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EDITORIAL

Mycorrhizal mediation of sustainable development goals

1 | IT'S A MYCORRHIZAL WORLD

Mycorrhizas, the symbiotic associations formed between plant roots and certain groups of soil fungi, underpin many of the world's terrestrial ecosystems (Smith & Read, 2008). Their role as key interfaces between plant roots and the soil environment drives the movement of organic carbon and nutrients between the lithosphere and biosphere, underpinning the communities, habitats and ecosystems we see today. Mycorrhizal fungi play a critical part in the soil environment, not only in their role in channelling nutrients from the soil to their host plant but also through their physical presence as often vast, underground mycelial networks; binding soil particles together into aggregates and forming and maintaining the pore spaces in the soil that form critical microhabitats and reservoirs of below-ground water and air. Uniquely, mycorrhizal fungal hyphae can interconnect individual plants to form common mycorrhizal networks, which require us to think differently about how ecosystems function. There may even be scope to explicitly manage these networks to add value to the often-positive effects of mycorrhizal fungal colonisation on ecosystem function (**Alaux et al., 2021**).

Many mycorrhizal fungi form edible, often highly prized and culturally significant, mushrooms; the collection and consumption of which are important across human civilisation in terms of nutritional benefit, culture and economy (**Pérez-Moreno et al., 2021**). Mycorrhizas are also critical for the production of other high-value food crops including distinctive flavours such as vanilla (**Johnson et al., 2021**), as well as staple cereal crops (**Frew, 2021; Thirkell et al., 2021; Watts-Williams & Gilbert, 2021**). As such, the presence and functions of mycorrhizal fungi have important, albeit often overlooked, consequences for human societies ranging from the food we eat, the land we farm, the green spaces we enjoy and the biodiversity that underpins many essential ecosystem services, raw resources and medicines.

Earth's landscapes and climate are dynamic, but the rate of environmental change has increased exponentially since the invention of the combustion engine and the industrial revolution of the 1800s. Our reliance on fossil fuels for energy has driven huge increases in human productivity, powering changing industries, lifestyles, and increasing demands on and for resources from the natural environment. Together, these factors have driven an exponential rise in emissions and consequent environmental damage, powering unprecedented rates of change in global climate. Such changes are set to continue into the next century unless drastic and urgent action is taken to reduce anthropogenic CO_2 emissions, increase carbon sequestration and improve sustainability in all sectors (IPCC, 2021). Accordingly, there is increasing focus and political drive to implement sustainable technologies (**Brito et al., 2021; Cobb et al., 2021**) and practices to reduce, and even mitigate, human impacts on climate and the environment (**Verbruggen et al., 2021**). These aims are reflected globally in the United Nation's 17 Sustainable Development Goals. The application and exploitation of mycorrhizal fungi in soils has great potential to play an important part in these global efforts by improving host-plant access to soil nutrients and water, and by improving host-plant pest and disease resistance. Mycorrhiza-forming fungi may also have critical roles to play in conservation, remediation of contaminated land, and even enhancement of ecosystem functionality (**Alaux et al., 2021**). In order to successfully integrate mycorrhizal fungi into achieving these efforts, it is essential that the scientific community fully engage in stakeholder partnerships whereby key information and technologies can be shared (**Silva-Flores et al., 2021**).

This special issue, brought together during a time of unprecedented global change, represents a unique collection of papers that shed light on the current and future significance of mycorrhiza-forming fungi in the human world. Across this selection of papers, we explore the significance and potential of mycorrhizal fungi to contribute towards our achievement of global change goals of improved sustainability, food security and conservation as well as how we might best implement mycorrhizal knowledge and technologies to achieve these outcomes in modern societies.

2 | WHAT IS THE POTENTIAL FOR MYCORRHIZAL FUNGI IN IMPROVING SUSTAINABILITY?

Application and exploitation of mycorrhizal fungi in agricultural systems is the subject of much recent research on sustainability and food security. The papers in this special issue provide new insights into the potential for incorporation of mycorrhizal fungi into agricultural systems to address these critical goals. Usually, mycorrhizal approaches to sustainable agriculture are targeted and considered at either large-scale, industrial agricultural systems, or much smaller scale, smallholder or cottage garden systems. **Oviatt and Rillig (2021)** consider the application of mycorrhizal technologies to the important, yet often-overlooked, agricultural systems that fall in between these two extremes and are likely to represent key areas of impact.

While the role of mycorrhizal fungi in plant nutrient acquisition is reasonably well-documented in non-managed ecosystems, their role in crops and managed ecosystems is surprisingly sparse. This knowledge gap is explored across several papers within this issue, with the influence of interacting factors such as crop species (**Watts-Williams & Gilbert, 2021**), cultivar (**Elliott et al., 2021; Thirkell et al., 2021**), environment (**Tran et al., 2021a; Thirkell et al., 2021**) and fungal diversity (**Lee & Hawkes, 2021**) considered alongside the impacts and trade-offs that might be associated with mycorrhizal symbioses in landscapes managed for food and fuel (**Tran et al., 2021b**). The benefits of introducing mycorrhizal fungi as part of a sustainable approach to agriculture seem clear, with crops benefiting from enhanced access to soil N and P (**Watts-Williams & Gilbert, 2021**) as well as micronutrients and alleviation of stress resulting from soil contamination (**Neidhardt, 2021**).

