IN FOCUS
https://doi.org/10.1071/MA23002
Microbiology Australia

Friends to the rescue: using arbuscular mycorrhizal fungi to future-proof Australian agriculture

Meike Katharina Heuck[A,*], Christina Birnbaum[B,C] and Adam Frew[A,C]

For full list of author affiliations and declarations see end of paper

*Correspondence to:
Meike Katharina Heuck
Hawkesbury Institute for the Environment, Western Sydney University, Locked Bag 1797, Penrith, NSW 2751, Australia
Email: m.heuck@westernsydney.edu.au

Received: 16 February 2023
Accepted: 27 February 2023
Published: 10 March 2023

Cite this:
Heuck MK *et al.* (2023)
Microbiology Australia
44(1), 5–8. doi:10.1071/MA23002

ABSTRACT

With a rising global population and the challenges of climate change, there is an increasing need to find solutions to maintain crop yields in an ecologically sustainable way. Although many studies have focussed on this issue, comparatively few are conducted in the southern hemisphere. This is worrisome because the geographical and geomorphological conditions within Australia differ greatly from the northern hemisphere. To ensure food security, approaches can rely on conventional agricultural methods as well as commercial arbuscular mycorrhizal (AM) fungal inoculants. Both approaches lack the capacity to be successful in the long term or could have unknown negative effects on the naturally occurring microbial communities. We advocate for a sustainable and holistic approach that combines the effective management of functionally diverse AM fungal communities with precision farming techniques while integrating landscape elements into agricultural fields. In addition, landowners and scientists should collaborate and communicate their work with industry and government to take forward the shift to a more-sustainable agriculture. In this way, we will be better able to secure our food production while restoring our soil ecosystems.

Keywords: arbuscular mycorrhizal fungi, Australia, conventional agriculture, food security, multifunctionality.

The agriculture which feeds us currently faces several formidable threats. Owing to population growth, we are required to produce more food in a reliable way.[1] Further compounding the issue is climate change that will cause longer droughts or extreme heat and will therefore likely reduce agricultural productivity.[2] The urgency to find solutions is reflected in the abundance of scientific papers published on the subject, which has considerably increased since 2005.[3]

In efforts to address these challenges, considerable attention has been given to the arbuscular mycorrhizal (AM) fungi. AM fungi are a group of soil organisms that are found in almost all terrestrial ecosystems and form a symbiotic relationship with ~80% of land plants.[4] AM fungi are widely recognised to have vast potential in sustainable agriculture as they can provide plants with water and nutrients, mainly phosphorus, and in return receive carbon in the form of sugars and lipids from their host plant.[4] Furthermore, AM fungi are functionally diverse and contribute to many important soil functions.[5] These include nutrient cycling,[6] reducing soil nutrient loss[7] and decomposition.[8] They also have the ability to increase plant resistance to biotic stressors such as herbivores and pathogens, as well as abiotic stressors including drought or high temperatures.[9,10]

Conventional farming techniques often include tillage as well as the use of synthetic fertilisers and pesticides. Although these methods can ensure high yield production in many contexts, they are becoming increasingly expensive and restricted in their use. Furthermore, they often have negative environmental impacts,[11] which include a reduced soil organic matter content, long-term soil acidification[12] as well as a negative effect on AM fungi (see Fig. 1).[13–15]

Soil acidification has been shown to reduce AM fungal diversity[16] and high soil fertility due to fertilisation can reduce plant dependency on the symbiosis with AM fungi, which may cause plants to lose the remaining benefits of symbiosis, such as pest and drought resistance. Furthermore, the use of certain pesticides can inhibit enzymatic pathways and stop the protein production of AM fungi.[17] Pesticides can also inhibit hyphal growth and thus several physiological processes including the uptake and transport of metabolites and nutrients between the fungus and the plant.[15] Additionally, common agricultural practices may shape the functional composition of AM fungi, for

