FUNGI - Curated Transcript of BBC In Our Time podcast
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In Our Time is hosted by Melvyn Bragg. Melvyn's guests on this podcast are:

Lynne Boddy
Professor of Fungal Ecology at Cardiff University

Sarah Gurr
Professor of Food Security in the Biosciences Department at the University of Exeter

David Johnson
N8 Chair in Microbial Ecology at the University of Manchester

Producer: Victoria Brignell.

Transcript:

[Melvyn Bragg] Hello. Our planet is home to millions of species of fungi, and the role they play is vital. Without fungi, life on Earth as we know it simply wouldn't exist. They also play an important part in our everyday lives. The making of bread, beer and wine wouldn't be possible if fungi were not available. In the field of medicine, they've been part of the production of certain antibiotics since penicillin. However, there are other fungi which can cause nasty diseases in humans and destroy trees. Some fungi are even toxic to humans and can kill if consumed. Despite their significance, much of the way in which fungi operate remains a mystery. With me to discuss fungi are Lynne Boddy
Professor of Fungal Ecology at Cardiff University, Sarah Gurr
Professor of Food Security in the Biosciences Department at the University of Exeter
and David Johnson, N8 Chair in Microbial Ecology at the University of Manchester.

[Melvyn Bragg] Lynne Boddy, what is a fungus and what do they look like?

[Lynne Boddy] Well, fungi are not plants, they're not animals, they're not bacteria. They're a kingdom of their own. You could be forgiven, I suppose, for thinking that they're plants because their fruit bodies, the things which we think of as toad stalls or brackets on trees, I suppose superficially they look a bit like the flowers or fruits of plants, but they're not. The flowers and fruits of plants, we know that's not the only part of a plant - there's the leaves and the roots and the shoots. And in the same way, the fungus has much more to it than that toadstool that we see when we wander through the woods. The toadstool is just the tip of the iceberg. Underground we have the main body of the fungus, the mycelium. Mycelium is a network of fine filaments. That's the body of the fungus. This is what sets fungi apart from all other organisms. It's the living part of the fungus. It grows and it feeds as a network of fine tubes with a large surface area with a huge enzyme capacity.

[Melvyn Bragg] I'm told from the notes that I've been given by the three of you that there are about three to 5 million species of fungi and we ...have identified only 150-170 thousand of them. Something like that. So there's a long way to go. What do they have in common?

[Lynne Boddy] Well, the vast majority of them have this mycelial structure. Some of them are unicells though, such as yeasts. They have chitin in their cell walls as a common feature. And that's also found in animals, invertebrates in their exoskeleton. So actually, fungi are more closely related to animals than they are to plants.

[Melvyn Bragg] How do they differ? They're related to animals and plants. How do they differ from them? Can you just develop that a bit? ...You've said more or less [that] they're sui generis at the start of the program and they are inside us and inside plants. So there's a bit of a crossing of lines there...

[Lynne Boddy] Yes, there is. There's a bit of all sorts of worlds, I suppose. Fungi in some way are like animals in that they have sort-of foraging behavior. They search around for food. They don't get up and wander around like many animals do, but they search for food. And when they find it, they respond. And actually, if you look at some of the patterns that they make, they rather look like the termite trails that you see when termites go investigating for food sources. They're a bit like plants in the sense that they don't wander around. They're just very different, they've got similarities to different organism groups, but they've got huge differences. One of the most important things about them is that they can't make their own food. So plants make their own food. Fungi can't make their own food. They have to get it in the same way as animals do from other organisms. So that is a crucial feature about fungi.

[Melvyn Bragg] When did fungi scholarship take root? Take "root"? If we can talk of that...

[Lynne Boddy] Yeah, I'm not sure what the answer to that is. I suppose people started thinking about fungi and classifying them in the seventeen hundreds. So Linnaeus, the great Swedish biologist, he was the first person to group organisms and he grouped things into animals and plants, but he threw the fungi into the plant category. So we're in good company when we think that perhaps they look a little bit like plants and then this sort of carried on from there.

[Melvyn Bragg] What about Hooke and his microscope?

[Lynne Boddy] I'll pass it over to Sarah for that one.

[Melvyn Bragg] Can I come back to you later then, Sarah? We can talk about Hook with you later. So we've got Linnaeus and classifying it comes in there, OK. David Johnson, what role of fungi played in the history of life on Earth?