In order to realise the potential benefits of mycorrhizas in agricultural landscapes, it is essential that the right tools and technologies are developed (**Brito et al., 2021**) alongside appropriate considerations towards the ecology of plant–fungal symbioses (**Lee & Hawkes, 2021**). One of the primary issues in effectiveness and deployment of mycorrhizas in agricultural systems is ensuring compatibility and efficacy in crop–mycorrhiza interactions. This concern requires exploration from multiple angles, from assessing and optimising the efficacy (**Elliott et al. 2021**) and applications (**Brito et al., 2021**) of commercially-available inocula in colonising crop roots and forming functional mycorrhizas that may improve crop nutrient uptake, biomass and defence against pests (**Frew, 2021**), to breeding new crop varieties with mycorrhiza-responsiveness as a key target trait (**Cobb et al., 2021**). These considerations should all be made with a view to counteracting previous years of selective breeding for traits that have inadvertently selected against mycorrhizal responsiveness, such as fungal resistance.

3 | CHANGING LAND USE AND MYCORRHIZAL-REMEDIATION

The majority of mycorrhizal fungi develop vast underground networks, linking plants within communities. Through these networks, soil nutrients flow; plant establishment and defence may be regulated across plant communities but mycorrhizal networks are rarely considered as management targets for improving plant performance and ecosystem services. However, as discussed above, there remain a number of barriers, highlighting the need for future research to consider common mycorrhizal networks in the promotion of mycorrhizas in sustainable soil management (**Alaux et al., 2021**).

The critical role of mycorrhizal fungi in the distribution and cycling of carbon and nutrient in terrestrial systems makes them key players in ecosystem structure and function, including those that are vulnerable to the effects of global climate change. Peatlands are important global carbon sinks but this ecosystem service is under threat from changing land use and climate, particularly warmer temperatures (**Defrenne et al., 2021**). Changing soil conditions, including pH and nutrient status, influence soil ecology and function with direct impacts on mycorrhizas. This response is particularly pertinent in managed ecosystems where disturbances, such as timber harvesting, dramatically affect the soil environment. This has large impacts on mycorrhizal fungal community structure and function with subsequent feedbacks on the wider ecosystem (**Burke et al., 2021**).

Changing lifestyles and increasing human population size place additional pressures on wild landscapes. Degradation and contamination of soils linked to human industry and leisure activities are critical environmental challenges that threaten biodiversity and ecosystem function. Through their role in mediating plant–soil interactions, mycorrhizal fungi may enhance plant assimilation of contaminants from the soil, with potential roles in remediation and restoration. Industry, such as mining and agri-chemical production, commonly generate soil-contaminating pollutants through various manufacturing processes. These contaminants are highly problematic given their high ecotoxicity and potential to enter and move through food webs. Arbuscular mycorrhizal fungi could play a key role in mobilising soil contaminants, facilitating their movement and sequestration into plant tissues. This ability appears to be linked to the identity of the fungi involved, paving the way for inoculants to improve phytoremediation of industrial soil contaminants (**Rosas-Moreno et al., 2021**).

4 | APPROACHES TO MYCORRHIZAL RESEARCH AND COMMUNICATION

Despite the exciting potential of mycorrhizal fungi in tackling challenges relating to global goals in sustainability, conservation and society, it is clear from the collection of papers in this special issue that significant challenges remain in the successful design and implementation of mycorrhizal technologies across all scales (**Brito et al., 2021; Oviatt & Rillig, 2021**).

One of the greatest constraints limiting research into mycorrhizal technologies is the mycorrhizal environment itself. By their very nature, mycorrhizal fungi and their impacts are challenging to study thanks to their underground growth habit and fine hyphal diameters, rendering them virtually invisible within the darkness of the soil environment. The applications of technologies such as mini-rhizotrons are likely to help improve our view into the rhizosphere and provide new insights into the responses of plants and mycorrhizal fungi to changes in environment (**Defrenne et al., 2021**).

The relative invisibility of mycorrhizal associations can also be problematic in communicating their potential benefits and importance to stakeholders and the general public. **McGaley and Paszkowski (2021)** provide a compelling case for wider sharing of mycorrhizal images amongst researchers and communicators, highlighting the potential such an approach might offer in terms of opportunities for engagement with these critical groups. Outreach and engagement will be an essential tool in communicating the potential for application of mycorrhizal fungi to global change challenges (**Silva-Flores et al., 2021**).

5 | MYCORRHIZAL CONSIDERATIONS FOR THE FUTURE

From this collection of papers, spanning many and varied applications of mycorrhizal ecology, technology and communication, it is clear that there is real potential for mycorrhizal fungi to help achieve UN Sustainable Development Goals (Keesstra et al., 2016) relating to sustainability, conservation and societal well-being. However, it is also clear that much remains to be done in order to fully realise these aims, ranging from improving our fundamental understanding of the diversity, ecology and function of mycorrhizal fungi, through to modes of communication to key stakeholder groups to ensure successful implementation.

KEYWORDS

agriculture, climate change, conservation, ecosystem services, mycorrhizas, remediation, society

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