COMMENT

YI LU/VIEWSTOCK/CORBIS

A hyena surveys a flock of flamingos in South Africa.

Time to model all life on Earth

To help transform our understanding of the biosphere, ecologists — like climate scientists — should simulate whole ecosystems, argue **Drew Purves** and colleagues.

No report from the Intergovernmental Panel on Climate Change would fail to mention global climate models. Yet the international bodies that are charged with addressing global challenges in conservation — including the Intergovernmental Platform on Biodiversity and Ecosystem Services, which holds its first plenary meeting next week in Bonn, Germany — cannot refer to analogous models of the world's ecosystems. Why? Because ecologists have not yet built them.

General circulation models, which simulate the physics and chemistry of Earth's land, ocean and atmosphere, embody scientists' best understanding of how the climate system works and are crucial to making predictions and shaping policies. We think that analogous general ecosystem models (GEMs) could radically improve understanding of the biosphere and inform policy decisions about biodiversity and conservation. Currently, decisions in conservation are based on disparate correlational studies, such as those showing that the diversity of bird species tends to decline in deforested landscapes. GEMs could provide a way to base conservation policy on an understanding of how ecosystems actually work.

Such models could capture the broad-scale structure and function of any ecosystem in the world by simulating processes — including feeding, reproduction and death — that drive the distribution and abundance of organisms within that ecosystem. Ecologists could apply a GEM to African savannas, for instance, to model the total biomass of all the plants, the grazers that feed on the plants, the carnivores that feed on the grazers and so on. Over time, the flows of energy and nutrients could be mapped between them. All of the organisms would be grouped not by species, but according to a few key traits such as ▶

whether they are plants, birds or mammals, cold blooded or warm blooded, diurnal or nocturnal. By encoding processes such as migration and predation into simple mathematical and computational forms, ecologists could model what happens to the various groups over time.

Metrics such as the diversity of animal types inhabiting the grasslands could be used to assess the savannas' health, stability and resilience, and to analyse the fate of particular groups of organisms such as top predators. Ecologists could explore how these attributes might change in response to, say, climate change, the introduction of invasive species or poaching. And, because the rules of play are likely to be broadly similar no matter what the ecosystem, the GEM could equally be applied to forests, lakes or the remotest parts of the ocean, providing a common framework for understanding and managing disparate ecosystems on local and global scales.

There are huge challenges to building GEMs — not least, obtaining the appropriate types of data to validate the models' predictions. But the difficulties are not insurmountable. Theories abound for describing the processes that drive ecosystems, many of which are backed up by data.

BUILDING A PROTOTYPE

Over the past two years, we at Microsoft Research and at the United Nations Environment Programme World Conservation Monitoring Centre, both in Cambridge, UK, have built a prototype GEM for terrestrial and marine ecosystems. Called the Madingley model, it uses real data on carbon flows as a starting point. We have hit all sorts of computational and technical hurdles, and are expecting more as we develop the model. Yet the project demonstrates that building GEMs is possible. From the relationship between the mass of individual organisms and how long they live, or the effects of human perturbations such as hunting, to the distribution of biomass across Earth (see 'Model life'), the model's outputs are broadly consistent with current understanding of ecosystems.

Modelling every organism in an ecosystem such as a tropical rainforest would be impossible.

SIMON LONG/FLICKR/GETTY

Modelling ecological phenomena at various scales is not new. Conservationists frequently use models to predict how much habitat fragmentation an endangered species can tolerate. But few ecologists have tried to build models of how general ecosystem properties emerge from the interactions of individuals. One attempt — known as Ecopath with Ecosim[1] — is being developed at the University of British Columbia's Fisheries Centre to address management and ecological questions. This combines modelling at the phytoplankton scale with that at the level of fisheries and marine mammals. Another, called Atlantis[2], developed by Australia's Commonwealth Scientific and Industrial Research Organisation, incorporates biophysical, economic and social factors to provide an integrated tool for modelling marine ecosystems. But these consider fewer processes and organisms than would a GEM.