[4:55]
[David Johnson] They have a hugely important role, and one of the main events that they were responsible for was the greening of the Earth. So the movement of plants from the aquatic environment into the terrestrial environment, which happened about 450 million years ago. And that process was only possible because of the role of fungi. So when plants are growing in the aquatic environment, they have nutrients that are fairly readily available to them in solution. So taking up nutrients is rather easy. On land, that's not the case. And the primitive roots that these early plants had were really not up to the job of acquiring nutrients. And so one of the critical processes was the evolution of the mycorrhizal symbiosis, so the interaction between fungi that live on land with plant roots. So they develop these very intimate associations that enable plants to colonize the terrestrial environment and take up nutrients via these root borne fungi to enable the plants to diversify and form the huge diversity of plants that we see today.

[Melvyn Bragg] This happened about 450 million years ago?

[David Johnson] It did, yeah.... And we know that because there are some remarkable fossil evidence to show this and some of that's in the UK, so. the famous Rhynie chert near Aberdeen. This dates back to the early Devonian. It's about 400 million years ago, and it contains some incredible preserved specimens of these early primitive plants.

[Melvyn Bragg] From 450 million years ago?

[David Johnson] Maybe slightly younger, maybe 420 million years in the case of the Rhynie chert. But they don't just contain the fossilized plants, but you can actually see evidence inside the root systems of structures that are remarkably similar to the structures that you see in modern day plants. You can see hyphae colonizing plant roots and developing the distinctive coils inside the roots, all beautifully preserved. So that provides some of the best evidence to date, this greening of the Earth.

[Melvyn Bragg] Will you tell us about the range of environments that fungi inhabit?

[7:08]
[David Johnson] It's more a question of where they don't inhabit. They're literally everywhere. So in this room, there are probably fungal spores floating around.

[Melvyn Bragg] What are they up to?

[David Johnson] Well, they're very tiny. So, one of the reasons they're so successful is that the spores can disperse very easily because they're so tiny and they're produced in huge abundance, so that's enabled them to colonize virtually all [habitats].

[Melvyn Bragg] Sorry, it's a very simplistic question, but they're floating around here in this room [that we are broadcasting from]. Are they looking to do anything or is it just an accident? Will they do anything other than float around?

[David Johnson] They will find a suitable substrate to colonize and to germinate. Many fungi are associated with humans, on their skin, for example. It's maybe a scary thought, but we are covered in microbes, including fungi. So they're essentially looking for this suitable environment to germinate and to colonize, and that's enabled them to colonize all terrestrial biomes. So the boreal forest, the Arctic, the dry valleys of Antarctica, tropical forests. Every terrestrial biome contains thousands of fungi, and also the aquatic environment, so particularly freshwater environments, but also the marine environment. So they're really incredibly successful at at colonizing Earth.

[Melvyn Bragg] And they are incredibly diverse.

[David Johnson] And incredibly diverse as a result of that. Yeah.

[Melvyn Bragg] Can you give us some examples of the diversity - that sometimes they're like this and then sometimes they're like sometimes like a sometimes they're like z.

[8:46]
[David Johnson] Yeah. So, I mean, Lynn mentioned that some of these fungi produce very distinctive mushrooms, which I think most people are familiar with. So that's that's one group of fungi that produce these very distinctive but very transient, very short lived, spore-bearing structures. Not all fungi produce those. Some produce much more cryptic fruit bodies. So, the so called ascomycetes, which produce cup-shaped fruit bodies, and some don't produce fruit bodies at all. So they have very different morphologies and that's meant that we can classify them in very different ways. Often the early classification systems were based on their morphology, but they also have very different modes of nutrition. So some fungi are parasitic, some fungi are separatrophic, so they're breaking down dead organic material to get their nutrients. Some fungi have formed mutually beneficial associations. I mentioned before the greening of the earth. That's an example of the evolution of a mutually beneficial association between the plant and the fungus. So they have very different modes of nutrition.

[Melvyn Bragg] Sarah, you are going to tell us something more about Robert Hooke?

[10:04]
[Sarah Gurr] So, in 1665 Hooke, who is responsible for inventing the compound microscope in Oxford, looked down his microscope and the first thing he described were cork cells. Then he picked up a red leather book and he looked at what was growing on it and he described the fungus "mucor". He then wandered out into his garden in Oxford and he picked some rose leaves and on his rose leaves he saw

powdery mildews. So his contribution was the ability to see fungi for the first time, in 1665, with his compound microscope.

[Melvyn Bragg] How many... can we talk about the species then of fungi?

[Sarah Gurr] So how many are there? Well, we know the names of perhaps 130-140 thousand, as you said at the beginning, and out there in the biosphere there may well be between 2.8 and 5 million other species that we don't yet know about. So a huge biodiversity.

[Melvyn Bragg] And ...are all three of you and friends of yours, colleagues, on the case of trying to, trying to discover those and class categorize those, classify them?

