures rise, so too does the toxicity of cadmium to oysters. "Concentrations not toxic at lower temperature become extremely toxic at higher temperature," she said. Oysters in the inter-tidal zone already experience a summer temperature range of 25–35 °C, across which the toxicity of cadmium increases tenfold. Add just two degrees more and oysters may be little more than a fond memory to an industry that in Louisiana alone is worth an estimated US\$250 million annually. As temperatures rise, cadmium increasingly poisons the oysters' mitochondria, 'decoupling' the proton flux across their membranes from ATP synthesis: they essentially run like power stations whose steam turbines have been disconnected from the generators (Sokolova, 2004). This is important for fishermen, restaurateurs and gourmets, not to mention ecologists and conservationists, some of whom want East Coast oysters taken off the menu and placed on the endangered

species list. And there could be further implications: Sokolova believes that poikilotherms (cold-blooded animals) in general may show a similar temperature-related sensitivity to cadmium.

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Until recently, pollution was just one suspected culprit behind the demise of coral reefs. But coral bleaching (Fig 1), the principle symptom of 'sick reef syndrome', is now almost certain to be a result of warming oceans. The death of the symbiotic dinoflagellate algae that give corals their colour results largely from heat-induced damage to their photosystem II (PSII), a hypothesis first voiced by a group of researchers from the University of Georgia (Atlanta, GA, USA) six years ago (Warner *et al*, 1999). "Basically, when you heat up a photosystem, its ability to process captured excitations is reduced. The Calvin cycle is short-circuited, and the electrons are passed instead to oxygen, creating superoxide radicals (the Mehler reaction)," explained Ove Hoegh-Guldberg, Director of the Centre for Marine Studies at the University of Queensland (Brisbane, Qld, Australia). These radicals damage not only the photosystem but also other components of the cell. "Just 1 °C rise in sea temperature causes massive bleaching, and there's no evidence that [the corals] are keeping up." As to the prospects for reefs in the next 20–30 years, Hoegh-Guldberg thinks "they're stuffed".

Australia's Great Barrier Reef attracts around 2.4 million tourists every year, who

spend US\$1.5 billion, which amounts to 80% of the local communities' earnings. Globally, coral reefs are estimated to be worth US\$375 billion per year to the economy. Tourism-based economies can sometimes adapt to changing resources, but for people who depend on reef ecology for their food, the picture is bleak. "In Indonesia, around 50 million people depend on corals for fish, etc. You'll end up producing countless 'ecological refugees', who will go to Jakarta, and live in slums," said Hoegh-Guldberg. Across the world, around 400,000 km² of coral reef support 100 million people directly, and 500 million indirectly.

Over their long evolutionary history, corals have seen bad times before, but these have been slow climatic changes that allowed some form of adaptation. The fact that global temperatures are higher now than they have been in the past one million years is less significant than the fact that they are rising faster than ever before—100 times faster, to be precise. Although corals are tough as an evolutionary group, their ecological manifestation as reefs is fragile. Corals will probably not die out, but reefs will almost certainly disappear for the foreseeable future. And the falling pH of the oceans—another by-product of elevated atmospheric CO₂—only makes matters worse, because corals have calcium carbonate exoskeletons that become harder to build and maintain at lower pH levels. A report from the Royal Society (London, UK), published in June this year, predicts that at the current rate of acidification—also caused by increased atmospheric CO₂—the pH of the oceans will fall from 8.2 to 7.7 by the year 2100 (The Royal Society, 2005).

Terrestrial habitats are similarly experiencing many changes in variables. Prominent among these is a longer growing season, which results in the re-adjustment of biological clocks in many species. This April, the Royal Society for the Protection of Birds (RSPB; Sandy, Bedfordshire, UK) and Newcastle University (Newcastle upon Tyne, UK), reported that golden plovers (*Pluvialis apricaria*) in the UK have brought their hatching time forward by eight days on average compared with 20 years ago—a result of earlier springs (Pearce-Higgins *et al.*, 2005). Unfortunately, it is not always the early bird that gets the worm, because crane fly larvae, the main food for plover chicks,

Fig 1 | A partially bleached coral on reefs off Heron Island on the Southern Great Barrier Reef, Australia. Courtesy of Ove Hoegh-Guldberg, Centre for Marine Studies, University of Queensland (Brisbane, Qld, Australia).

have not changed their habits in accordance. As Oilly Watts, an Environmental Policy Officer at the RSPB, commented, "my biggest fear is that it's a very complex web, and poking something at that web has the potential to produce a lot of surprises." Among his predictions are a general movement of species north and uphill, and a spread of invasive species and disease into hitherto unaffected populations.