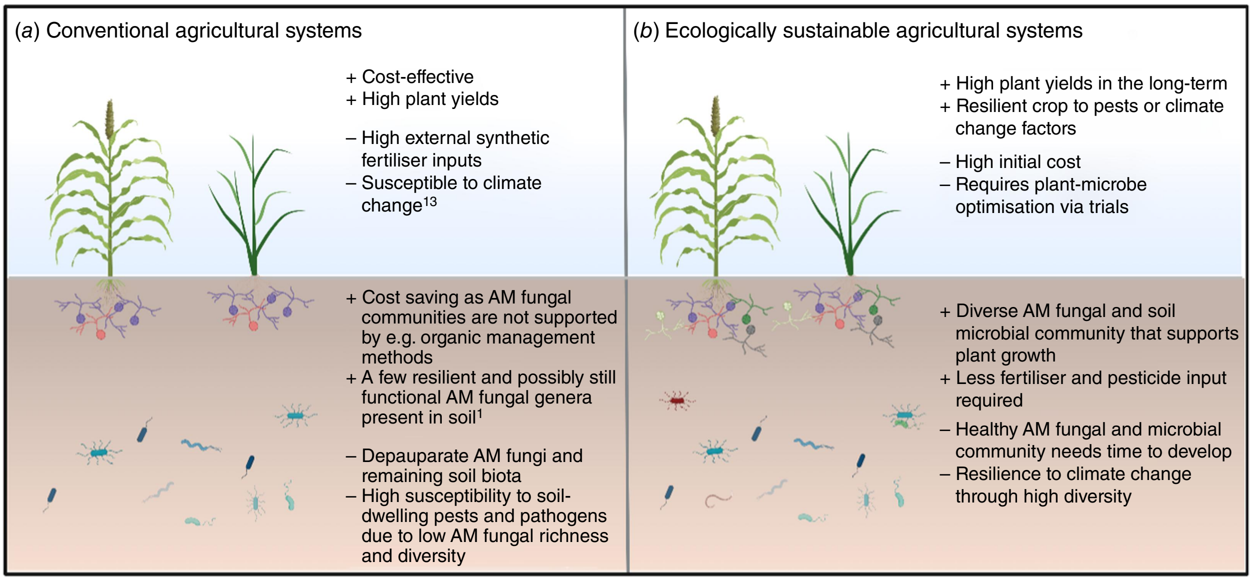

Fig. 1. Positive and negative effects of conventional (*a*) and ecologically sustainable (*b*) agriculture on plants and the soil microbial community. Created with BioRender.

example, it may select for taxa that are more-aggressive competitors for plant carbohydrates, resulting in a net cost to the plant.[18,19] Along with the use of synthetic fertilisers and pesticides, the tillage regime can disrupt the symbiosis between plants and the fungi. For example, tillage can physically disrupt plant access to the fungal network,[20] and bare fallow areas after tillage can leave AM fungi without a symbiotic partner and consequently the next generation of plants experiences lower colonisation rates.[21]

Moreover, the use of synthetic fertilisers and pesticides leaves residues in the soil that negatively affect AM fungi even for years after the field has been converted to a sustainable method. This is, for example, reflected in a lower rate of colonisation of the roots by the fungi.[15]

Notably, research focusing on AM fungi is mainly limited to the northern hemisphere.[22] This is concerning because the distinct geography and geomorphology of Australia hampers our ability to apply our current knowledge from the North to the Australian continent.

The climate in Australia is diverse, considering that the continent extends from 10° to 43°S, as well as being located between 153° and 113°E. Therefore, the climate ranges from arid to tropical and cool montane,[23] which, in conjunction with the bedrock, results in many different soil types and agricultural systems. Owing to Australia's history, a variety of agricultural methods were used in a reasonably short time, which is a contrast to the agricultural industrialisation history in Europe or Asia.[24] Before British colonisation of Australia, the soils were mainly used in a low-intensity way by the Indigenous peoples. This type of agriculture meant only small impacts on the nutrient cycles and low soil disturbance, and therefore was less disruptive to the natural ecosystem.[25] From 1800 onwards, the land was intensively used by the settlers and many native landscapes were converted into agricultural fields, which was mainly cultivated using conventional techniques.[26]

The constant degradation of the soil and thus, the negative impact on microorganisms is problematic, since Australia's soils generally have a low nutrient availability – phosphorus content being particularly emphasised here – because of the absence of glacial overprinting, and have a reasonably thin A horizon (topsoil).[27] Such characteristics only amplify the crucial need for adequate food security solutions that are suited to the Australian landscape.

