'The future is fungal': New research finds that fungi that live in healthy plants are sensitive to climate change

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Cladonia, a lichen, grows in a white puff only a few inches above a carpet of a moss called Pleurozium. Like the iconic black spruce (Picea) of the boreal belt, they harbor diverse endophytic fungi that live symbiotically within their healthy tissues. Credit: Betsy Arnold

Spruce, pine, fir and other trees tower across the frigid swaths of land that span North America, northern Europe and Russia in a great ring around the world. These boreal forests constitute the largest land ecosystem and the northernmost forests on Earth.

Nestled within the photosynthetic, or light-eating, tissue of the boreal trees—and within the bountiful cloud-like lichens and feathery mosses that carpet the ground between them—are fungi. These fungi are endophytes, meaning they live within plants, often in a mutually beneficial arrangement.

"To be a plant is to live in a fungal world," said Betsy Arnold, a professor in the School of Plant Sciences in the College of Agriculture, Life and Environmental Sciences and the Department of Ecology and Evolutionary Biology in the College of Science and a member of the Bio5 Institute. "Endophytic fungi are vital to the health of plants in ways that aren't yet totally understood, but what we do know from endophytes in general is that they're very good at protecting plants against disease and helping plants be more resilient to environmental stressors, like heat. They've been part of an important revolution in our thinking about plants."

Over a decade ago, Arnold and her team set out on a monthlong adventure deep into the wilderness of northeastern Canada to understand how these fungal species adapted across different microenvironments and how they might fare under future climate change.

They found great diversity among the fungi and that they were adapted in highly specific ways to their local conditions, implying that they will be sensitive to future changes in climate. With the health of fungi so closely tied to the health of their hosts, these findings have implications for the overall health of future boreal forests and for our planet.

"Boreal forests are central to our planet's carbon and water cycles," Arnold said. "And our work highlights that they are home to some of the most evolutionarily diverse fungal endophytes in the world—endophytes that are found nowhere else."

After over a decade of analysis, their findings were published in the journal *Current Biology*.

"Our collaborative study shed light on the diversity in the boreal biome of newly discovered endophytic fungi and their sensitivity to climate," said study co-lead author Shuzo Oita, who completed his doctoral studies in Arnold's lab and is now a research scientist at Sumitomo Chemical Co., Ltd. "Endophytes are often overlooked because they occur in healthy plant tissues, but their importance in biodiversity and ecosystems has been revealed recently."

Flying for fungi

Collecting the data to come to this conclusion was a gargantuan effort that required Arnold and her colleagues to undertake some of the most intense fieldwork of her life, she said.

For a month during the summer of 2011, the team contracted with an expert pilot "to access places where the roads don't go," Arnold said. The team of six traversed the southern boreal forests of Canada all the way up to the edge of the Arctic tundra, landing their float plane in lakes along the way.

Betsy Arnold and her team accessed remote areas of the boreal forests of eastern North America by floatplane. A view from the window shows spruce trees growing from a carpet of moss and lichens, and the lake on which the researchers were to land. Credit: Betsy Arnold

Thirty-six times they took off and landed among remote lakes dotting the landscape. Typically, they spent about six to 24 hours at each sample site.

By day, they collected healthy spruce tree leaves and fresh mosses and lichens from the ground, stowing their scientific treasure in zip-close bags as they went. They also drilled tree ring cores, hoping to reveal their pasts, such as their age and wildfire exposure. They also measured various forest characteristics to understand how plants vary across the landscape.

By night, as the northern lights fluttered overhead, they processed their samples in portable laboratories inside the pilots' quarters. They surface-sterilized fresh tissues to prepare them for DNA extraction and isolated fungal cultures to visualize and document strains living within their samples.

"We often worked until 2 or 3 in the morning and would sleep for a few hours before flying on to the next site," Arnold said. The long days paid off: "In the fungal world, an hour of fieldwork is a year of characterization and a decade of potential analysis. And in just a few weeks' time, we covered a lot of ground."