[Sarah Gurr] There are many people in the world looking at classification and building trees, so family trees, of relatedness between fungi and the animals across the world. But my particular interest is in fungal diseases of crops. So, there are many scientists doing these sorts of things but not me.

[Melvyn Bragg] So what are you finding out about the fungal diseases of crops that we ought to know and be aware of?

[Sarah Gurr] So I think if you look at the balance of disease in humans we are rather obsessed with getting diseases caused by bacteria and viruses. But in plants and in crops, the number one agent of plant disease is actually the fungi. So fungi are number one and bacteria and viruses and nematodes cause diseases but they're not as important. So in terms of crop diseases at the moment, despite the fact that we spray our crops with fungicides and we breed disease resistance into them, we're still losing between 10-23% of our crops per annum to crop disease and we're also losing up to about 20% after harvest. So, post harvest storage diseases caused by fungi. And so food security is hugely challenged by the march of fungi across the world, not only by trade and transport, but also due to climate change.

[Melvyn Bragg] People listening will know about a mushroom. Can you tell us how that is a fungus?

[Sarah Gurr] Yes. So for me, defining a mushroom is rather like looking perhaps at the London Eye and say the London Eye is London. A mushroom is just one small part of the kingdom of fungi. What it represents, as David said, is the fruiting body. So the ability of this particular creature to put up something that looks a bit like an umbrella and from the bottom of the umbrella, where the gills are, to release thousands upon millions of spores to make sure that the next generation of mushrooms or jelly, moulds or rust and smuts occur. So this is one part of the fungal kingdom where it makes a fruiting body and it disperses its spores. But that part of the kingdom of fungi is only one very small part - perhaps 11% of the fungi that we currently know.

[Melvyn Bragg] And how about these fairy circles?

[Sarah Gurr] Fairy circles are also caused by these sorts of fungi which grow not only by producing the fruiting bodies, but they grow out from a central point by raidiating out as these long threads of filaments that Lynne described, the mycelium, under the grass.

[Melvyn Bragg] Lynne, can I come back to you? Can we develop the idea of why they're so crucial to plants, please?

[Lynne Boddy] Yes, certainly. I think there are quite a lot of reasons. Firstly, they form this relationship called mycorrhizas, which Dave has already explained [in the context of] the greening of the earth. And that's where the fungus associates with the roots of plants. So mycorrhiza is from the Greek - literally "mykes" means "fungus", "rhiza" means root, so literally "fungus root". So, the fungi associate with the roots of plants, probably ... 90% of all the plants that we see in nature have these associations. The fungi spread out their fine filaments into soil, they absorb water and mineral nutrients and they give that water and those nutrients to the plant. They also protect the plant roots from pathogens that are in the soil. And there's a swap for this. The plant pays by giving the fungus sugar. So, sort of exchanges is no robbery, it's a mutualistic relationship. Vast numbers of plants have these, as I say, 90%. [The] second reason is that fungi are the garbage disposal agents of the natural world. They're the decomposers, they break down the dead stuff. If it wasn't for fungi, we'd be up to our armpits in dead stuff. And I suppose that's not probably the real issue. The point is that in all of that dead plant material, there are nutrients locked up inside and by breaking down that dead material, fungi release those nutrients and they're then available for plants to carry on growing. So that's two of the main reasons why plants absolutely depend on fungi. And indeed, our planet depends on fungi because they depend on plants. Fungi are also intimately related to plants in another sort of way. There's these fungi called endophytes. So, endophyte literally means endo-"within" , phyte-"plant" or fungi within plants. And if you look around you, every plant you see has fungal endophytes inside, in the leaves and the roots and the shoots. They're just very, very tiny, little tiny, just a few hyphae here and there. But they're interacting with the plants. They're not showing any symptoms. The plant just doesn't look ill or anything. They're not doing bad things, but they're in the plants and in fact, lots of them confer important properties to the plants. So, fungi often make chemicals which are inhibitory to other animals. So some of these endophytes are making nasty chemicals which deter grazers. So, these could be grazers like aphids or insects or indeed bigger animals. There's a situation with horses sometimes that eat rye grass that have got these fungi in them and they stagger around as if they're drunken and it could deter the horses from eating the grass. But it's the fungi that are producing those chemicals. Other fungi give plants the ability to colonize very saline soils, so these endophytes are very important too. And then, of course, the fourth reason why fungi are important to plants is sort of the negative side that Sarah has already alluded to and that's when fungi are pathogens - killers of plants.

[Melvyn Bragg] David Johnson, can we develop the idea of a different sort of fungi?

