Current Biology

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Feature

When ecosystems collapse

Ecosystems are more than the sum of their parts, more than a piece of habitat and its resident species. As biodiversity loss and species extinctions spread, the loss of connectivity could mean that ecosystems may collapse faster than has previously been predicted. **Michael Gross** reports.

The much-delayed biodiversity summit COP15 at Montreal ended with a deal signed by 200 countries (but not the USA) that aims to improve the outlook for endangered species and their habitat. The deal includes the target to protect 30% of land and sea surface by 2030 as well as pledges to reconstitute 30% of degraded ecosystems and to redirect funding that is currently subsidising harmful industries.

As with the climate summit held the previous month, funding was a key issue, with several African countries objecting to the final document as it did not contain a new separate fund for biodiversity. The wealthier countries have agreed to pay 30 billion US dollars towards the costs of biodiversity conservation through the existing mechanisms.

Montreal is already linked to the biggest ever success of any international conference aiming to protect the environment — the phasing out of halogenated hydrocarbons agreed in the Montreal Protocol of 1987, which saved the atmospheric ozone shield from destruction. Whether the new Montreal pact will follow in the tracks of this success, or rather in the wake of the previous biodiversity conferences, whose targets were all missed, remains to be seen.

One fundamental problem that may put any progress at risk is the highly connected nature of the ecological networks that are currently at risk of destruction. Even if habitats and species are going to be protected according to the new pact, the fabric of life on Earth may already be unravelling.

Extinction cascades

Current modelling of extinction risks is typically based on the parameters known for the species of interest and its environment. In reality, however, each species is tied up in multiple interdependencies with other species, some of which may respond to the same environmental change in different ways. A real-world ecosystem consists of complex organisms and several trophic layers, embedded in an environment that is subject to chaotic change triggered by human disruption — all this makes for too much complexity for modelling.

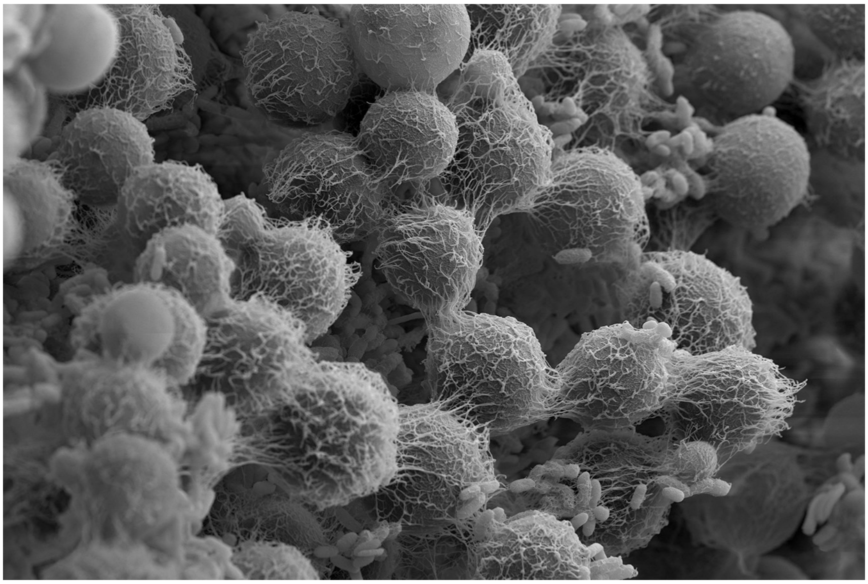
Therefore, Giovanni Strona from the European Commission's Joint Research Centre (JRC) at Ispra, Italy, and Corey Bradshaw at Flinders University, Australia, set up synthetic worlds with virtual species representing all vertebrate species on a supercomputer and studied the effects of real-world climate change scenarios on their artificial system (Sci. Adv. (2022) *8*, eabn434).

Studying multiple simulations for each climate scenario, the researchers found that, irrespective of their specific position in the ecological network, the species suffered a breakdown of connectivity, which eventually led to coextinctions on a level not predicted by previous modelling efforts. The domino effect of coextinctions was most strongly present in the intermediate climate scenarios — i.e. conditions which on their own would be survivable for most species but proved fatal for the network. The authors acknowledge that their model may still be too optimistic in that their virtual vertebrates feed on an unlimited supply of plant and insect food not affected by the environmental change in the virtual world.

