Q&A


Alpine ecosystem. Species in mountain habitats are especially sensitive to climate change.

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Climate change and the ecologist

Wilfried Thuiller

The evidence for rapid climate change now seems overwhelming. Global temperatures are predicted to rise by up to 4 °C by 2100, with associated alterations in precipitation patterns. Assessing the consequences for biodiversity, and how they might be mitigated, is a Grand Challenge in ecology.

How serious is climate change compared with other factors affecting biodiversity?

Very — but it tends to act over a longer timescale. The ecological disruption wrought by climate change is generally slower than that caused by other factors. Such factors include habitat destruction through changes in land use; pollution, for example by nitrogen deposition; the invasion of ecosystems by non-native plant and animal species (biotic exchange); and the biological consequences of increased levels of carbon dioxide in the atmosphere (Fig. 1, overleaf). In the short-to-medium term, human-induced fragmentation of natural habitat and invasive species are particular threats to biodiversity. But looking 50 years into the future and beyond, the effects of climate are likely to become increasingly prominent relative to the other factors.

What are the effects of climate change?

Most immediately, the effects are shifts in species' geographical range, prompted by shifts in the normal patterns of temperatures and humidity that generally delimit species boundaries. Each 1 °C of temperature change moves ecological zones on Earth by about 160 km — so, for example, if the climate

the Northern Hemisphere may have to move northward by some 500 km (or 500 m higher in altitude) to find a suitable climatic regime. Higher temperatures are likely to be accompanied by more humid, wetter conditions, but the geographical and seasonal distribution of precipitation will change. Summer soil moisture will be reduced in many regions such as the Mediterranean basin, thus increasing drought stress. Overall, the ability of species to respond to climate change will largely depend on their ability to 'track' shifting climate through colonizing new territory, or to modify their physiology and seasonal behaviour (such as period of flowering or mating) to adapt to the changed conditions where they are.

What about the effect of atmospheric gases?

Carbon dioxide is, of course, known as one of the main drivers of the greenhouse effect, and so of increasing temperatures. But it is also essential for green-plant photosynthesis. Increased atmospheric CO_2 results in an increase in photosynthesis rates (through CO_2 fertilization), which could potentially balance the effect of temperature increase. This has the largest effect in regions where plant growth is limited by the availability of water, and will probably alter the competitive balance

photosynthetic pathway or 'woodiness', as well as the subterranean organisms associated with them. Likewise, an increase of anthropogenic atmospheric nitrogen deposition affects nitrogen-limited regions (temperate and boreal forests, and alpine and Arctic regions) by conferring a competitive edge on plants with high maximum growth rates.

Which ecosystems are we talking about?

All of them, but climate change will affect them in different ways. For example, in marine ecosystems the possible consequences include increased thermal stratification (in which temperature differences separate water layers), reduced upwelling of nutrients, decreased pH and loss of sea ice. These changes will influence the timing and extent of the spring bloom of phytoplankton, and so the associated food chain (krill to fish to marine mammals and birds). On the terrestrial side, deserts, grasslands and savannahs in temperate regions are likely to respond to changes in precipitation and warming in various ways. Mediterranean-type ecosystems, which occur worldwide and are characterized by shrublands, are especially sensitive, as increased temperature and drought favour development of desert and grassland. In tropical regions, CO_2 fertilization — in which plants absorb carbon of naturally occurring fires will have a strong influence. On tundra, low-growing plants are especially important as habitats for other organisms: their poleward movement will have an ecosystem-wide impact. Finally, species living on mountains are particularly sensitive to changed conditions, in that migration upwards can occur to only a limited extent.

How do biologists monitor changes in biodiversity?

Long-term observations and re-surveys of previously sampled sites are traditional approaches. In certain areas, natural-history societies have long recorded the seasonal time of appearance (of flowers, for instance, or migratory birds), or species' ranges. Such data sets are then viewed against measured variations in temperature or precipitation. Another approach is the re-survey of sites sampled 50 or 100 years previously. Species' identities and abundances are then compared with changes in such external factors as climate or land use. The drawback of both approaches lies in distinguishing a true cause from a correlation.