[16:52]
[David Johnson] Yeah, so I think that the modes of nutrition are a good way to start. So, we've talked about parasites, saprotrophs and mutualisms. So that's a nice way of grouping fungi away from the classical taxonomic approaches. So, for example, the saprotrophs, they're breaking down organic matter, they're using energy locked up in that dead material to gain their energy, to gain their carbon and their nutrients. Lynne

also mentioned the mycorrhizal fungi which are dependent on plants for their sugars and in return provide plants with mineral nutrients. And then there's the parasites which are doing harm to their particular host organism. So, for example, there's a group of parasites that colonize ants which produce mind altering chemicals in the ant's brain that forces the ants to crawl up onto the top of plant leaves, hook themselves onto the leaf where they die, and then the fungus can produce its little fruit bodies and disperse from the ant. So it's a remarkable adaptation as a strategy to gain a source of nutrients, which is the body of the ant, and to gain a suitable site to disperse their spores.

[Melvyn Bragg] Sarah, I asked you about the beginning of the serious study of fungi. You mentioned Linneas. Can we say how it went in the 19th and into this and in and the 20th century? How did how it developed?

[18:21]
[Sarah Gurr] Yes. So the first scientific paper in the world of plant disease biology happened in the "Gardener's Chronicle", which was in the Royal Horticultural Society magazine in 1865. and the description was about the potato murraine, which at that stage people thought was a disease that came from the cattle. Thereafter, in 1865, the Reverend M J Berkeley wrote the next paper saying, no, it was due to a fungus. And we now know it wasn't quite a fungus. It's something closely related to fungi. But the Irish potato famine was probably the most significant moment in the 19th century in terms of the study of fungal biology associated with disease.

[Melvyn Bragg] Could you develop that? Because people will know about that - that great blight

[Sarah Gurr] Yes. So, the blight's actually caused by, I dare say, a fungus-like creature called phytophthora. And it's still a problem today on tomatoes and aubergines and potatoes. But in the 1860s, [in Ireland?] we had a very extraordinary time in history. Most of the land owners were absentee landlords in London. They were Protestant, and their people who worked the land were Roman Catholics living in Northern Ireland, and they were extremely poor. They were eating between two and a half and six and a half kilos of potatoes a day and drinking water. If they were wealthy, they had a cow, so they had milk. So what happened then was that they divided the potatoes that they harvested and they went moldy as they stored them from year to year, and they replanted their potatoes. So what you would do is you'd take a tuber and you put it in a darkened sack, and then the following year you would take the tuber, the potato, and cut it into lots of pieces. So what they did very effectively was to spread a monoculture - so, a genetically uniform stock of susceptible potatoes throughout Ireland. And then in perhaps in the ballast of a boat that traveled from the Isle of Wight came the potato disease, phytothra. And this rampaged through the Irish potato fields, leaving in its wake a million dead Irish folk and a million who emigrated to the New World. What was it in that boat from the Isle of Wight specifically?

[Melvyn Bragg] Can you tell what went there and caused such devastation?

[Sarah Gurr] This is a rumor. No one really knows quite how phytophthora arrived in Ireland, and this is one of several stories. Just simply that there were potato peelings in the boat which had arrived from South America. And of course, South America is the home of the potato.

[Melvyn Bragg] I see. Lynne, how do fungi obtain their nutrients?

[Lynne Boddy] How do they feed? Well, they're not like us. So, you and I would "eat" food: We ingest food and inside us, in our digestive tracts, enzymes break down that food into small molecules, which then diffuse into the blood system and spread around our bodies to wherever the energy and other nutrients are needed. Fungi sort-of, in a way, do almost the opposite of that. They do sort of "external" digestion. So they don't take food into their bodies directly. They secrete enzymes which break down big molecules outside of their bodies into smaller molecules, and then these are absorbed into the fungus. Of course, it's a bit of a risky business doing that because other organisms could be around which steal the breakdown products. And this does happen, I dare say, quite frequently with other fungi and with bacteria that don't have those enzymes that can break down these complicated molecules. And actually quite a lot of other organisms have capitalized on this ability of fungi to break down big molecules. So, for example, termites, the higher termites, they actually "farm" fungi. Termites and other animals don't have the ability to break down complicated molecules in plants such as lignin, and often not celluloses either - the main things that plants are made of. So they culture fungi, they have a garden in their nest, they cultivate the fungi, they clean them up and take any contaminants away. But they bring plant material to the fungus. Fungus then grows on it, secretes enzymes, breaks it down. Of course, the fungus can use that material to grow itself, but also some of the termites come along and eat the fungus. So it's a sort of a swap again. The fungi get the food brought by the termites, they break it down into something that the termites can eat. So there are quite a lot of mutualisms like this in South America. Ants do similar things, the attine ants. In fact, there are loads of these mutualisms which have evolved because of what fungi can do and how they feed.