A strategy that is employed in Australia and worldwide to address the adverse effects of conventional agriculture on soil organisms, including AM fungi, is to directly inoculate the soil with soil microbiota. Various distributors offer commercial AM fungal inoculants.[28] Providing access to such inoculants does advance greater awareness of the importance of soil microbiota and AM fungi to the public and practitioners. However, such inoculants typically contain a single fungal species, or a small group of cosmopolitan species.[29] As AM fungi are functionally diverse, it is unlikely that single species can provide the necessary functions that a more-diverse AM fungal community could offer.[30] Moreover, there is a risk that the species introduced into the soil will disrupt the naturally occurring community. If the introduced AM fungal species do not naturally occur in the local ecosystem, this may have unintended consequences and even displace the native community, jeopardising soil health in the long run.[31] However, there is insufficient evidence to show that an introduced species will be able to persist in a new environment, one that presumably already has an established AM fungal community.[32] Furthermore, the viability of the inoculants currently available is questionable as a recent study demonstrated, showing that most of the tested Australian inoculants failed to support mycorrhizal root colonisation, although most of these inoculants contain AM fungal species known to colonise a broad range of host plants and soil types.[28]

The aforementioned issues highlight that we need to keep our crop yields high in the long term while simultaneously establishing healthy soil ecosystems. Therefore, we propose an ecologically sustainable and holistic approach. Since AM fungal communities are functionally diverse and may assume partially similar roles of pesticides and fertilisers, the approach involves supporting the local, naturally occurring, AM fungal communities. Emam found that live soil inoculum containing the original AM fungal community is more effective at supporting plant growth than using a commercial inoculum.[33] The notion that live soil inoculum is more effective has also been shown for plant resistance to pests.[34] Given the extensive diversity of soil types in Australia and their generally limited nutrient availability, it is essential to adopt site-specific management solutions to promote ecologically sustainable agriculture. We need to shift from methods motivated by short term productivity to broader incorporation of ecological indicators of sustainable agricultural functioning, exploiting the potential benefits of soil microorganisms as effectively as possible in a way that can significantly reduce the need for synthetic inputs.

Conventional farming practices have been critical in food security and ensuring livelihoods of people around the world and in Australia. We recognise that for many, working with a focus on soil ecology is not feasible due to barriers such as costs or accessibility. Despite being a world leader in organic agriculture in terms of the area certified between 2000 and 2018, only 8.8% of Australia's agricultural land is certified as organic.[35] To encourage adoption of organic agriculture in Australia, the government could take several steps, including: enhancing information dissemination through research and extension services, developing more effective market-based tools for environmental performance, and addressing the current institutional bias against organic agriculture.[36] Where possible, we also suggest broader accessibility to technologies such as precision farming, an approach that analyses specific crop needs by using *inter alia* remote sensing and GPS. With this approach, it is possible to apply fertilisers in small doses as required by the crops,[37] which may mitigate any negative effects on the mycorrhizal symbiosis. Furthermore, the integration of landscape elements such as small forest patches, field margins or hedgerows as well as cover crops can be beneficial. These not only serve as a biodiversity pool for AM fungi and other soil microorganisms, but also protect the soil from erosion.[21,38] Moving away from monocultures could also be an important method, as polycultures have been shown to double AM fungal richness.[39]

For a rapid rethink in agriculture, we suggest scientists work together synergistically with industry and farmers to deliver healthier soils that will support plant growth while reducing costly external inputs. On one hand, it will be important to map and successfully monitor AM fungi across agroecosystems in Australia, which is currently being undertaken by a national research project called DigUpDirt (see https://www.digupdirt.net/). On the other hand, it is increasingly important to test the effect of resident AM fungal species on crops and how this differs between AM fungi derived from different management practices. We encourage scientists to communicate their work with the industry and respond to needs of the farming community. Close collaboration and knowledge sharing between scientists and land managers is what is needed to advance the shift to sustainable agriculture.