Translating their findings to the real world, Strona and Bradshaw predict that, under average climate scenarios, coextinctions will increase the biodiversity impact of primary extinctions by 184%, leading to an average of nearly 18% of loss in local vertebrate biodiversity by the end of this century. Moreover, the authors find that ecosystems are likely to lose around half of all ecological interactions, leading to a loss of network complexity and resilience.

Ironically, the ability of individual species to adapt to environmental change does not help at a larger scale. Upregulating the likelihood of adaptation in their models, the authors found that, while it helped the survival of individual species, it reduced the average persistence of global biodiversity.

In conclusion, the authors warn that "Unless conservation practitioners rapidly start to incorporate the complexity of ecological interactions



Microbial world: The group of Jeff Gore at MIT is using microbial ecosystems such as this for studies to test hypotheses derived from theory. (Photo: William Lopes, Gore Lab.)

Drying out: The receding water levels of the Great Salt Lake in Utah, USA, have left microbial reefs exposed to bleaching. (Photo: Wikicommons/Farragutful (CC BY-SA 4.0).)

and their role in extinction processes in their planning, averting the ongoing biodiversity crisis will become an unachievable target."

An alternative way to study ecosystems at a manageable scale is to look at microbial ecosystems in the laboratory, which also have the advantage that one can perform controlled experiments on them. The group of physicist Jeff Gore at the Massachusetts Institute of Technology, USA is using laboratory cultures of two to 48 species of microbes to test predictions made by theory.

In a recent publication, the group could show that such simple experimental ecosystems can be switched from a stable equilibrium to more dynamic phases by manipulation of only two parameters (Science (2022) *378*, 85–89). By driving up the species density or increasing the strength of connections between species, the researchers could turn a stable equilibrium state into a more dynamic state with some extinctions. Further intensification led to a state with persistent fluctuations in species abundance.

The researchers are now planning to use the same approach to study transfers between otherwise isolated populations. This is relevant to biodiversity conservation as the exposure of endemic island species to invasive species has been a frequent cause of recent extinctions (Curr. Biol. (2022) *32*, R721–R723). In earlier work, Gore's lab has also investigated how disturbances can lead to population collapse, an experience we are likely to witness on larger scales in the near future.

Real-world collapse

Apart from island ecosystems overrun by invasive species, lakes gradually drying out are offering real-world examples of spatially well-defined ecosystems suffering and possibly collapsing under environmental stress. The Aral Sea, which has disappeared from the map after much of its feeding waters were diverted for agriculture, provides a dramatic warning (Curr. Biol. (2017) *27*, R43–R46).

After years of drought and water diversion, the Great Salt Lake in the USA is at risk of disappearing as well. Speaking at a conference of the Geological Society of America last October, Carie Frantz of Weber State University at Ogden, Utah, warned that the crucial microbialite reefs in the lake are at risk of dying due to the sinking water levels and increasing salinity. The photosynthesis of algae and cyanobacteria in these reefs is the nutritional basis of the lake's ecosystem, which is unique in that it lacks fish but hosts brine shrimp and brine flies, which in turn serve as food to migrating birds stopping over.

Field studies of the microbialites in the summers of 2021 and 2022 revealed their worsening situation. In 2021, Frantz and her students were able to revive pieces of the reefs that had been left to dry out simply by re-immersing them in lake water. They typically observed exponential growth and quick recovery within the duration of their field work, suggesting that a reef re-immersed could fully recover on the timescale of months. Repeating the experiment a year later, they did not observe the same speedy recovery.

Frantz attributes the difference in outcomes to the increasing salinity of the brine. A healthy range for the established lake ecosystem would be 12–15% salinity. In the course of their investigations Frantz and colleagues determined levels around 18% in 2021 and above 19% in 2022. If this trend continues, the researchers fear the unique lake ecosystem could collapse within months or a few years. Although some legislative measures have been taken, Frantz warns: "It's a slow shift in response to an emergency — we're not acting as fast as the situation calls for."

On the other side of the world, in Papua New Guinea, a major freshwater lake is also showing signs of ecosystem collapse. Lake Kutubu is PNG's second largest lake and was listed as a site of international significance under the Ramsar Convention of Wetlands in 1998. Kelsie Long from Australian National University at Canberra and colleagues have studied sediments from the lake to identify baseline conditions and monitor recent anthropogenic change. In the process, they also detected what they believe to be early indicators of ecosystem collapse (Proc. Natl. Acad. Sci. USA (2021) *118*, e2022216118).