[Melvyn Bragg] David Johnson what about the decomposition of material? How does that occur?

[23:01]
[David Johnson] Well, as Lynne mentioned, it's the production of these enzymes by the hyphae - these filaments that grow through soil. That's the critical process.

[Melvyn Bragg] It's all to do with feeding, is it?

[David Johnson] Absolutely, yes. So the fungi are decomposing stuff either to get carbon and or to get growth limiting nutrients like nitrogen and phosphorus. So some of the enzymes that Lynne mentioned are rather specific to those particular forms of nutrients. Some enzymes break down complex forms of carbon like cellulose, one of the main constituents of plant material. Other enzymes break down organic phosphorus - compounds which are prevalent in soils. Other enzymes break down organic nitrogen. So you end up with a kind of cascade of enzyme reactions going on simultaneously facilitating the breakdown of that organic matter in order for the fungi to extract the particular nutrients that they require. But it's not just about the chemical warfare. I mean, the key feature of fungi is their ability to physically colonize stuff. So this external digestion process only really works if you're actually physically attached to the substrate you're interested in. So a key feature of fungi is the ability to grow through organic matter and to penetrate all those tiny crevices and pores that are found in bits of organic matter in order to facilitate the breakdown of that material.

[Melvyn Bragg] Sarah Gurr, do the cells of the fungi have any special characteristics? Particular characteristics?

[24:37]
[Sarah Gurr] Yes. I think if you imagine that you're looking at an elongate balloon and the balloon can be anything from a micron (so, ten to the minus six, a millionth of a meter) right up to a long tube, like you can see ... like licorice bootlaces with dry rot fungi. So those are the filaments which form the hyphae. So the balloon like structure is the membrane. And what a very particular feature of this fungus, or a particular fungus, is that it has a cell wall which confers rigidity to it. So it protects the fungus and it also allows it to go through different surfaces and also into plants or humans or whatever. And very characteristic of fungi is that they grow by the tip, so they grow by polarized tip growth, so they grow fast forwards with the tube following them, if you see what I mean. And they're able to colonize all sorts of different environments. But the organelles, that is the structure within the cell, is very much in common with other mammalian and indeed animal cells. So there are features that are common and also features that are different, particularly the cell wall.

[Melvyn Bragg] We mentioned animals now and then. What are the [cellular] features [that are] the same as animals.

[Sarah Gurr] So the features that are same are things like the nucleus, so where all the genetic information is held; the way that fungi might make energy; the fact that fungal cells have almost a highway of cytoplasmic contents that are funneled down a cytoskeleton, so it's like thinking you have the motorway, like a neuron, that takes organelles down it to feed the very tip for polarized growth. So many of the organelles within a fungal cell are common to animal cells.

[Melvyn Bragg] Lynne, ... Is there a regular life cycle of fungi...?

[Lynne Boddy] Yes... Well, obviously there are millions of species of fungi, and so there are lots of different life cycles. But if we take a mushroom so imagine there's that there's a mushroom there.

[Melvyn Bragg] Very useful, a mushroom, for purposes of illustration.

[Lynne Boddy] Absolutely, because we can see them in our minds eye quite easy. They produce ... all of these billions of spores, so little, little tiny spores, which I suppose are equivalent to the seeds of flowering plants. So these little spores are blown around or maybe taken around by invertebrates or other animals. And a spore might land somewhere. If it lands in a good environment where conditions are just right and there's a food source, it will germinate. So the fine filaments grow out from the spore and it branches, higgledy-piggley, to start with, starts exuding, secreting its enzymes, breaking down the big molecules and feeding itself and then it can grow bigger and bigger and bigger, and it might grow just for a short while, or maybe for a long while before it finds a suitable mate. Maybe just a few minutes of spore might have landed right by it, which germinates and grows, and it can mate with that, or it might be sometimes perhaps even years.

[Melvyn Bragg] When you say mate, are we talking about any sexuality that we describe?

[Lynne Boddy] Yes, we can, and it's quite suitable for our listeners as well. So fungi mate in a rather different way than animals do. The hyphae of fungi come together and they simply fuse together, but that's only successful if they are compatible. Of course, we as humans have two sexes, male and female, but fungi have hundreds of sexes very often and they can...mate or fuse with many different mycelia of the same species which come close. So maybe spores traveled, I don't know, a few hundred yards away from a fungus of the same species and it makes it's mycelium. And the chances are that they will be compatible. So they will mate. They can even mate with mycelium, which has developed from spores of, of their siblings...they can mate very often with about 25% of their very close relatives, their siblings sometimes 50%. So they will mate like this and then they're a little bit different. To start with, they just have one nucleus in each of their cells, but when they've mated, they have two. And these stay as separate nuclei for a very long time until something triggers them to produce these fruit bodies, these mushrooms again. So when the conditions are right and the mushrooms start to form, then those two nuclei will join together and the genetic material in each of them will be recombined and then separated again into separate nuclei which go into separate spores. And so the cycle continues, they will spread away. So that's the main part of the life cycle. But fungi can also reproduce asexually without the need to mate. So they can form little spores at the tips of their hyphae, or sometimes the hyphae, these fine filaments that's the main body of the fungus, just separate out into very small compartments which then break up. Other life cycles are more complicated. Some of the fungi which Sarah studies as a plant pathologist have loads and loads of different types of spores, but I think perhaps that's a bit too much to think about here.