As they traveled from the warmer southern regions to the colder north, they repeated their sampling at approximately 100-mile intervals. They also sampled along a single band of latitude that was equally vast but represented very little change in climate, Arnold said.

They strategically sampled in these two dimensions to ensure that any differences in fungal biodiversity were truly driven by environmental differences rather than distance alone. Together, they flew nearly 1,500 miles in the DeHavilland Otter that was their mobile home, often sharing their traveling space with extra tanks of fuel.

Older studies have examined the correlation between biodiversity and latitude, which is often used as a proxy for climate. These studies found that in general, life becomes more diverse closer to the equator, Arnold said. For example, for many groups of organisms, those in tropical rainforests are more biodiverse than those in the Arctic tundra.

It turns out, it's not that simple when it comes to fungi in the boreal zone.

"We show that boreal fungal communities don't necessarily change with climate in the same predictable way as plant communities. Instead, the effect of climate on these fungi is highly dependent on both the fungal species and the host," said co-lead author Jana U'Ren, who completed her doctoral work and conducted the laboratory analysis for this project as a postdoctoral scientist with Arnold before moving to Washington State University. "This means that we need to protect plants and their fungal endophytes across the boreal biome, and not just in one location, or we risk losing vital biodiversity and protective fungi in these important forests."

Arnold thinks that the special climate dependence of these fungal endophytes reflects a process of co-evolution with their hosts—or "research and development," as she put it—as plants find the ideal endophyte partner and flourish despite the distinctive stresses that plants face in these harsh northern landscapes.

The team flew from lake to lake in a DeHavilland Otter with expert pilot Jacques Bérubé (center) providing access to remote sites for the project's field team, under the co-leadership of François Lutzoni (left) of Duke University and UArizona's Betsy Arnold. Credit: Betsy Arnold

"Endophytes are found all around the world, but there are distinctive ones in different environments. We think that symbioses with endophytes are, in part, how plants overcome environmental challenges at a global scale—that is, with their internal fungal partners," Arnold said.

"There's not a lot of information about exactly what an individual endophyte does for an individual plant. So, our study is foundational in the sense that we tried to figure out who these endophytes are, and how they're distributed, and how they might change with a shifting climate."

She hopes that future research can build off their findings.

"What we do know is that we're losing that biodiversity when those forests are changing, and we don't yet know what the key functional elements are," she said.

Collaborator François Lutzoni, a professor of biology at Duke University and co-architect of this study with Arnold, agreed.

"This was some of the most complex fieldwork I have ever done, but also one of the most exhilarating research experiences I have had," Lutzoni said.

"To document biodiversity in our changing world is essential research. The specimens we collected are deposited in herbaria and therefore have lasting value to understand how species, their distributions, their genes and the ecosystems they inhabit change over time. In turn, the best way for herbaria to serve the scientific community is by being integrated with research labs in world-class universities."

Within this mindset, Arnold is now working to use home-grown Arizona endophytes to enhance crop resilience in this changing world.

"Just like boreal forests harbor an unexpected diversity of endophytes, so too do plants here in Arizona," Arnold said. "Our next steps are to tap these rich and ancient endophytes as tools for helping plants thrive. Ultimately, we hope that by understanding these fungi at a global scale, we can not only chart the past and future of a key element of our planet's biodiversity, but we also can harness those in our local areas to make crops thrive with limited water and rising temperatures. You might say that the future is fungal."

Other co-authors are Jolanta Miadlikowska from Duke University, Bernard Ball from University College Dublin and Duke University, Ignazio Carbone from North Carolina State University, Georgiana May from the University of Minnesota, Naupaka B. Zimmerman from the University of San Francisco, Denis Valle from the University of Florida and Valerie Trouet from the University of Arizona Laboratory of Tree Ring Research.

More information: Jana M. U'Ren et al, Environmental drivers and cryptic biodiversity hotspots define endophytes in Earth's largest terrestrial biome, *Current Biology* (2024). DOI: 10.1016/j.cub.2024.01.063

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