Do experimental studies help?

Monitoring programmes can be complemented by research in microcosms or, for example, on existing plots of grassland or forest. In these experiments, temperature, precipitation and even CO_2 concentration can be manipulated, and such work often reveals unexpected responses arising from the complex interplay of different factors. But for obvious reasons these experiments are difficult to carry out on large spatial and temporal scales.

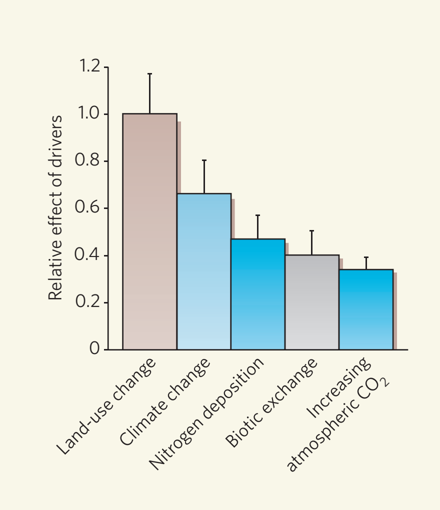

Figure 1 | The main factors, or 'drivers', affecting biodiversity. This summary of the relative effects by the year 2100 is a composite derived from calculations carried out for 12 individual terrestrial and freshwater ecosystems by O. E. Sala *et al.* (*Science* 287, 1770–1774; 2000). Overall, changes in land use constitute the main estimated impact on biodiversity, but the pattern varies considerably for different ecosystems. According to Sala and colleagues' calculations, climate change will have the strongest effect on Arctic, alpine and boreal ecosystems, whereas biotic exchange (that is, invasion by non-native species) will exert its

What responses to climate change are actually documented?

In the Northern Hemisphere, the range of terrestrial plants and animals has shifted, on average, 6.1 km per decade northward or 6.1 m per decade upwards, with advance of seasonal phenomena by 2.3–5.1 days per decade over the past 50 years. These changes are significantly correlated with measured changes in temperature and precipitation. The relationships are correlative in essence, but are too robust, numerous and consistent to be random or to have arisen from other factors (such as natural climatic variability or land-use change). Similarly, the remarkable increase in the plant diversity of some high-elevation peaks in Switzerland over the past 100 years, owing to the upward shift of species that traditionally inhabited lower elevations, can be attributed to changed climate regimes.

Is there a consistent global picture?

We can only guess that patterns such as these are likely to be global in compass, but to differing extents. The two poles are probably being most affected, because the greatest changes in temperature and precipitation are occurring there. By contrast, biodiversity in the equatorial belt is likely to suffer more immediately from deforestation and land degradation. Most of the detailed quantitative studies come from the Northern Hemisphere, or from well-studied 'hotspots' of biodiversity such as the Cape Floristic Region in South Africa. Even in these regions, it is difficult to disentangle the effects of climate change from those of other factors. And we have little or no data on vast swaths of territory in South America, Africa and Asia.

Do climate change and other factors interact?

They do. A notable example concerns invasive species: change in climate can trigger change in biodiversity by creating opportunities for previously innocuous alien species by enhancing their reproductive capacity, their survival and their competitive power against the native flora and fauna. The dispersal of many species, including microorganisms, has been immeasurably increased by the globalization of human economic activity and trade. A combination of climate change, species invasions and reduced areas of natural habitat is likely to promote biotic homogenization in biodiversity hotspots in particular, and to foster unpredictable interactions between plants, animals and microorganisms.

