SYMBIOTIC ROOTSCAPES

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In the rainforests of Central America lives a small gentian flower, *Voyria tenella*. Their flowers are a vivid blue, and their stalks pale white. These 'ghost plants' have no leaves, nor any trace of green. In the place of branching, exploratory root systems they have clusters of fleshy fingers that sit like small fists in the shallow soil. With no leaves and no green pigment, *Voyria* plants are unable to eat light and carbon dioxide in the process of photosynthesis. Their stubby rootlets are ill-suited to absorb water or nutrients from the soil. How, then, can *Voyria* survive?

A few years ago, I travelled to Panama to study the symbiotic relationships that form between plants and the fungi that live in their roots, known as mycorrhizal fungi (from the Greek *mykes*, meaning fungus, and *rhiza*, meaning root). More than 90 per cent of terrestrial plants depend on these partnerships. They are a more fundamental part of planthood than flowers, fruit, leaves, wood or roots, and lie at the base of the food chains that sustain nearly all terrestrial life. Fine threads of tubular fungal cells – known as mycelium –

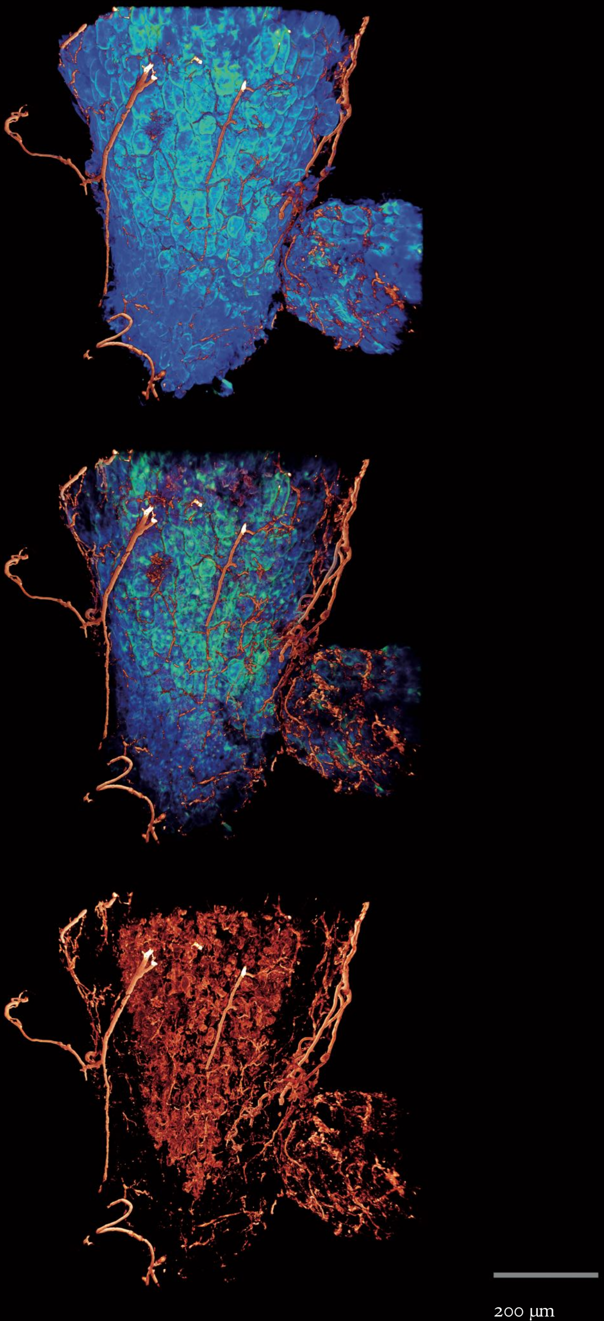
emanate from plant roots into the surrounding soil. These cells can link different plants in shared networks that have come to be known as the Wood Wide Web. This is how *Voyria* are able to make a living. Through shared fungal networks, nutrients and energy-containing sugars pass into *Voyria* from neighbouring plants. Mycorrhizal associations are so prolific that between a third and a half of the living mass of soils is made up of mycorrhizal fungi; their mycelium is a living seam that helps to hold the soil together. Globally, the total length of mycorrhizal mycelium in the top ten centimetres of soil is around half the width of our galaxy. In 1845, Alexander von Humboldt described the 'living whole' of the natural world using the metaphor of a 'net-like, entangled fabric'. Mycorrhizal fungi make the net and fabric real.