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The most celebrated victims-to-be of global warming are alpine and polar inhabitants, such as mountain goats, polar bears, penguins and small plants. The famous edelweiss, a cold-loving alpine flower, is racing up the hillsides at 1–4 m per decade, and rapidly running out of terrain. "But alpine and polar habitats are relatively species-poor. Where we will see larger changes are rather in tropical mountain ecologies in relatively cool and moist conditions," said Chris Thomas, Professor of Ecology at the University of York (UK). "These species are not likely to be able to move anywhere to escape climate change. They're already

marooned in tropical mountains at the tip of their physical niche." Many species that cannot adapt to the speed of climate change are replaced by lowland species spreading upwards. Baird's tapir (*Tapirus bairdii*), a native of Mexico, Central America and parts of South America, is perilously close to extinction: probably fewer than 1,000 individuals survive. And the golden toad (Fig 2; *Bufo periglenes*), indigenous to Monteverde (Costa Rica), was last seen in 1989.

But not all species experiencing environmental pressure are caving in or changing range. Some appear to be evolving in response, a concept that is still hard for many ecologists to accept. As Ruth Shaw, Professor at the Department of Ecology, Evolution and Behavior at the University of Minnesota (St Paul, MN, USA), commented, "In some quarters there's a deeply embedded view that evolution is too slow to be seen in the frame of climate change. But in the last 50–60 years there has been a phenomenal amount of data to show that evolutionary change can be very rapid." Plasticity of phenotype allows a certain amount of adaptation to occur without the need for genetic change, but not all observations can be explained in that way.

Some of the most compelling evidence of evolution driven by global warming comes from the *Drosophila* genus. In January this year, Max Levitan from Mount Sinai School of Medicine (New York, NY, USA) and William Etges from the University of Arkansas (Fayetteville, AR, USA) reported that *Drosophila robusta*, the North American woods fly, is showing evolutionary responses to environmental change over timescales of a few years (Levitan & Etges, 2005). Levitan is studying paracentric inversions, blocks of genes that have been cut out and reinserted in reverse order, and which are now genetically isolated from the rest of the genome. "Carriers of these blocks show very discrete geographic trends," he said. Inversions in individuals in more southerly areas are now appearing increasingly in flies in more northerly latitudes, and migration or interbreeding is not the cause. "I've been studying chromosomal inversions in *Drosophila* since 1945; these changes seem to have started around 1965 and increased subsequently at the rate of around 1–2% per year [of the population carrying the new inversion]," Levitan remarked. The conundrum is what the advantage of a particular

Fig 2 | Male golden toads at a breeding pool in the Monteverde Cloud Forest (Costa Rica). © Michael & Patricia Fogden/CORBIS

inversion could be: the *D. robusta* genome has not yet been sequenced, so the function of these gene inversions is not known. Still, the evidence is stark: the genomes of tiny flies are acting like biological thermometers of global warming.

The pitcher plant mosquito (*Wyeomyia smithii*) is also evolving, taking advantage of longer warm seasons by shifting its breeding time earlier year after year. Even species as large as the North American red squirrel (*Tamiasciurus hudsonicus*) are keen to prove Darwin right, as they shift their breeding season six days earlier for each generation. Quantitative genetics shows that phenotypic plasticity is certainly not the main cause. But could such astounding findings damage the cause of ecologists and nature conservationists? "My concern would be the evidence that [organisms] can evolve due to climate change implies that we don't need to change anything, because evolution is there to take care of us," Shaw said. On the contrary, thermal tolerance is no simple

matter in genetic terms. As Hoegh-Guldberg commented, "There are many genes involved... and people who don't understand the complexities think: oh well, it's just like the Galapagos finches or bacteria on a plate."

Seen cynically, adaptation and extinction are two sides of the same coin as far as the mechanism of evolution is concerned, and Earth's history is a chronicle of climate change accompanied by extinctions. So should we really care so much about the biological responses? Moore is sanguine: "I have seen estimates that over 90% of all species that have existed have gone extinct. Those species that are of particular importance to humans will be maintained by humans." Crop plants are among them, and optimists would say that global warming would be beneficial for agriculture and, thus, humankind as a whole. "The higher temperatures combined with more carbon dioxide will favor plant

and crop growth and could well provide more food for our burgeoning population," Moore predicted in his 1995 article.