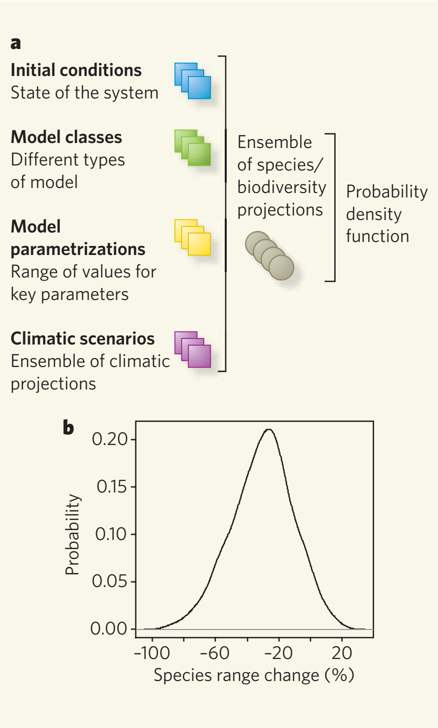

Figure 2 | The probabilistic approach to forecasting biodiversity. a, Each sub-activity produces an ensemble of projections based on subtly different initial conditions (such as factors influencing species distributions); on the class of model involved and its parametrization; and on the climate-change scenarios chosen. These ensembles are then combined to extract the possible range of outcomes and the likelihood of each occurring. Such estimates are called the 'probability density function' of the event being studied. b, An example of such a function, in which the projected range change of a given species is expressed as a probability of occurrence. In this case, there is an 80% probability that the given species will lose 20–60% of its current range. (Graphic based on M. B. Araújo & M. New *Trends Ecol. Evol.* 22, 42–47; 2007.)

How do ecologists set about forecasting the impacts of climate change on biodiversity?

Experimental studies are informative, but can rarely be generalized. Another approach

various scenarios of climate change. For example, statistical 'niche-based' models are used to determine the environmental conditions that currently account for species' distributions, and the results can be compared with models of future climate and patterns of land use to predict where these conditions will occur in the future. Validations are usually done by modelling past distributions (as, for instance, surmised for plants from a pollen database). These models don't take into account biological factors such as competition and evolutionary history, but have produced forecasts claiming that 15–37% of natural species will be 'committed to extinction' by 2050. An alternative is 'process-based' modelling, which aims to predict species distributions on the basis of resource allocation, demography or competition. They are theoretically more robust than niche-based models, but require much more ecological

What are the uncertainties behind forecasting?

All too many, starting with projections of climate change. It is no easy matter to accurately reflect complex interactions (such as those between the ocean and atmosphere), and account for different scenarios of greenhouse-gas emission. There is also our cruel lack of knowledge about the response of biota to rapid climate change. Few, if any, of the most popular models explicitly deal with migration, the dynamics at the trailing edge of shifting populations, species interactions, the interaction between the effects of climate and land use, and the direct effects of changes in atmospheric CO_2 and nitrogen deposition. At a basic level, ecologists are still debating the respective influence of interspecific competition and random events in shaping animal and plant communities. And different models tend to provide different predictions of species distribution or biodiversity under similar scenarios of environmental change, showing their limitations.

Can forecasting be improved?

Large-scale, long-term experiments and observations are required to provide the data to make generalization possible, and for modelling studies. Mountains lend themselves to being natural laboratories, given that research can be carried out over steep gradients to investigate the differential response of species and the influence of local adaptations. Overall, what is needed is information that, when appropriately synthesized, can be applied to determine and fine-tune the parameters to be used in process-based models. The building of global databases is a big step forward in accumulating meta-information for this purpose. These databases include compilations of genetic sequences of species (for example, GenBank), the phylogenetic relationships of species (Tree of Life, Phylocom, TreeBASE), and measures of species traits such as mode of dispersal and competitive ability (TraitNet). There is also a new generation of hybrid models of species distributions, which aim for a compromise between realism and accuracy, and complexity and simplicity. These developments are opening up new ways to address the pressing ecological questions: combining hybrid models with statistical advances in 'ensemble' forecasting promises to provide probabilistic projections (Fig. 2).

What use are forecasts for conservation planning?