Thinking about fungi makes the world look different. The longer I've studied their behaviours and remarkable abilities, the more fungi have loosened the grip of my certainties about how the world works. Over time, as the familiar has grown increasingly unfamiliar, many of the well-worn concepts that I use to organise my experience – including notions of identity, autonomy and individuality – have become questions rather than answers known in advance. *Voyria* have helped me pursue some of these questions. In Panama, I wanted to find out more about how mycorrhizal networks behaved, and spent weeks scrambling through the jungle searching for these charismatic flowers in the hope that they might tell me something about what was taking place underground.

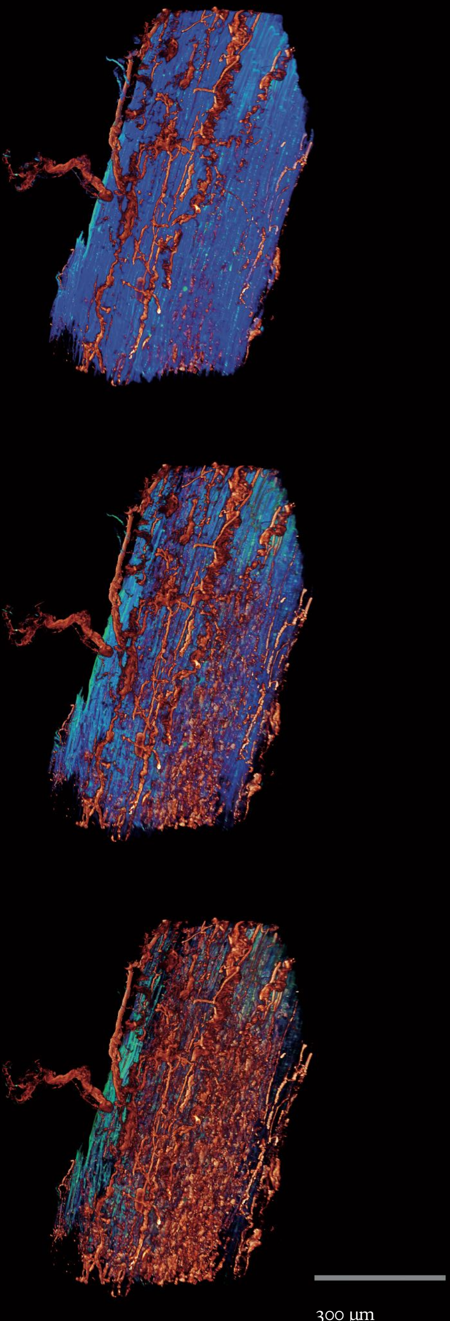
Symbiosis – the intimate association formed between different species – is a fundamental feature of life and enables new biological possibilities. Mycorrhizal fungi are some of the more striking examples. These ancient associations gave rise to one of the pivotal transitions in the history of the planet: the movement of plants' ancestors out of the water and onto the land. These algae had no roots and were ill-equipped to scavenge for water and nutrients in the open air. They struck up a relationship with fungi, accomplished foragers that served as their root systems for the first 50 million years of their life on land until early plants could evolve their own. This makes mycorrhizal associations the foundation of all recognisable life on land. To this day, plants' fungal partners help them cope with drought, heat and the many stresses that life on land has presented since the beginning. Plants supply their fungal associates with as much as 30 per cent of the energy they produce in photosynthesis. Mycorrhizal fungi supply their plant partners with nutrients, such as phosphorus and nitrogen, and defend plants from disease. Their association is literally radical.

Ecology is the study of the relationships between organisms. Networks of mycorrhizal fungi embody these relationships and help lead us out of reductive stories about self-contained individuals locked in a competition for resources. I like to imagine the bewilderment of an extraterrestrial anthropologist who discovered only yesterday, after several decades of studying modern humanity, that we had something called the internet. It's a bit like that for contemporary ecologists, grappling with the many ways that mycorrhizal fungi change our understanding of how organisms interact. As *Voyria* demonstrate, nutrients can move between plants via shared fungal connections. They are not exceptions. 'Normal' green plants in the shaded understorey might be sustained by resources acquired from their more amply provided neighbours. It isn't only nutrients that pass through these networks. A plant attacked by aphids can release signals that alert neighbouring plants to the imminent threat. Bacteria use fungal networks as highways to travel through the bustling obstacle course of the soil. Even if plants don't share the very same network, mycorrhizal fungi regulate plant coexistence, in some cases intensifying the competition between plants and in some cases relaxing it.

