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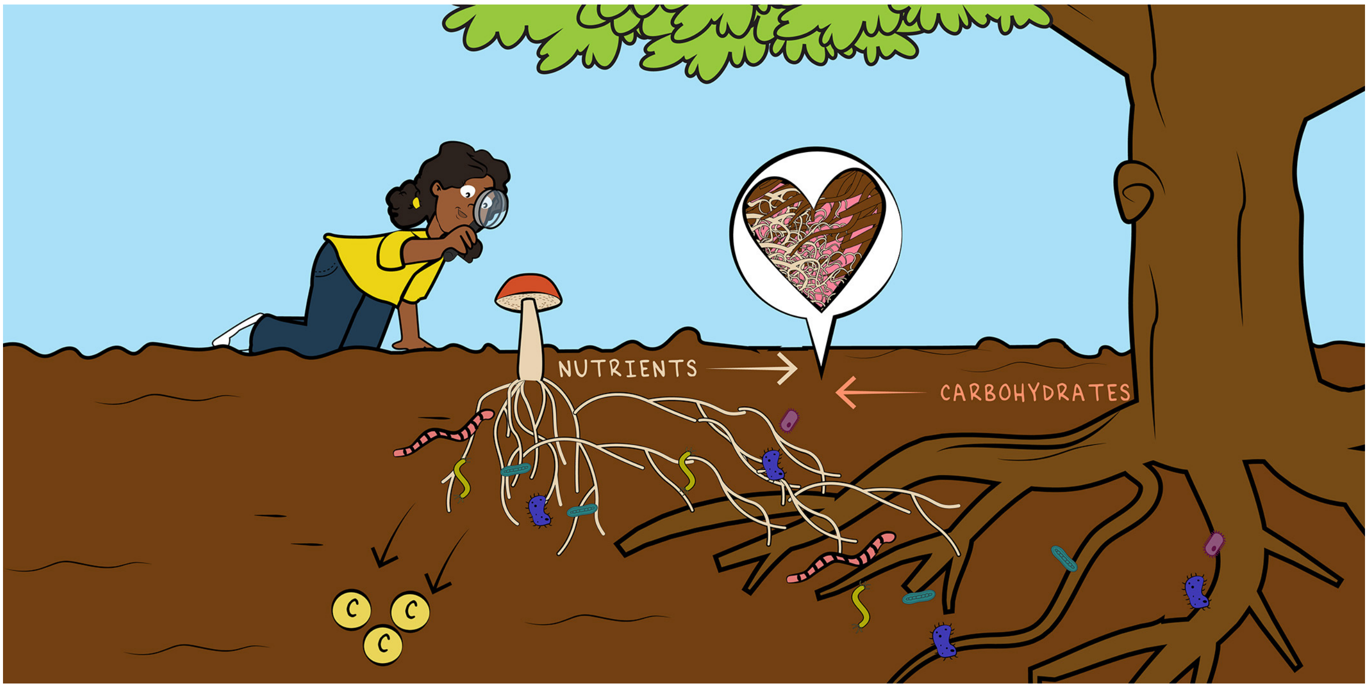

THE SOIL FUNGI: A WEB OF LIFE THAT PROTECTS TREES AND FIGHT CLIMATE CHANGE

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Ectomycorrhizal fungi are a type of fungi that develops a mutually beneficial relationship with plant roots. These fungi form ancient and extremely successful partnerships with forest trees worldwide. The trees and their associated fungi have developed a trading partnership: the fungi help the plants reach hard-to-get nutrients, and, in return, the fungi get constant and uninterrupted access to carbohydrates (such as sugars) from the plant. This largely invisible interaction affects the storage and cycling of carbon in soil and benefits plant health and nutrition. Ectomycorrhizal fungi are also important for breaking down dead plants and animals. These fungi contribute to soil biodiversity and can help us to protect our forests in the face of environmental stresses, such as climate change and excessive land use.

DECOMPOSER

They are bacteria, fungi or invertebrates that break down dead plants and animals, releasing nutrients back into the soil. Without them, dead organisms and waste would just pile up and plants would not be able to get essential nutrients.

ORGANIC MATTER

Any material produced originally by living organism such as plants, animals and microorganisms that is returned to the soil and can be further broken down (decomposed). Organic matter is carbon rich.

SYMBIOSIS

Any type of close, long-term biological interaction between two different organisms.

MUTUALISM

A relationship between two or more species, in which each species benefits.

MYCORRHIZAL FUNGI

Fungi that form a mutualistic relationship with the roots of plants. The plants receive nutrients and protection from the fungi and the fungi receive sugars from the plants.

FUNGI AND THEIR ROLE IN FOREST ECOSYSTEMS

We often hear that variety is the spice of life. This statement can easily be applied to the many interactions in nature, such as those taking place in forest ecosystems. To lead long and healthy lives, nearly all plants in the wild rely on a complex and varied network of soil organisms feeding on one another. This mostly invisible underground network is made up of tiny bacteria, archaea, fungi, and many other microscopic organisms.

