In Search of Lost Worlds

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There were reindeer running around, lemmings, mastodons (mammoth-like animals), but also horseshoe crabs and black geese. And there were trees such as poplars and various types of conifers. These are just some of the more than 100 animal and plant species that scientists could identify in more than two-million-year-old genetic material brought to the surface from the soil of an area in northern Greenland. The soil in the area is not covered by the giant ice sheet and therefore lies free – not because it's not cold enough, but because the air is too dry for snow. In late 2022, the discovery made the cover of *Nature*, which read that the scientists had discovered a «lost world». This was because the genetic material – DNA – testified to a time when the area, as well as the rest of Greenland, was much warmer than today. The many animals and plants whose DNA was recovered lived in a lush, green coastal landscape – a huge contrast to the desolate polar desert the area is today. That landscape disappeared, along with its inhabitants, when Greenland ended up in the freezer of the Pleistocene, the age of ice ages separated by short warmer periods, which partly explains why the DNA was preserved for so long – though it is far from intact. With its age of at least two million years, it is, for now, the oldest preserved DNA.

More important than that record is how that DNA brought the lost world back to life. That is the power of so-called environmental DNA (or eDNA): it reveals which organisms occur in a particular environment. Today, eDNA is popular among biologists and ecologists, as it provides them with a handy tool to monitor ecosystems without having to go looking for specific animals or plants – they simply collect the DNA that the organisms leave behind. But for ecosystems that have long since disappeared, eDNA – if preserved – can help scientists discover and reconstruct them. As has thus happened with the lost world in Greenland.

According to Danish evolutionary biologist and (paleo)geneticist Eske Willerslev, one of the laureates of the 2023 Balzan Prizes, ancient environmental DNA provides a window to look deep into the biological and ecological past of our planet. Willerslev led the team that discovered the lost world in Greenland, and with that, he returned to his first research interest when he was a young PhD student.

Willerslev is a pioneer in ancient eDNA research. In 2002, he managed to ferret out DNA from mammoths and musk oxen (typical ice age animals) as well as from several plants from the Siberian permafrost, genetic material which had ended up in an icy environment from the beginning, allowing it to be preserved. By contrast, in soil samples from the Greenland area which were taken in 2006, it was much more difficult to isolate readable DNA fragments. Only when Willerslev's colleagues developed a method to detach DNA from quartz (a mineral to which DNA can adhere and be better preserved) did they succeed. Nearly three billion DNA fragments were isolated from some forty soil samples. They were sequenced and compared with reference DNA from existing, living species, which yielded about one hundred matches. The more than two-million-year-old DNA had revealed its secrets. «We went further back in time than anyone had ever dreamed of,» Willerslev told the news site of the journal Science. And to think that the Dane came up with the idea of searching for ancient eDNA when he looked out of the window of his Copenhagen flat in 2000 and watched a dog defecating in the street. He wondered: could DNA from faeces and other organic material perhaps be preserved in soil for thousands of years if the conditions were right?

Fast-forward to November 2023. The young PhD student is now a professor at both the University of Cambridge and the University of Copenhagen. I interviewed him while he was in Bern to receive the Balzan Prize. However, the motivation of the jury mainly mentions ancient human DNA. Willerslev is being lauded for his research on historical human mobility and migrations, through the analysis of (ancient) DNA from bone remains. In this research, among other things, he focused on the spread of diseases, often linked to the arrival of nomadic steppe peoples to Europe from Asia in the third millennium BC. These migrants are thought to have brought, for example, an increased predisposition to multiple sclerosis. The research also took Willerslev to Greenland. In 2010, he was the first to sequence the complete DNA (the genome) of a prehistoric human, a Greenlander who lived 4,000 years ago.

But during our interview in Bern, it soon became clear that Willerslev is done with research on ancient human DNA. «I don't like the way this research happens today. There is a lot of competition, and as a result there is a real hunt for scarce human fossils. Who owns the fossils or can get their hands on them often decides what happens in the research. This is totally different with environmental DNA: there are tons of it in the soil, so there is enough for everyone. You just have to go and get it.»

In addition, the technology to search for DNA in soil sediment, to isolate it and then sequence it has also improved a great deal over the past 20 years, since Willerslev's interest in ancient eDNA was aroused. This is why he calls eDNA the new frontier in the ancient DNA field. «We can now start exploring the field of ancient eDNA, as we did in Greenland. As a scientist, I find that much more exciting than further elucidating the picture of prehistoric human migrations – of which, after all, the broad contours are known by now.»

But the switch – and return – to ancient eDNA comes with challenges. One is the huge amount of data that the analyses produce, data that must then be compared with reference DNA in databases, which at the same time are also only getting bigger. This calls for solutions in the form of computational techniques. Willerslev has therefore decided to use half of the money of the Balzan Prize to support young researchers to develop such solutions.

What does Willerslev ultimately want to do with the results of his ancient eDNA research? «We can learn how ecosystems responded to changes in the past, not least in terms of climate. How did ecosystems adapt through natural evolution? How resilient were they to the changes?» The link to the current climate crisis is obvious. In the Arctic, global warming has been must faster than the rest of the world, and so Greenland's climate is getting closer and closer to that of pre-Pleistocene times, when it was on average ten degrees warmer than today. Eventually, the lush, green lost world disappeared. But how long was it able to drag out the slow dying? How resilient was it?

Answers to these kinds of questions – for instance, in the form of adaptations of ancient ecosystems or genetic mutations in individual species – may come in handy to better arm the world today against climate change. They can show the way to sustainable, climate-resilient agriculture. At least that is the ambition of a new international research project: the Ancient Environmental Genomics Initiative for Sustainability, Aegis for short. Led by Willerslev, the project brings together partner institutes from Europe, Asia, and the US.

Aegis is highly interdisciplinary: it involves geneticists (such as Willerslev), but also bioinformaticians, ecologists, geologists, and archaeologists. Together, they will study how the ancestors of important modern food crops such as wheat, barley, and rice responded to environmental factors in the past – natural factors, such as climatic changes, as well as human, such as crop breeding. To do so, the researchers will search for the DNA of those ancestors, in soil on land, under seas and lakes, and in ice – they will thus look for ancient environmental DNA. Ultimately, they hope to discover vanished ecosystems that were sustainable and resilient in their time. These systems can then serve as a blueprint for modern climate-resilient agricultural ecosystems.

Tobias Richter, an archaeologist at the University of Copenhagen, is involved in the project. He helps to find suitable locations to take soil samples. «This mainly involves places where we can see the transition from wild crops to early agriculture,» he says. In addition, he provides genetic research with context, both economic, cultural, and technological. «This context is needed to understand changes in plant genetics.» Finally, he helps to interpret the results of the genetic analyses. «For example, what do they tell us about domestication or crop breeding?»

But how do you recognize an ancient sustainable agricultural ecosystem purely with genetic data? «That's a key question, for which there are different answers,» says Richter. «A past agricultural ecosystem can be considered sustainable if it survives across episodes of major climatic or environmental change, or if it operates without problems for long periods of time. But you could also measure this in socio-economic terms: perhaps an ecosystem is sustainable when large numbers of people benefit from it (as opposed to a small elite) and it leads to population growth and prosperity. We shouldn't think only in terms of environmental sustainability, but also in terms of socio-economic sustainability. These two aspects go together.»

The Aegis project shows the huge potential of ancient eDNA research, whether on ecosystems that existed millions of years ago, or on agricultural ecosystems that were shaped «only» thousands of years ago by both natural and human causes. It shows that searching for lost worlds can not only satisfy our curious and interested mind, but also help save today's world.