Throughout the history of ecology, most researchers have resisted abstraction because ecological complexity is so obvious in nature. Ignoring the myriad shapes and colours of different bird species, for example, seems instinctively wrong. Instead, ecologists have tended to stress the importance of species identification as well as a vast number of ecological processes, from individual adaptation to the social dynamics of groups. Many in the field also emphasize that findings in one ecosystem do not generalize to others, and that randomness and history could be as important in affecting some particular measurement as any deterministic rules[3]. But comprehensive species-specific data will always be in short supply (at least 80% of the millions of species on Earth are undescribed[4]), so a better understanding of ecosystems demands a broad-brush approach.

Building a GEM will require different types of data — to help define the ecological rules at play, to provide reasonable starting conditions for the simulation (such as a realistic ratio of herbivores to top predators) and to evaluate the model's predictions. For these three goals, enough data are available to get started, although information on ecological processes far outweighs the rest.

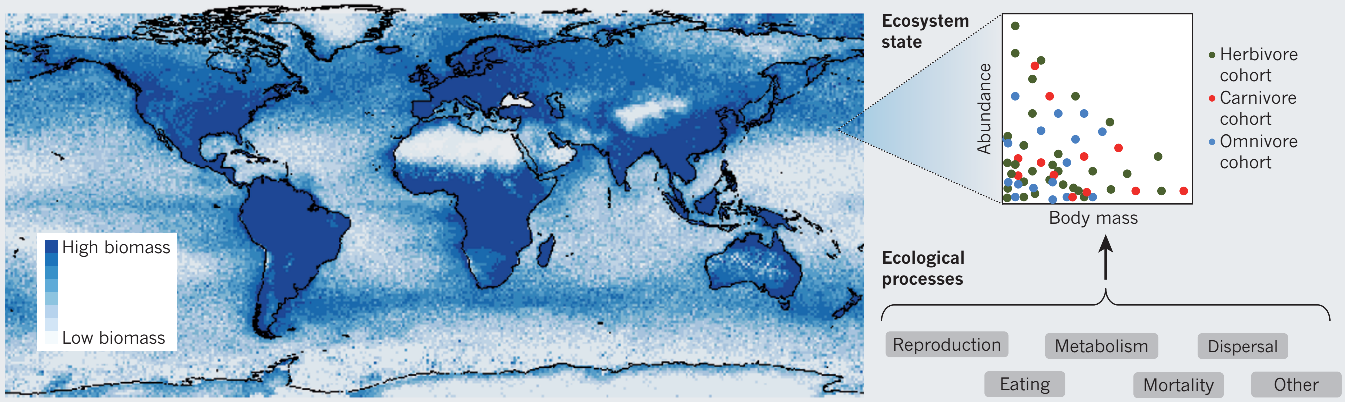
Metabolic rates, for instance, have been measured in hundreds of animals in the lab, and researchers in the field have documented lifespans, growth rates and reproductive success for thousands (in some cases, millions) of birds, mammals, plants and bacteria. Ecologists have also mathematically determined numerous 'rules of existence' for some organisms, such as that an animal's metabolic rate is proportional to its mass raised to a power of around 0.70 (ref. 5).

MODELLING BEHAVIOUR

Obviously, modelling every organism within an ecosystem is impossible. (We estimate that it would take a standard laptop computer around 47 billion years to model for 100 years every multicellular animal within just one of the 1-degree grid cells covering

MODEL LIFE

Variation in biomass across the world simulated by the Madingley model for terrestrial and marine ecosystems. Fundamental ecological processes, encoded into simple computational forms, determine the abundance and body mass of organisms (grouped into cohorts for simplicity) and so indicate the state of ecosystems.