In forest soils, the role of fungi is one crucial piece of the wider ecological network. Fungi have many ecological roles, but two of these are especially important. First, fungi play an important role as **decomposers**. Fungi excel at decomposing dead plant material (called **organic matter**) because they are better than other organisms at completely breaking down the particularly tough materials found in the cells of woody plants [1]. Equipped with a wide range of enzymes, which are special proteins that help produce and speed up chemical reactions, fungi can degrade organic matter and release hard-to-get nutrients, making the nutrients available to plants and other soil dwellers. However, during decomposition, fungi release CO_2 gas as a waste product, which results in movement of carbon from the soil into the atmosphere. Fungi are such excellent decomposers that fungal decomposition is one of the largest global sources of carbon emissions, releasing 85 gigatonnes (one gigatonne equals 1 billion tons) of carbon into the atmosphere every year. For comparison, in 2018, the combustion of fossil fuels produced around 10 gigatonnes [2].

In this article, we will focus on a different important role also played by fungi: their **symbiotic** relationship with trees and other plants. A symbiotic relationship in which both species benefit is known as **mutualism**. Fungi that form mutualistic relationships with plants are known as **mycorrhizal fungi**, from "myco," which means "relating to fungi" and "rhizal," which means "roots." Mycorrhizal fungi form ancient, mutualistic relationships with the roots of around 80% of all terrestrial plant species [1]. Even seemingly barren Antarctica has a fossil record of mycorrhizal communities. Studies show that this teamwork has been ongoing for 400 million years, from the time that plants started to colonize land [3]. Like all fungi, mycorrhizae cannot make their own food, so they receive sugars from their plant hosts, and in exchange provide the plants with water and nutrients, such as nitrogen and phosphorus, from the soil.

Unlike the decomposing fungi that tend to predominantly inhabit the upper portion of the soil and release lots of carbon from their activities, symbiotic mycorrhizal fungi delve deeper into the soil. By doing this, the fungal network becomes a significant carbon sink in the soil, meaning that these fungi keep the carbon locked away from the atmosphere, stored as hard-to-decompose organic matter in the

Figure 1

Figure 1

The ectomycorrhizal fungus *Lactarius camphoratus*, forming a white sheath around the roots of an oak tree (Photograph credit: Laura Martinez-Suz).

soil. It has been estimated that plants with mycorrhizal association can transfer up to 35% more carbon to soil than non-mycorrhizal plants, and a considerable amount of the carbon in mycorrhizal tissues may stay in the soil for many years [4]. This is important because we need to keep carbon stored in the soil for long periods of time so that there is less in the atmosphere causing rising global temperatures.

Despite the critical roles that fungi play in forest ecosystems, fungal diversity is often overlooked during forest management decisions. Human interference, such as logging or indiscriminate use of fertilizers, can alter the underground network and upset the balance of the entire ecosystem. Like any other web, if just one of the connecting segments is missing or weakened, the whole structure may suffer.

THE FUNGAL SPHERE

There are two main types of mycorrhizal fungi. One type, called endomycorrhiza, live inside plant cells. While we will not focus on these in this article, they are interesting because they are incredible experts in adaptation to many different environments. Endomycorrhizal fungi include arbuscular, ericoid and orchid mycorrhizas. However, the main focus of our article is **ectomycorrhiza** (pl. ectomycorrhizae), which live on the outside of plant cell walls. While multiple mycorrhizal types can coexist in an ecosystem, ectomycorrhiza are dominant in temperate and boreal forests, with ∼6,000 fungal species establishing symbiotic associations with many trees and woody plants.

Ectomycorrhizae consist of two types of important structures: **fruiting bodies** and **hyphae**. Fruiting bodies are structures containing spores used by ectomycorrhizae in order to reproduce. Around 4,500 species of ectomycorrhizae have above-ground fruiting bodies (mushrooms),

ECTOMYCORRHIZA

The relationship between a fungus and the roots of certain plants (plural, ectomycorrhizas, or ectomycorrhizae).

FRUITING BODY

Structures made by fungi so they can reproduce. A mushroom is a common type of fruiting body.

HYPHAE

Long, branching structures of a fungus that spread through soil to absorb and transport nutrients (singular, hypha).

Figure 2

Figure 2

The well-known poisonous fungus called fly agaric (*Amanita muscaria*) can form a mycorrhizal association with several types of trees, including pine trees, as shown here (Image credit: Angela Mele).

while up to a quarter have underground fruiting bodies (for example, truffles). Ectomycorrhizae also have hyphae (from Greek meaning "web"), which are long filaments or tube-like structures used by the fungi to absorb and transport nutrients. Hyphae form a mat of fungal tissue around plant roots, creating a casing that envelops the roots like a cast on a broken bone (Figure 1). Fungal hyphae also grow outwards like veins, pushing their way between soil particles, roots, and rocks to capture nutrients that are beyond the normal reach of plant roots. The ectomycorrhizal association also produces antibiotics, hormones, and vitamins useful to the plant, and protects plant roots from harmful conditions in the soil such as low nutrients, disease-causing organisms, and toxic substances. In return, the fungi gain constant and direct access to carbohydrates (such as sugars) produced by their plant hosts during photosynthesis.