References

1. Godfray HCJ *et al.* (2010) Food security: the challenge of feeding 9 billion people. *Science* **327**, 812–818. doi:10.1126/science.1185383
2. Malhi GS *et al.* (2021) Impact of climate change on agriculture and its mitigation strategies: a review. *Sustainability* **13**, 1318. doi:10.3390/su13031318
3. Skaf L *et al.* (2020) Applying network analysis to explore the global scientific literature on food security. *Ecol Inform* **56**, 101062. doi:10.1016/j.ecoinf.2020.101062
4. Smith SE, Read DJ (2008) *Mycorrhizal symbiosis*. Academic Press.
5. Powell JR, Rillig MC (2018) Biodiversity of arbuscular mycorrhizal fungi and ecosystem function. *New Phytol* **220**, 1059–1075. doi:10.1111/nph.15119
6. Phillips RP *et al.* (2013) The mycorrhizal-associated nutrient economy: a new framework for predicting carbon–nutrient couplings in temperate forests. *New Phytol* **199**, 41–51. doi:10.1111/nph.12221
7. Cavagnaro TR *et al.* (2015) The role of arbuscular mycorrhizas in reducing soil nutrient loss. *Trends Plant Sci* **20**, 283–290. doi:10.1016/j.tplants.2015.03.004
8. Taylor MK *et al.* (2016) Mycorrhizal associations of trees have different indirect effects on organic matter decomposition. *J Ecol* **104**, 1576–1584. doi:10.1111/1365-2745.12629
9. Chourasiya D *et al.* (2021) Unraveling the AM fungal community for understanding its ecosystem resilience to changed climate in agroecosystems. *Symbiosis* **84**, 295–310. doi:10.1007/s13199-021-00761-9
10. Frew A *et al.* (2022) Plant herbivore protection by arbuscular mycorrhizas: a role for fungal diversity? *New Phytol* **233**, 1022–1031. doi:10.1111/nph.17781
11. Gomiero T *et al.* (2008) Energy and environmental issues in organic and conventional agriculture. *Crit Rev Plant Sci* **27**, 239–254. doi:10.1080/07352680802225456
12. Geisseler D, Scow KM (2014) Long-term effects of mineral fertilizers on soil microorganisms – a review. *Soil Biol Biochem* **75**, 54–63. doi:10.1016/j.soilbio.2014.03.023
13. Altieri MA *et al.* (2015) Agroecology and the design of climate change-resilient farming systems. *Agron Sustain Dev* **35**, 869–890. doi:10.1007/s13593-015-0285-2
14. Ryan MH, Graham JH (2018) Little evidence that farmers should consider abundance or diversity of arbuscular mycorrhizal fungi when managing crops. *New Phytol* **220**, 1092–1107. doi:10.1111/nph.15308
15. Riedo J *et al.* (2021) Widespread occurrence of pesticides in organically managed agricultural soils—the ghost of a conventional agricultural past? *Environ Sci Technol* **55**, 2919–2928. doi:10.1021/acs.est.0c06405
16. Liu Y *et al.* (2015) Phylogenetic structure of arbuscular mycorrhizal community shifts in response to increasing soil fertility. *Soil Biol Biochem* **89**, 196–205. doi:10.1016/j.soilbio.2015.07.007
17. Karpouzas DG *et al.* (2014) Effects of nicosulfuron on the abundance and diversity of arbuscular mycorrhizal fungi used as indicators of pesticide soil microbial toxicity. *Ecol Indic* **39**, 44–53. doi:10.1016/j.ecolind.2013.12.004
18. Johnson NC (2010) Resource stoichiometry elucidates the structure and function of arbuscular mycorrhizas across scales. *New Phytol* **185**, 631–647. doi:10.1111/j.1469-8137.2009.03110.x
19. Thirkell TJ *et al.* (2017) Are mycorrhizal fungi our sustainable saviours? Considerations for achieving food security. *J Ecol* **105**, 921–929. doi:10.1111/1365-2745.12788
20. Kabir Z (2005) Tillage or no-tillage: impact on mycorrhizae. *Can J Plant Sci* **85**, 23–29. doi:10.4141/P03-160
21. Bowles TM *et al.* (2017) Ecological intensification and arbuscular mycorrhizas: a meta-analysis of tillage and cover crop effects. *J Appl Ecol* **54**, 1785–1793. doi:10.1111/1365-2664.12815
22. Cotton TA (2018) Arbuscular mycorrhizal fungal communities and global change: an uncertain future. *FEMS Microbiol Ecol* **94**, fiy179. doi:10.1093/femsec/fiy179
23. Kottek M *et al.* (2006) World Map of the Köppen–Geiger climate classification updated. *Meteorol Z* **15**, 259–263. doi:10.1127/0941-2948/2006/0130
24. Klein Goldewijk K, Ramankutty N (2004) Land cover change over the last three centuries due to human activities: the availability of new global data sets. *GeoJournal* **61**, 335–344. doi:10.1007/s10708-004-5050-z
25. Paterson A (2018) Once were foragers: the archaeology of agrarian Australia and the fate of Aboriginal land management. *Quat Int* **489**, 4–16. doi:10.1016/j.quaint.2016.12.047