[Melvyn Bragg] ...How are they kept in check? What should all be joining about? I sort of wonder why fungi have not be on the rampage and just taking the whole thing over.

[Lynne Boddy] Well, in a sense that I suppose in a way they have taken over the planet, but not from a bad point of view, from a good point of view, they are absolutely everywhere. As Dave has already said, they're intimately connected to plants, helping them all the time. They are breaking down all of the dead stuff that's about. Now, obviously, when they've completely broken down dead organic matter, there wouldn't be anything left for them to carry on breaking down so that would call a halt to their activities. So they're governed by and limited by who they can make partnerships with in terms of plants and animals and how much dead stuff there is for them to use.

[Melvyn Bragg] David, can you tell us about these networks and the connections?

[David Johnson] Just to pick up with that final point quickly. They're also under attack. So many of these fungi occur in soil where they produce these vast networks of hyphae, but those hyphae are susceptible to attack by animals that live in the soil. So, things like springtails, little jumping collembola, many of those eat fungi and they do a very good job at it. There's thousands of these little collembola in soil, so it's not all rosy for the fungi. But, yeah, a key feature of fungi is the ability to produce these vast networks. And mycorrhizal fungi in particular,

[Melvyn Bragg] What would a fungal network be?

[David Johnson] It's a mycelium that develops through soil. That's it. That's the simple definition. But some of the fungi, the mycorrhizal fungi, can colonize multiple plants simultaneously, so they develop what's called a common mycorrhizal network. So an individual fungus can simultaneously colonize several individual plants, sometimes of different species. So soon as you have a physical connection between different individual plants, there is the potential for resources to move between those plants via this common mycorrhizal network. And in fact, for some species of plants, that's absolutely critical. So, many orchids, for example, a hugely diverse family of plants, about 25,000 species worldwide, many of those plants have actually lost the ability to produce their own carbon. They don't produce any, they don't photosynthesize, and they're entirely dependent on carbon moving from a neighboring green plant via a common mycorrhizal network to the orchid to facilitate their growth. So that's like the extreme end of resource movement through these common mycorrhizal networks to such an extent that the orchids have evolved away from photosynthesizing on their own. But these networks can also transfer other molecules. So we now know that they can transfer signaling molecules produced by plants when they're under attack from herbivores like aphids. So it's been found out that when a plant is attacked by an aphid, it can produce signaling molecules that are designed to repel the aphids, but that these molecules can somehow be transferred through these underground fungal networks to neighboring plants that aren't yet colonized by the aphid and activate their own defense mechanism before they become under attack.

[Melvyn Bragg] It's bewildering - so much going on, isn't it, the intensity and the range of it. Sarah Gurr, can we take an example of the devastating effect fungi can have? Can you give us one or two?

[33:58]
[Sarah Gurr] Yes. I could divide that into two or three different topics. We could either talk about ecosystems, we could talk about human health or diseases of crops. So perhaps I'll start with trees. So I think historically, many of us were drawn to the study of this subject, plant disease biology, by the fact that when we were growing up, the landscape was changing. And it was changing because of a fungus which caused Dutch Elm Disease. It arrived on a consignment of logs from Ontario in 1974, a very aggressive strain of the fungus, and rampaged through the elm trees of Great Britain, leaving in its wake up until the late 90s, about a million dead elm trees. So that's something that's profoundly changed our landscape in the UK.

[Melvyn Bragg] You emphasize Britain. Did it happen in Holland and Germany?

[Sarah Gurr] It happened in Europe. It happened devastatingly in Northern America as well. So a huge number of elm trees died. In America, they then had a terrible outbreak of a fungus called chestnut blight, which wiped out 1.4 billion chestnut trees. So those two are historical examples, but today people are very much aware of Ash Dieback. So, this is a disease that probably came from Poland and was probably imported into a nursery in Buckinghamshire in about 2012. And ... up to today, I think, there are just over 1350 notations or where people have said they've seen the Ash dieback fungus. So this is beginning to change the landscape in the UK too.