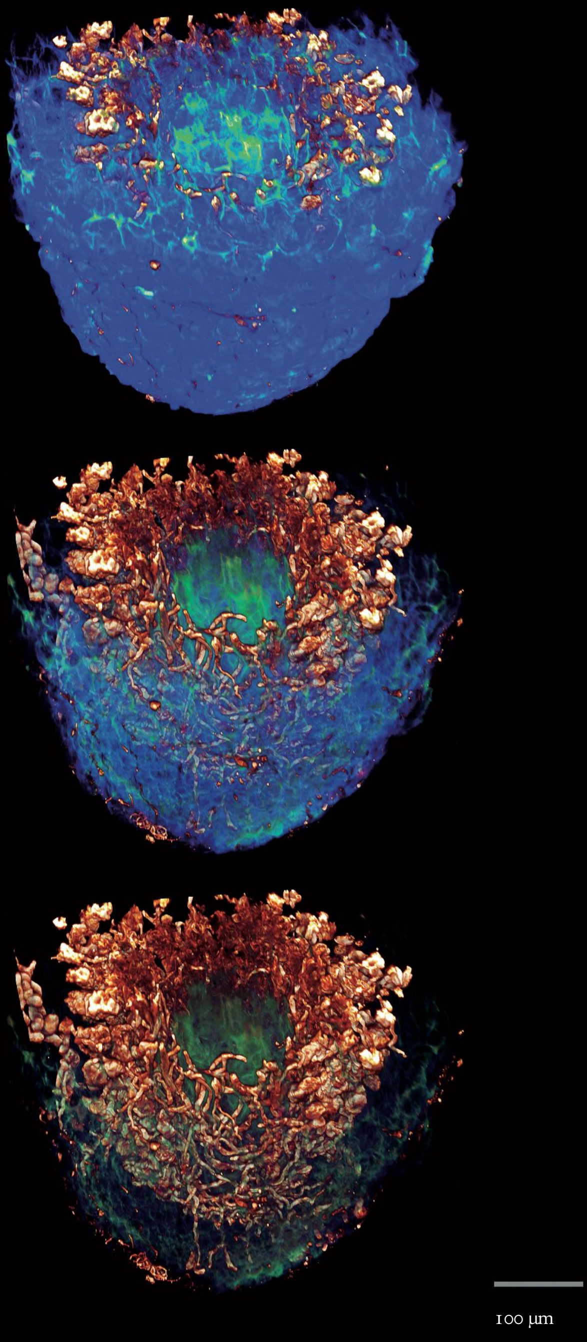
Whether in agriculture, forestry or in our attempts to restore degraded ecosystems, we depend entirely on the healthy functioning of mycorrhizal relationships. But they are hard for us to see, hidden within plant roots and underground. In this photoessay, I use laser scans of roots to explore the astonishing intercourse between plants and their fungal partners, subterranean worlds of intimacies within intimacies. All of these images are scans of non-photosynthetic ghost plants, whether the blue-flowered *Voyria* or otherwise. The roots of these plants are densely inhabited by fungi and the resulting rootscapes are particularly spectacular. I collected the samples while in Panama, where I conducted research at the Smithsonian Tropical Research Institute, and imaged them using a novel technique developed by Magnus Rath and colleagues at the Philipps University of Marburg in Germany. With a watchmaker's precision, Magnus prepared the roots for scanning. I then used a laser microscope to scan 'slices' of a sample ('confocal laser scanning microscopy'), and from stacks of these images reconstructed three-dimensional projections. By using different coloured lasers it was possible to render the plant and fungi separately. In all of the images that follow, plant tissue is artificially coloured in blue-green, and fungal tissue in red. Many consist of three panels showing the same section of root with the plant tissue made increasingly transparent. These techniques provide extraordinary new vantage on the entangled flourishing that underlies our past, present and future. ■