Lake Kutubu is at the heart of a tropical rainforest with high biodiversity, in an area that is also noted for the cultural and linguistic diversity of its human population. With the beginning of oil extraction operations in the 1990s, the area has been exposed to deforestation, pollution and human influx. In the lake sediments, Long and colleagues could study the impact that this sudden change had on the regional ecosystem. The sediments show a recent collapse of algal communities which they describe as an ecological tipping point that is likely to have knock-on effects on other species. A likely cause is the metal pollution detected in sediments formed since the 1990s, which is unusually enriched in barium.

Another freshwater system that is suffering ecosystem collapse is the river Oder, which marks the frontier between Germany and Poland. In the summer of 2022, a sudden and widespread die-off of virtually all fish species in the river was observed. The direct cause of the die-off was a bloom of the toxic algal species *Prymnesium parvum*, which has been triggered by unusually high salt concentrations. The salts, in turn, may have been released by Polish mining operators on the upwaters in the industrial region around Wrocław.

While the official joint report from the German and Polish governments doesn't identify a source of the salt pollution, an independent investigation by Greenpeace pinpointed a mining company in Gmina Polkowice as well as a separate location on the Gliwice Canal, which connects to the river Oder. Insufficient monitoring of potential polluters was identified as a root cause. To improve the treatment of the river system, the German environment ministry is currently conducting a project to assess the damage to the ecosystem and lay the foundations for regeneration and recovery.

Splash out: Among the endemic species specifically adapted to the Antarctic environment, emperor penguins have been identified as the most acutely threatened by environmental change. (Photo: Christopher Michel/Flickr (CC BY 2.0).)

Pulses and presses

Ecosystem collapses make the news when they happen fast and spectacularly, but on a more moderate timescale, they are occurring in many places. Dana Bergstrom from the Australian Antarctic Division and colleagues have analysed the status and recent trajectories of 19 separate ecosystems ranging across 58 degrees of latitude from the reefs off the northern coast of Australia to the coast of Antarctica (Glob. Chang. Biol. (2021) *27*, 1692–1703). The systems studied include the Great Barrier Reef, mangroves in the Gulf of Carpentaria, the Mediterranean forests and woodlands, the arid zone of central Australia, Shark Bay seagrass beds in Western Australia, Great Southern Reef kelp forests, Gondwanan conifer forests of Tasmania, Mountain Ash forest in Victoria, and moss beds of East Antarctica.

The researchers found that some degree of ecosystem collapse, defined as potentially irreversible change to ecosystem structure, composition and function, was happening locally in all 19 systems studied, although never across the entire ecosystem. They categorised pressures driving these changes into chronic "presses" and acute "pulses". They note that these have become more severe, frequent and widespread in the last few years.

The authors suggest management strategies to minimise the impacts of these pressures. Ultimately, however, they conclude that, to preserve the natural systems and the services they offer, a drastic change of course is needed: "Pivotal for the future of life on Earth is a reduction of pressures that lead to ecosystem collapse […], some of which can only be achieved through significant change in our collective behaviours."

One of the ecosystems studied, the Great Barrier Reef, is finding attention globally. In March 2022, the reef suffered its fourth major bleaching episode in seven years. Notably, this was the first bleaching to happen during a La Niña period, which, in contrast to the El Niño condition of warmer ocean water, should make bleaching less likely. This bleaching was less severe than those in 2016 and 2017 and produced less coral mortality.

The annual survey of the reef conducted by the Australian Institute of Marine Science in August 2022 showed higher than previous coral cover for the central and northern parts of the reef, with reduced cover for the southern part, where an outbreak of the invasive crown-of-thorn starfish caused additional mortality.

In November 2022, the UNESCO has again recommended to put the reef on the list of world heritage sites in danger. The previous application to do so was rejected by the world heritage committee in 2021 after the Australian government lobbied against the classification.

While the coral cover in the northern and central parts seems to suggest the reef is proving resilient to environmental stress currently occurring, the general trend of warmer waters and higher sea levels suggests that reef ecosystems are going to be at risk very soon.

Jasmine Lee from the British Antarctic Survey and colleagues have conducted a detailed investigation of the threats facing Antarctic biodiversity and found that two thirds of the native species are at risk of extinction or serious decline by 2100 (PLoS Biol. *20*, e3001921). The iconic emperor penguin (*Aptenodytes forsteri*) emerged as the most endangered species, followed by other seabirds and nematode worms.