... the genomes of tiny flies are acting like biological thermometers of global warming

Pete Smith, Reader in Soils and Global Change at the University of Aberdeen (Aberdeen, UK) does not share Moore's optimism. While global warming could increase agricultural production through longer growing seasons and higher yield, climate-related changes in terrain could be very disruptive. "In the next 50 years, Southern Europe, especially the Mediterranean countries, will become extremely arid and one won't be able to grow many crops there," he said; a worrying prospect for communities that have worked the land for centuries. "Those are the places that are really going to have less capacity to

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adapt. I wouldn't subscribe to the view that global warming is on balance good for agriculture." Moreover, warmer temperatures may also bring about more disease and pests, thus nullifying any gains from longer growing seasons. Temperature is merely one of many linked variables. According to Smith, rising temperatures accelerate the decomposition of organic material, which causes a decrease in the fertility and water-holding capacity of soil, while releasing additional carbon and nitrogen into the atmosphere (Knorr *et al.*, 2005). "There will be lots of surprises and most will be negative," he predicts.

Moore is unperturbed by local problems and maintains his stance that on balance—as far as humans are concerned—we are better advised to live with global warming than to struggle to stop or reverse it. The cost of such action would be an estimated US\$800 trillion for the USA alone; a high price for the preservation of a few species, perhaps. "We, the advanced nations, could spend a fraction of the cost of reducing emissions on technologies designed to mitigate the damage from warming and also spend some on reducing disease and sickness in Africa and Asia," said Moore.

But to Thomas, at least, species do matter. Their extinction means a loss in the genetic capacity to deal with changing environmental conditions. "At some point we'll go past our reliance on fossil fuels, and then the climate may change once again." Cooler times may, indeed, return, but extinct species will not. And here is the dilemma: most people would say that humankind should take care of the majority of its own species first. Perhaps the effort to halt global warming would be better directed elsewhere, especially if CO₂ emissions cannot be cut drastically enough to decelerate the process significantly. Put another way, the solution to save the unfortunate species that are on the brink of extinction may not be the same as the solution for much of the human race. However,

people living in poorer economies, or even poorer regions of rich economies, may have a different perspective, and not just because of rising sea levels—many people rely on natural ecologies for their livelihood, if not their supper. As Hoegh-Guldberg remarked, "[Coral] reefs may disappear for hundreds of years under our current trajectory...tell that to the tour guide who needs a healthy reef for his or her business, or the subsistence gatherer trying to feed his or her family."

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The bigger picture

Dramatic progress in imaging and microscopy enables scientists to see even greater detail

The pace of research in biology and medicine has always been closely linked to progress in imaging and microscopy, which allow scientists to probe the innards of organisms and cells. It is therefore no surprise that many spectacular developments in the past decade were made possible through advances in the ability to resolve structural details down to the molecular or even atomic level, using electron microscopy, x-ray crystallography and nuclear magnetic resonance (NMR) imaging.

Scientists and engineers have made progress in improving imaging systems and radiation sources. Concomitant are the advances in biochemistry, sample preparation and the processing of imaging data to remove noise, amplify signals and identify patterns such as the geometric signatures of specific proteins. In addition, the integration of different imaging systems to combine their individual strengths has helped biologists to obtain a more complete and detailed picture of cellular and molecular structures than would be possible using any single approach. The application and further improvement of these

techniques will have a significant role in one of biology's largest, although loosely defined, projects: to construct a complete map of the proteome, comprising not just static structural detail within cells, but also information on the dynamic interactions between all components. Such a map would ultimately help to unravel many cellular pathways—for example, those within immune system cascades.

It is perhaps the oldest technique, optical microscopy, in which the most dramatic progress is being made. The central aim is to overcome the diffraction limit, defined by the German physicist Ernst Abbe, which theoretically restricts the maximum resolution to about half the wavelength of light, or around 250 nm. In practice, however, it has rarely been possible for resolution to exceed 500 nm with conventional wide-field optical microscopy. Even so, optical microscopy has retained a unique role for observing biological processes in real time, particularly *in vivo*.

However, developments over the past few years have yielded substantial progress in optical microscopy, particularly in