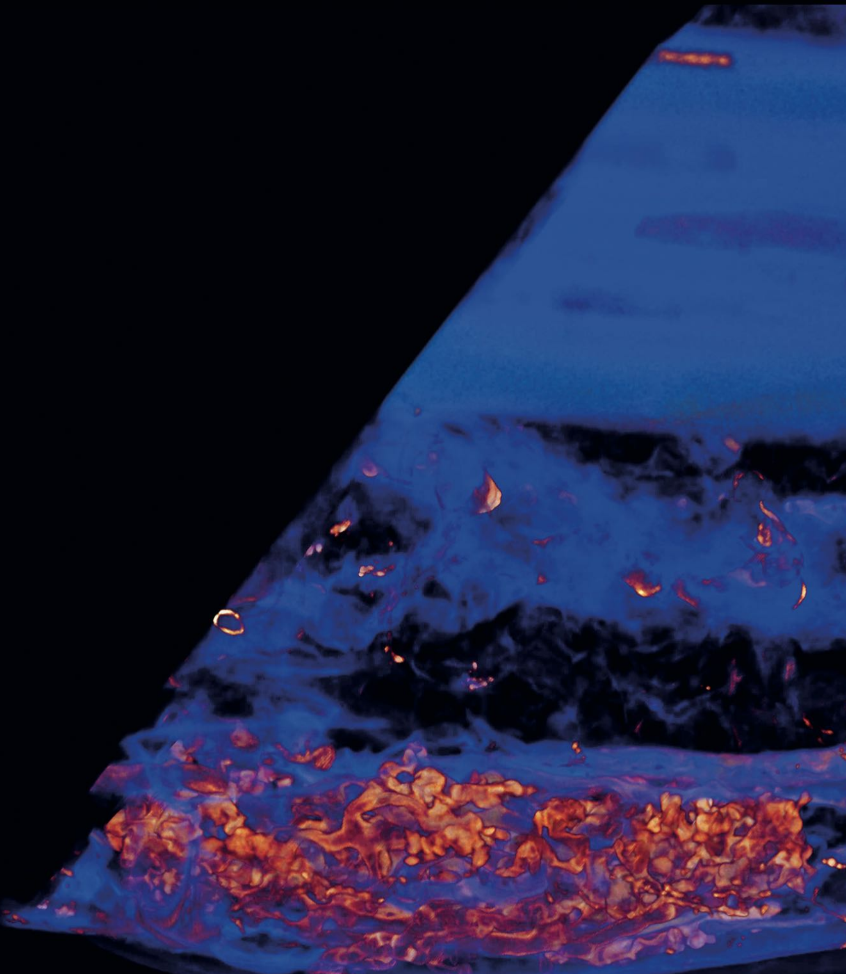
Root tip of *Voyria tenella*. The root systems of *Voyria* have evolved into fleshy fingers that serve as fungal 'gardens' or 'farms'. Most of these roots are about half a millimetre, or 500 micrometres (µm) in diameter.