[Melvyn Bragg] So that's one example, and you said you had two others.

[Sarah Gurr] So the examples of the impact of fungi on human health is kind of an unseen problem in the world today. About a .. thousand million people [?] are suffering from skin infections. And in fact, the mortality from skin infections when they go invasive, particularly if you are immuno-incompetent or your immune system is down, means that each year about a million people die from fungal infections. And that means that fungal infections are a hidden peril, causing more deaths than malaria and, in fact, more deaths than HIV and tuberculosis added together.

[Melvyn Bragg] And the third one?

[Sarah Gurr] And the third one is the fact that fungi, as I said earlier, are the most important agents of crop disease. So if you look at the major calorie crops of the world, we know that ...wheat and maize and rice cover 40% of global agricultural land. And each of these individual crops suffer from different perils. So the wheat suffers from rust disease, the potatoes suffer from phytothera, as I talked about earlier (so that's the fourth, not the third [major crop]) ...rice from rice blast disease and maize from a disease called corn smut. And these individually wipe out a vast amount of crops each year. And if you take just the five major pathogens of plants, we know that they produce or that they compromise our crops so that we are unable to feed between 600 and 4,000 million people, 2000 calories per day each year. So, very significant losses due to fungal disease on crops.

[Melvyn Bragg] Lynne, this is maybe an odd question. Is there any way that fungi compete with each other?

[Lynne Boddy] It's not an odd question at all, it's a very good question. Fungi is very, very competitive. Probably competition has been looked at mostly in fungi that rot wood. So if you went to the woodland and sawed through a tree trunk that's fallen down, or a branch, you'd see lots of lines in there often dark colored lines, sometimes bright oranges. And they're not just straight lines, they sort of demarcate territory a little bit like how we put fences or walls around our homes and gardens to show which is our area. So fungi do this too, in quite an aggressive way. They completely surround a volume of wood which they can occupy with these defensive materials. So, when they've got this territory, they can use the nutrients in that region at their leisure. But of course, they're battling all the time against their neighbors who would also like to come in and get that wood from them. And some fungi are better fighters than others. Some of them, when they meet, they would just deadlock - neither manages to get any of the territory from the other one. Other ones are much more aggressive and can replace completely [another] fungus. And they do this in different ways. They produce volatile compounds, a bit like the gases in the trench warfare in the First World War. They produce poisonous compounds that dissolve and diffuse through wherever they grow into it to kill their opponents. They produce masses of enzymes which can eat their opponents and sometimes they're parasitic on them. So there are these great interactions going on - these battles all the time. Of course, we can actually use some of these battles for our human benefit. So there's a fungus that's called Trichoderma, which is parasitic and also produces lots of chemicals which can kill plant pathogens - the sorts of things that Sarah has been talking about a lot. There are other ones which can kill insect pests. So we can gradually begin to manipulate fungi to kill some of the organisms which we find as pests.

[Melvyn Bragg] ...We are coming to the end now, but David Johnson, so this is part of the positive uses that fungi have for humans?

[David Johnson] Yeah. So you mentioned at the start, I mean, imagine life without blue cheese, bread, wine and beer. It seems terrible. So that's clearly one use. We like eating fungi and they do great things to enable us to eat very nice food. So many of the important crop plants, so things like wheat, barley, maize, rice, they're all plants that have evolved to form mycorrhizal fungi and they wouldn't exist without that symbiosis. So I think increasingly we're looking at using fungal diversity to improve the way we grow crops - try and grow them in a more sustainable way so we're not relying on use of fertilizers and so on. We're not relying on the use of pesticides so much. We're trying to embrace the power of fungi to help grow our crops in a more healthy and sustainable way.

[Melvyn Bragg] Finally, Sarah Gurr, have we been able to notice the effect of climate changes on fungi?

[40:23]
[Sarah Gurr] Yes. So in a very large modeling project, we've recently shown that fungi are on the move and unfortunately they're on the move in concert with climate change. ...

[Melvyn Bragg] What does "on the move" mean?

[Sarah Gurr] So they're moving northwards, or polewards, at a rate of about 7km per year. So this will have a profound impact not only on the crops that we grow, but the way that we control fungal diseases of crops. So they're marching at the moment.

[Melvyn Bragg] So ...can you just tell the listeners...[what effect] they'll have an effect on the crops that we grow? Can you illustrate?

[Sarah Gurr] Yes. So, of course, the crops that we grow will probably change as well as the climate warms up and, in many regions, becomes also considerably drier. So we'll probably be changing our crops. And as we change our crops, there's a so called honeymoon period between the planting of the crops and the arrival of new pathogens on these crops. So we've got fungi moving and crops demography also moving. So we'll see new diseases further north and we'll see diseases as we begin to grow, for example, grapevines more prolifically in the northern parts of Europe rather than southern Europe. And we'll probably see the pathogens on the march with the crops.