Threats include the rapid warming of their environment, as well as the increasing tourism traffic (around

100,000 visitors are expected this season), which carries the risk of importing invasive species (Curr. Biol. (2022) *32*, R247–R249). Keeping climate warming below 1.5 degrees would have the biggest benefit. Failing that, the authors call to reduce human impact by improving the management of tourist visits and infrastructure plans.

Threatened biodiversity in ecosystems like Antarctica, coral reefs and shrinking lakes is already reasonably well studied and research has helped to raise awareness of the growing threats. Other ecosystems including those in the deep sea (Curr. Biol. (2022) *32*, R807–R810) and in the deep subsurface (Curr. Biol. (2021) *31*, R415–R417) remain largely unexplored and are at risk of falling victim to the anthropocene before science has even had a chance to investigate them.

Join the dots

In the last months of 2022, it has been remarkable to observe how the separate global summits on climate and on biodiversity followed each other as if the problems discussed were unrelated, and both did not dent the widespread enthusiasm for another round of global overconsumption for Christmas, with political leaders declaring their undying commitment to unlimited growth, and the investment in new fossil fuel extraction including even new coal mines.

As Unai Pascual from the University of Bern, Switzerland, and colleagues have elaborated in a recent policy paper, transformative governance across these areas is needed to meet the challenges facing our globalised society (BioScience (2022) *72*, 684–704). Based on their analyses of four case studies including forest ecosystems, marine ecosystems, urban environments, and the Arctic, the authors conclude that “building on such transformative governance principles is not only possible but essential to effectively keep climate change within the desired 1.5 degrees Celsius global mean temperature increase, halt the ongoing accelerated decline of global biodiversity, and promote human well-being.”

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Essay

Pesticide licensing in the EU and protecting pollinators

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Intensive agriculture is reliant on pesticides to control crop pests, but these chemicals can have negative environmental consequences. This has resulted in repeated calls for pesticide risk assessments to be modified to better protect ecosystem services such as pollination. However, the pesticide licensing process is complex, and consequently there is often confusion between risk assessments where the environmental impact of pesticide use is considered, and risk management where licensing decisions are made. Using bees as a case study, we provide a roadmap for how pesticides are licensed for use in the European Union. By outlining the regulatory process, we highlight key data gaps that need to be addressed to generate a holistic approach to environmental risk assessment. Such an approach is vital to protect pollinators and wildlife more broadly from the unintended consequences of pesticide use.

In 1962, Rachel Carson published the best-seller *Silent Spring*, in which she outlined the environmental impact of pesticide use. *Silent Spring* resulted in then-commonly used pesticides such as DDT being banned globally from agricultural use, and consequently pesticide risk assessments are now required prior to licensing[1]. Despite this, 60 years later, intensive agriculture is still dependent on pesticides (e.g., insecticides, herbicides, fungicides), with widely documented negative environmental consequences from their use[2–4]. For example, neonicotinoid insecticides can have severe negative impacts on pollinators[4,5], which has resulted in restrictions in the European Union (EU). New-generation insecticides such as sulfoxaflor and flupyradifurone can also have detrimental impacts on beneficial insects[2,6] and sulfoxaflor is now also banned from agricultural use outdoors. These examples are emblematic of a broader pattern where a pesticide is licensed for use, found to have a negative environmental impact, and is banned or restricted, only to be replaced with another pesticide with negative environmental impacts. This continuing cycle has resulted in repeated calls for pesticide risk assessments to be modified[6–8]. However, these risk assessments are complex and there is often a disconnect between risk assessments, whereby the safety profile of a pesticide is determined, and risk management, where licensing decisions are made. Consequently, pesticide regulation can appear opaque and confusing. Here, using pollinators as an example, we outline how pesticides are licensed for use in the EU, where concentrations of pesticides detected are typically lower than in other western agricultural environments[9,10] and more pesticides are restricted or banned[11]. In reviewing the limitations of the licensing procedure in the EU, we suggest areas of future research required to create a more rigorous approach to risk assessment both in the EU and globally.

Pesticides are a major anthropogenic stressor for bees

Bees are vital pollinators of crops and wildflowers, but are routinely exposed to pesticides[12]. In risk assessments prior to licensing, regulators test the toxicity of pesticides to confirm they do not pose a significant risk to honeybee mortality at field-realistic concentrations[7]. However, research from the last two decades has shown that pesticide exposure can have a host of sub-lethal effects. For example, field-realistic concentrations of neonicotinoids can impair bee foraging, learning, thermoregulation, flight and fecundity, with downstream consequences for reproductive success[4,5,13]. Sub-lethal assessments are not a mandatory requirement within risk