ECTOMYCORRHIZAE AND FORESTS: TEAMWORK AT ITS BEST

Ectomycorrhizae prefer woody plant species such as trees and shrubs as their partners. Occasionally they can form exclusive relationships, in which only one fungal species pairs up with a specific tree species. However, ectomycorrhizae typically associate with a wide range of tree species. It is common to find several different mycorrhizal fungi on the root system of a single tree, or one fungal species that is associated with several different tree species. For instance, the Norway spruce can form symbiotic associations with over 100 different fungal species. The well-known poisonous fungus called the fly agaric can colonize the roots of several types of trees, including pine, birch, spruce, and eucalyptus (Figure 2).

The range of plant species colonized by ectomycorrhizae is relatively small—only around 2% of the world's plants. However, the plants that ectomycorrhizae partner with cover large land areas and have a high economic value, for example as a source of timber. In northern temperate regions, pine, poplar, spruce, fir, willow, beech, birch, and oak trees all show ectomycorrhizal associations, while eucalyptus and southern beeches are more commonly associated with ectomycorrhizae in the southern hemisphere.

Ectomycorrhizae give trees and forests the ability to adapt to seasonal and landscape changes, for example by providing adequate levels of water throughout the year and helping the plants to establish themselves in new soils. The fungi also protect the plants from soil degradation, pollution, and shifting climatic conditions. Scientists have observed a direct relationship between the decline of ectomycorrhizal fungi and declining tree health. Because each type of ectomycorrhizal fungus has its own unique set of characteristics, every species is necessary and irreplaceable. For example, certain species prefer cool or moist conditions; others operate better during warm or dry seasons; some are experts at obtaining phosphorus and nitrogen from the soil; and still others are more effective at getting these nutrients from decaying organic matter [5].

Ectomycorrhizal fungi are also an extremely important link between plants and the soil food web, which is the complex community of organisms found in soil. These fungi provide important nutrients to organisms living in the soil around plant roots, such as other tiny fungi, bacteria, protozoa, and invertebrates. The fungi also produce fruiting bodies, which are essential food for wildlife in forest ecosystems. For example, many rodents, such as the northern flying squirrel and western red-backed vole, depend on truffles as their primary food source. Many other mammals eat fungi, including bears, deer, and mice. Humans marvel at the complex and often pretty structures of mushrooms, taking great joy from learning to identify them and studying their ecology, as well as enjoying them as culinary delicacies. Wild fungi are also used for medicines, and the pharmaceutical industry commonly studies the antibacterial properties of ectomycorrhizal fungi.

PROTECTING OUR FORESTS AND FUNGI

Despite the importance of mycorrhizal symbiosis in forests worldwide, conservation of ectomycorrhizal fungi and monitoring them to assess forest health are rarely considered in forest-management decisions. The functions and services that forests provide are dependent on soil biodiversity. Fungi are a major component of this biodiversity, which makes them an important partner for overcoming the global challenges that we currently face. Fungi could contribute to the long-term removal of carbon from the atmosphere, which could help us to combat the effects of climate change. By cycling essential nutrients, fungi could also help to prevent the degradation of soils, so that the land can continue to produce food and sustain life. Scientists and land managers must continue to study and protect ectomycorrhizal fungi, so that these important organisms can maintain their critical role in the web of life on our planet.

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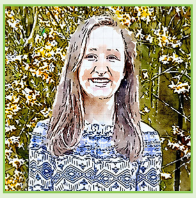
YOUNG REVIEWERS

ANNA, AGE: 16

I wanted to do Frontiers for Young Minds because I thought it would be a great opportunity to learn more about the world around me! I love the sciences, particularly biology and physics. After school I would love to do something with those subjects.



CATHERINE, AGE: 15

I love music and singing, I play the violin and guitar and I also enjoy writing! I am part of a highland dance troup and volunteer with children at local kids clubs and guides. I enjoy attending youth events at my church and doing fitness. I hoped that by reviewing these articles I could learn about new and interesting stuff!

AUTHORS

OLIVIA AZEVEDO

I am a former journalist who decided to become a soil scientist. I moved from Portugal to Scotland where I am currently a Ph.D., student at the University of Stirling. My research involves a lot of digging in forest soils in the hope of finding answers to one important question: what happens to soils and the things living in soils when you plant trees. My research interests include, but are not limited to, the following areas: Soil biodiversity; nutrient cycling; mutualistic relationships linking the above and belowground components of terrestrial ecosystems; soil degradation and management; historical soil landscapes. *olivia.azevedo@stir.ac.uk

FRANK ASHWOOD

A passion for nature encouraged me to study Biology at university, where I volunteered for research projects on invertebrate ecology in Scotland and Mexico. After working as an environmental consultant for a few years, I went back to Uni and did a Ph.D., studying earthworms on reclaimed landfill sites. I now have a great job as a soil ecologist for Forest Research, where I study soil biodiversity in UK woodlands. In my spare time I am a soil biology tutor and do macrophotography (taking photos of the tiny animals living in soil).