[Melvyn Bragg] Well, we'll leave the pathogens on the march. Thank you very much. Thank you very much, Sarah Gurr, Lynne Boddy and David Johnson.

And the In Our Time podcast gets some extra time now with a few minutes of bonus material from Melvyn and his guests.

[Melvyn Bragg] So what did we miss out? What were you bursting to say that you didn't say?

[Lynne Boddy] Oh, well, I think that there's lots of things really. I think one thing is that we use fungi or fungal products as humans in very important ways in addition to what Dave has mentioned earlier. For example, lots of medications, obviously penicillin, an antibiotic, is one of the things which brings firstly to mind. But fungi also make other drugs which we use so ephedrine, which is used to treat asthma, ergot-alkaloids, which are used as vasoconstrictors to treat migrains, [and to] induce uterus contractions. Statins we discovered from fungi in the first place to treat cholesterol, to lower cholesterol. They're also important in the production of some steroids. Citric acid - I think nearly all soft drinks have citric acid as an acidity regulator. That is made commercially by fungi in vast vats. And other things like ascorbic acid as well, alcohols and ethanol enzymes such as proteases for softening meat, tenderizing meat. Pectinaes for breaking down plant cell walls which releases more juice when you're making fruit juice. There are vitamins such as vitamin B, betacarotene. All sorts of things - plant growth factors for stimulating the rooting compounds, plant hormones. There's a vast amount of products from fungi.

[43:34]
[Sarah Gurr] Yes, I think we might have just emphasized too much the fact that fungi are our foes. In fact, they're also our friends as well. But borrowing an idea from Neil Gow in Aberdeen, I think we should think about fungi as citizens of modern society because they're ethnically diverse and huge in number, they're important for recycling. They're important as scholars and teachers, which is something that we didn't really dwell upon very much, because, in fact, many of the things that we've learnt from fungi, work by Sir Paul Nurse, have told us about the cell cycle pivotal to cell biology. They do all sorts of other things in the environment that are useful for us, that we've talked a bit about, but they [are] also ... problems. So, they make our feet smell, they make our houses rot and they destroy our crops. But we must emphasize that there are very positive things, such as the drugs and the enzymes that come from fungi, without which life would be very much sadder. Without the wine and the cheese.

[Melvyn Bragg] You are very keen on the wine and the cheese, though?

[David Johnson] Indeed, yeah. I do like a good blue cheese, which is a penicillin-like fungus that produces that type of cheese. So, it's not just producing the antimicrobial stuff, it's producing a delicious product. The other thing to emphasize, I think, is just the vast abundance of these fungi in soils. A teaspoon of soil typically contains something like ten to 100 meters of hyphae. It's a vast amount. And I think we need to understand that when we're thinking about our ecosystems, particularly our forests, there's just a vast underground world supporting that ecosystem which is so important for life on earth, you know, in regulating our climate, in producing food, fuel and fiber, it's really dependent on these fungi.

[Lynne Boddy] Yes, you've just talked about these huge long areas, long distances in areas that the hyphae cover. But actually the largest organisms on the planet are fungi. We often think that it's the blue whale or something like that. But the honey fungi, the armilarias, form networks through forests. And ... we have large ones in the UK, but probably the largest ones [are in] in the huge forests of North America where from one side of a network to the other could be over 3 miles. So they can be absolutely huge. We can't see this obviously, because they're below ground doing whatever it is they're doing, decomposing dead stuff and in some cases, using living trees and things but they can be quite huge.

[Melvyn Bragg] What benefits do they get for being so big?

[Lynne Boddy] Well, I think the benefits they get [are] from being networks rather than necessarily from their size. Dave mentioned networks earlier. It's not only the mycorrhizal fungi that form networks. Many fungis growing into soil form networks. And being a network, you can send stuff from one place to another. So if a fungus is growing into a region which is desert like in terms of maybe not enough moisture, not enough nutrients, through the network, a fungus can feed that region with food from elsewhere. Also ... if you break a network, like for example, if you've got a road network and you close a road, there are other ways that traffic can go. And that's also the same in these fungal networks. So these huge networks have access to nutrients all over the place.

[David Johnson] And in fact, some transport networks are remarkably similar in structure to fungal networks. There's been some very nice work comparing the underground networks of the major cities with fungal networks. So they're like an insurance policy. They provide resilience. If a host plant dies over there, while the fungus might have another source of energy over here, for example. And they can also help in this competition, so they can direct resources to these battlegrounds where the energy is most needed. So they're hugely important.