For all their imperfections, they are essential. For example, projections of species distributions guide the management of organisms under threat by helping to identify biological corridors for dispersal, sites for reintroduction and areas requiring protection. Lately, the conservation agenda has moved on to consider adaptation to climate change, and to test strategies such as habitat re-creation,

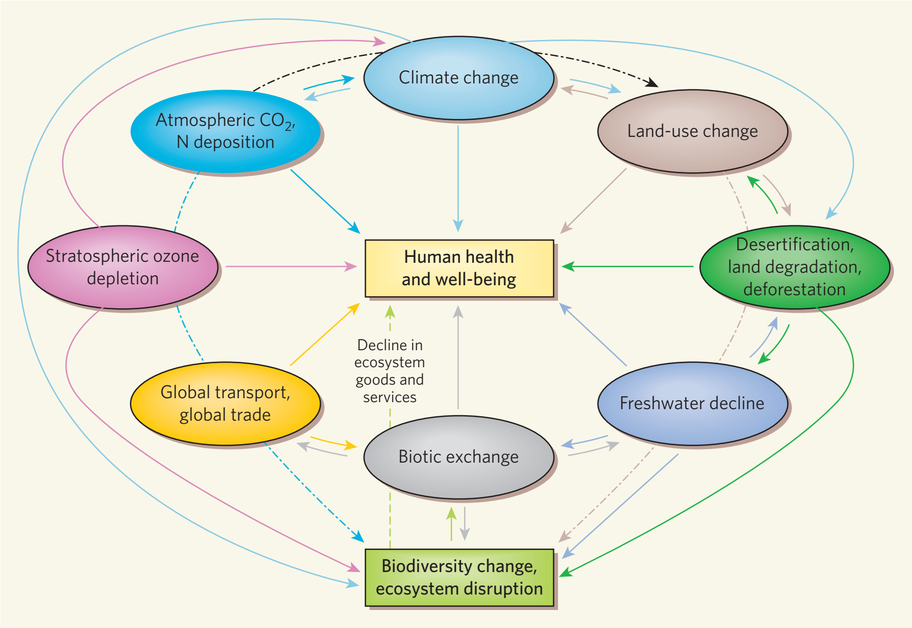

Figure 3 | The complex web of factors affecting human health and well-being, biodiversity and ecosystems. Changes in land use through land degradation, and climate change, are the most prominent factors. Perturbation of 'ecosystem goods and services' is just one part of this bigger picture.

the resilience of ecosystems to changed conditions. An alternative is to identify desired future states, and then use models for 'backcasting' to identify strategies for achieving those states. Modellers need to explore how far species-distribution models can be taken to answer the crucial questions that arise from rapidly changing climate. Invasive species are a case in point. In principle, forecasts can predict the probability of an invasive species becoming established, and can incorporate early warning systems for controlling it.

How do human societies fit into this picture?

Much debate has centred on how climate change will affect human welfare through, for instance, rising sea levels and different patterns of crop production. But that well-being also depends on the diversity of organisms used for such 'ecosystem goods and services' as food, energy production and medicines. In certain parts of the world, the chain linking biodiversity, ecosystem processes, and ecosystem goods and services is likely to be broken as biodiversity is affected by altered climatic conditions and the many other factors affecting human health and well-being (Fig. 3). Here again, forecasting can be used to formulate policies that will ameliorate the consequences. For instance, forests are among the most valuable sources of ecosystem goods and services. 'Forest-gap' models can predict tree growth and biomass, the result then being used to guide forest conservation and production strategies.

What can we conclude from all this?

As outlined above, our ecological knowl-

from adequate: making swifter progress will depend on attracting the best scientific talent and the funds to work on these immensely intricate issues. That apart, forecasts of the consequences of climate change for biodiversity need to be couched in probabilistic terms, by stating the possible range of outcomes and estimating the likelihood of each occurring — as is now common practice in weather forecasting. That then presents the problem of recommending a particular course of action for particular circumstances. But if that step can be taken, we reach the stage at which action comes down to political will, at levels running from the global to the individual village. ■

Wilfried Thuiller is at the Laboratoire d'Ecologie Alpine, UMR-CNRS 5553, Université J. Fourier, BP 53, 38041 Grenoble Cedex 9, France.
e-mail: wilfried.thuiller@ujf-grenoble.fr

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