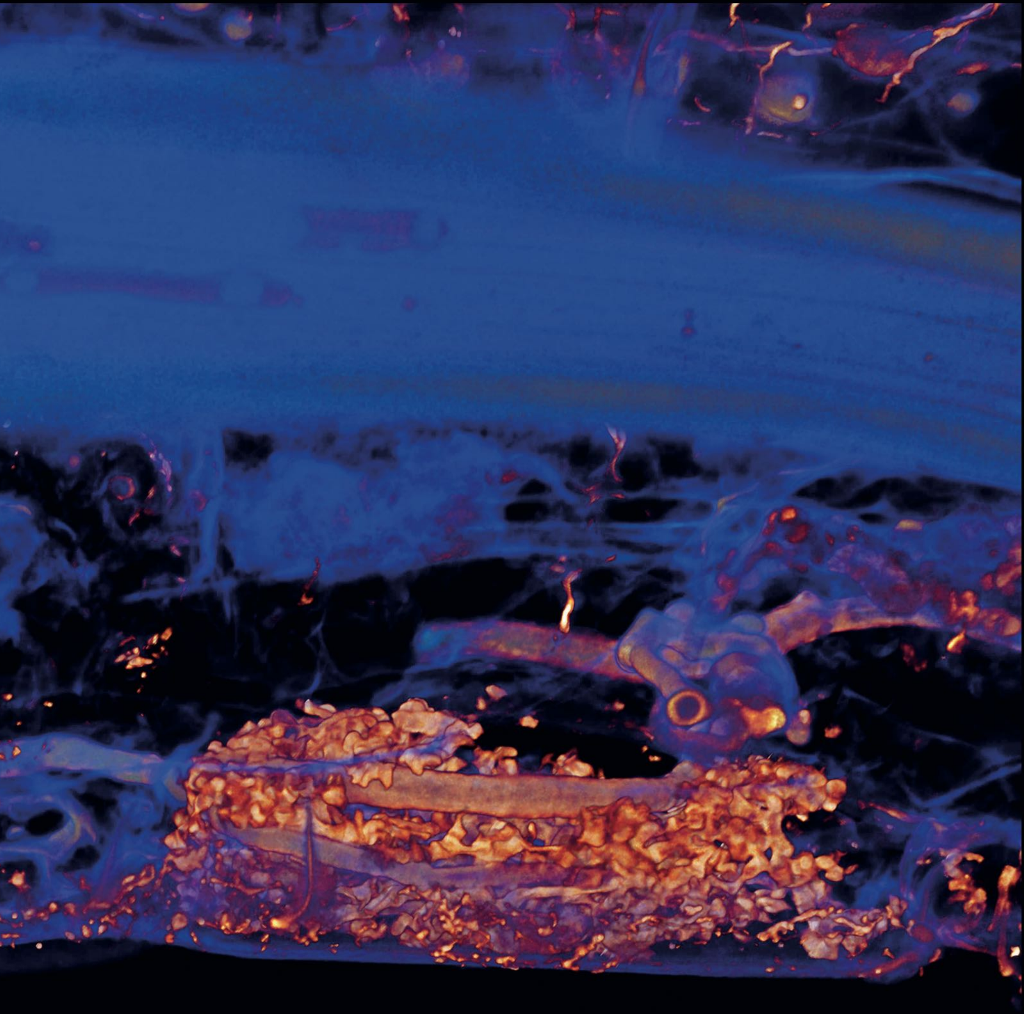
Root of *Voyria corymbosa*. You can see tubular fungal cells, or hyphae, extending out from the root into the space around the root, known as the rhizosphere. This is a rare glimpse of the connections that link plant roots with their surroundings.