ZEBRA: MANOJ SHAH/GETTY; WHALE SHARK: ANDY ROUSE/NATUREPL.COM

From hunting zebra to filter feeding, the process of predation in all ecosystems plays by similar rules.

Earth.) Yet certain computational techniques have been developed, mainly in marine ecology, that could allow researchers to model entire ecosystems using rules about the behaviour of individuals.

One approach is to model collections of organisms or 'cohorts'. The idea is that within a cohort, individuals are similar enough to be considered identical. For a shoal of small herbivorous fish meeting a cloud of plankton, say, ecologists could calculate the feeding rate for an exemplar fish and then apply that rate to the whole shoal. (In the simulation just described, we found that grouping organisms into cohorts on the basis of body size, functional group such as omnivore or carnivore and a few other traits reduced the computation time to 10 hours).

The biggest stumbling block to constructing GEMs (after convincing ecologists that they can and should be built!) is obtaining the data to parameterize and validate them.

Records of what species of plants and animals live in the world's forests, grasslands and oceans are often available to some extent, but far fewer data exist on the abundance of those species. And almost no data have been collected on the properties of whole ecosystems, such as on the distribution of body sizes from plankton to whales. Marine trawl surveys carried out for research or to assess fish stocks probably come closest to providing this type of information, although even these are restricted as to what size range of organisms they survey.

A new programme of data gathering is easy to envisage. Using automated cameras and image recognition, it should be possible to sample thousands of animals and determine their approximate size and what broad group they belong to: reptile or mammal, flying or non-flying. Motion-activated cameras used by conservationists and wildlife enthusiasts already produce tens of thousands of images of fish, birds and mammals every day. And stored away in numerous research institutions are vast samples of insects collected in traps that suck them out of the air, and data from continuous plankton recorders towed beneath ships for millions of kilometres.

Naturally, a major new data-gathering programme would be costly. But globally, governments already spend billions of dollars on satellite observations of vegetation and habitat distribution, fisheries surveys, forest inventories and species surveys. Diverting a small fraction of these funds to gathering the data needed to develop and evaluate GEMs could pay dividends. A first step would be for governments around the world to support programmes similar to the National Ecological Observatory Network — an international cooperation funded by the US National Science Foundation to manage large-scale collection of ecological and climate data.

To reduce costs and to harness the power of citizen science, data collection could even be crowd-sourced. Rapidly growing websites such as iNaturalist and eBird (on which users can share their observations of wildlife) currently focus on traditional species identification. Such sites could potentially collate an extraordinary amount of information on functional groups of organisms and traits such as body size.

"Ecological systems do not have the equivalent of the precise laws used by climate scientists."

TRUSTED ADVICE

Constructing realistic GEMs is one thing. The real challenge is to produce models from which the predictions are trustworthy enough to guide the decisions of conservationists and policy-makers. Recent progress in computational statistical methods offers a way for ecologists to formally build trustworthiness into models. For instance, tools are available to quantify the uncertainty associated with models' predictions. A healthy crop of alternative, competing GEMs will be crucial, together with mechanisms that enable their fair assessment. In blind-testing, for example, different models could be used to predict an ecosystem property that has been measured but not reported, allowing the models to be ranked in terms of how well they do.

We are not proposing that GEM predictions (which will always be simplistic) provide the only guide to conservation policy and the management of ecosystems. But coupled with models from other fields, such as economics and epidemiology, they could offer a means of managing human actions and the biosphere in an integrated, consistent and evidence-based way. Far from eclipsing traditional ecological research, GEMs would draw on it and give such work more focus. Using GEMs, ecologists could identify processes that are poorly understood yet crucial to ecosystem structure and function, rather than delve deeper into well-studied areas.

Ecological systems do not have the equivalent of the precise laws used by climate scientists. This is a significant challenge to building GEMs, along with the complexity of nature, the small number of GEM-like models under development and the paucity of data with which to constrain them. But just by attempting to build general models, ecologists will find out what they need to know to truly understand ecosystems. ■

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