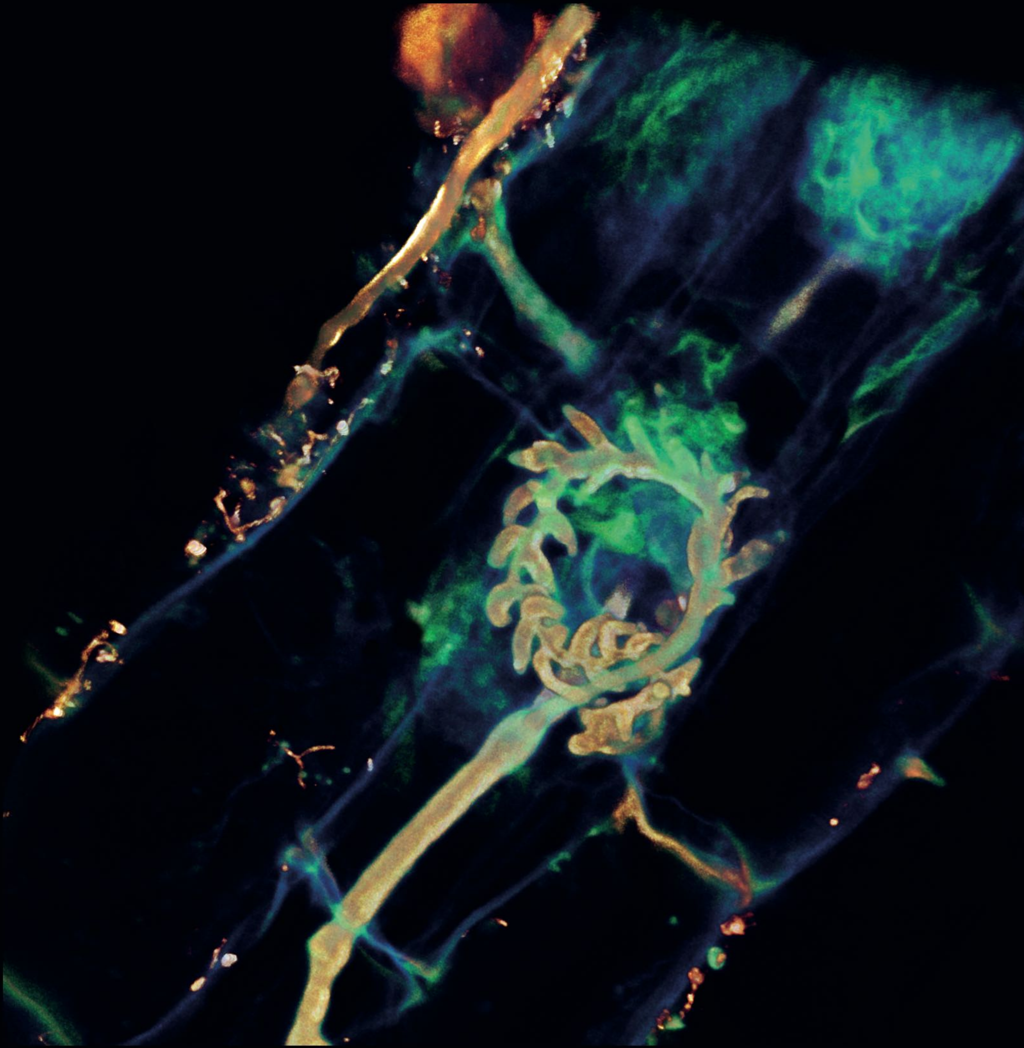
Root of *Voyria tenella*. Mycorrhizal relationships must be intricately managed. Fungi are confined to certain areas where the transfer of nutrients takes place.



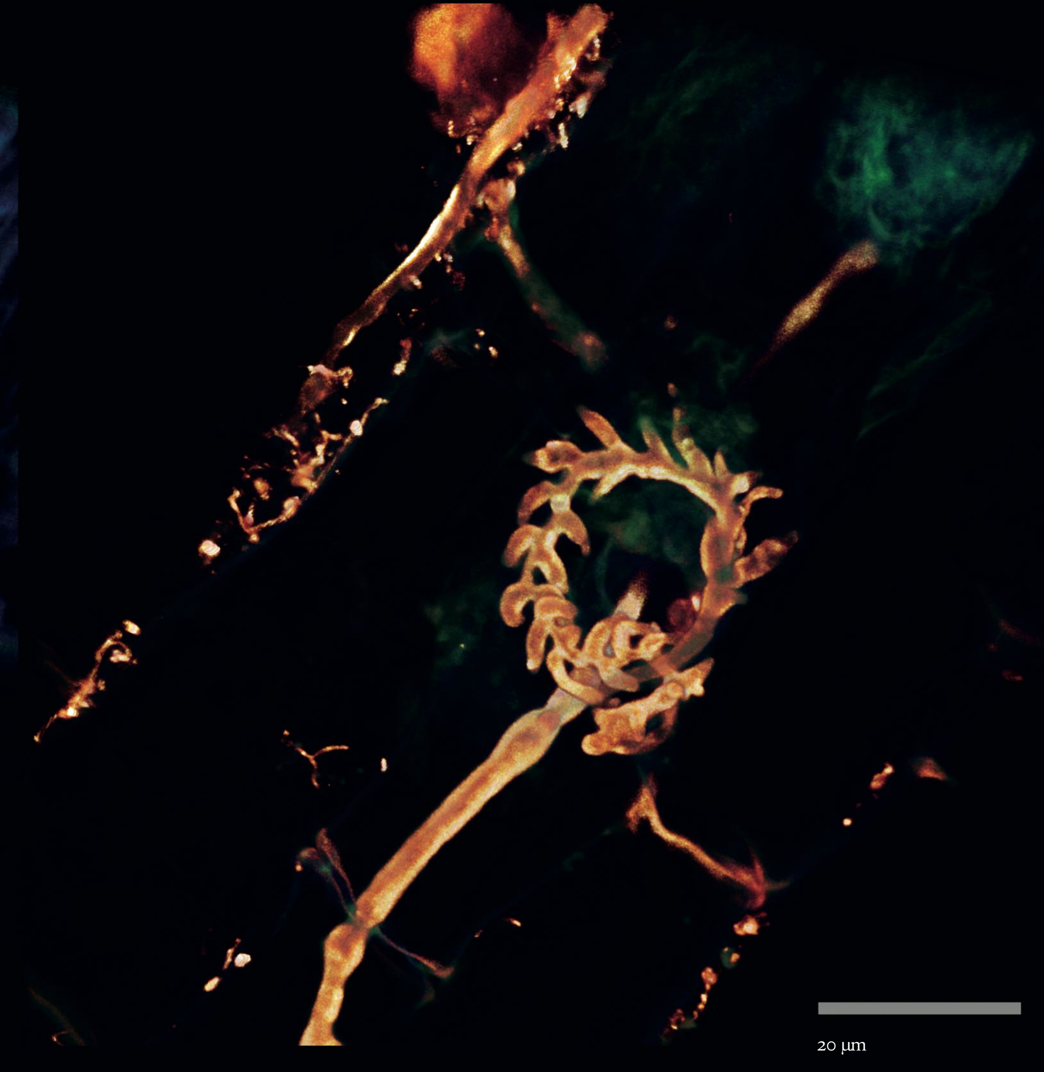
Section of *Gymnosiphon suaveolens* root. The organ of exchange between the fungus and *Gymnosiphon* is a branched structure, formed by the fungus, known as an arbuscule.

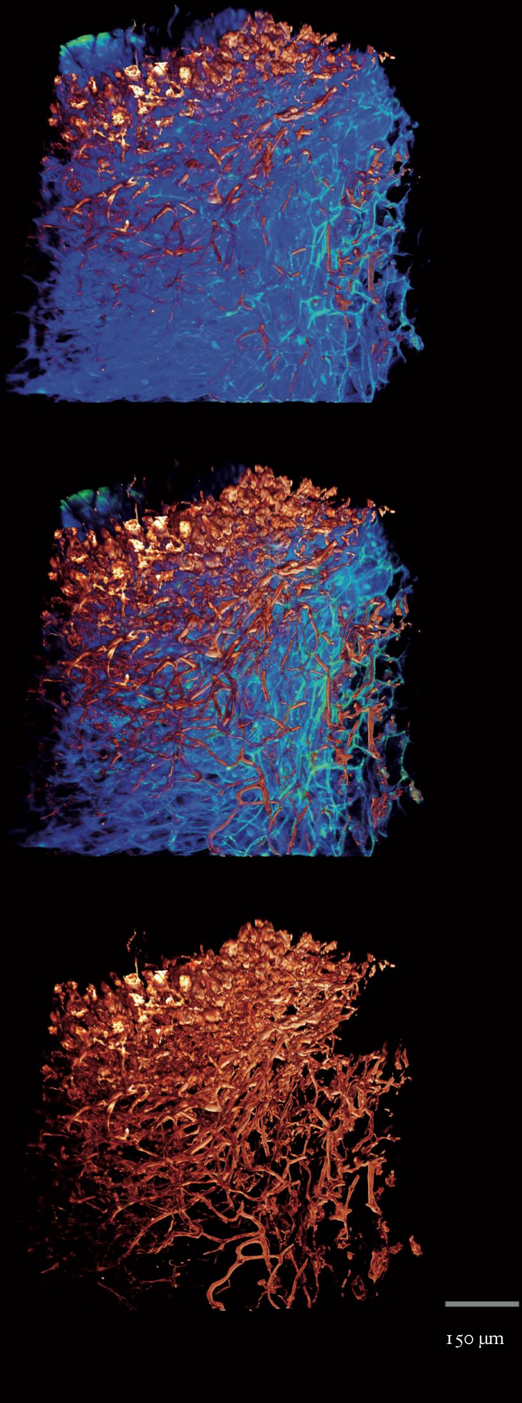


50 µm



Section of *Gymnosiphon suaveolens* root. This crown-like structure has never before been reported and its role is unknown.


20 µm



Section of *Voyria tenella* root. The different forms of the fungus within the root are clearly visible.