26. Dolling PJ *et al.* (2001) *Soil acidity and acidification*. National Land and Water Resources Audit, Commonwealth of Australia.
27. Hopper SD (2009) OCBIL theory: towards an integrated understanding of the evolution, ecology and conservation of biodiversity on old, climatically buffered, infertile landscapes. *Plant Soil* **322**, 49–86. doi:10.1007/s11104-009-0068-0
28. Salomon MJ *et al.* (2022) Global evaluation of commercial arbuscular mycorrhizal inoculants under greenhouse and field conditions. *Appl Soil Ecol* **169**, 104225. doi:10.1016/j.apsoil.2021.104225
29. Elliott AJ *et al.* (2021) A commercial arbuscular mycorrhizal inoculum increases root colonization across wheat cultivars but does not increase assimilation of mycorrhiza-acquired nutrients. *Plants People Planet* **3**, 588–599. doi:10.1002/ppp3.10094
30. Frew A (2021) Contrasting effects of commercial and native arbuscular mycorrhizal fungal inoculants on plant biomass allocation, nutrients, and phenolics. *Plants People Planet* **3**, 536–540. doi:10.1002/ppp3.10128
31. Schwartz MW *et al.* (2006) The promise and the potential consequences of the global transport of mycorrhizal fungal inoculum. *Ecol Lett* **9**, 501–515. doi:10.1111/j.1461-0248.2006.00910.x
32. Singh JS (2015) Microbes: the chief ecological engineers in reinstating equilibrium in degraded ecosystems. *Agric Ecosyst Environ* **203**, 80–82. doi:10.1016/j.agee.2015.01.026
33. Emam T (2016) Local soil, but not commercial AMF inoculum, increases native and non-native grass growth at a mine restoration site: soil inoculum type and method affect restoration. *Restor Ecol* **24**, 35–44. doi:10.1111/rec.12287
34. Frew A, Wilson BAL (2021) Different mycorrhizal fungal communities differentially affect plant phenolic-based resistance to insect herbivory. *Rhizosphere* **19**, 100365. doi:10.1016/j.rhisph.2021.100365
35. Paull J, Henning B (2018) Maps of organic agriculture in Australia. *J Org* **5**, 29–39.
36. Wheeler S (2011) Review of organic farming policy in Australia: time to wipe the slate clean? *J Sustain Agric* **35**, 885–913. doi:10.1080/10440046.2011.604119
37. Pandey H *et al.* (2021) Precision farming and its application. In *Smart Agriculture Automation Using Advanced Technologies* (Choudhury A, Biswas A, Singh TP, Ghosh SK, eds). pp. 17–33. Springer, Singapore. doi:10.1007/978-981-16-6124-2_2
38. González Fradejas G *et al.* (2022) Hedgerows increase the diversity and modify the composition of arbuscular mycorrhizal fungi in Mediterranean agricultural landscapes. *Mycorrhiza* **32**, 397–407. doi:10.1007/s00572-022-01090-5
39. Guzman A *et al.* (2021) Crop diversity enriches arbuscular mycorrhizal fungal communities in an intensive agricultural landscape. *New Phytol* **231**, 447–459. doi:10.1111/nph.17306

Data availability. Data sharing is not applicable as no new data were generated or analysed during this study.

Conflicts of interest. The authors declare that they have no conflicts of interest.

Declaration of funding. M. K. Heuck and A. Frew acknowledge funding from the Australian Research Council (DE220100479).

Acknowledgements. We thank the reviewers for providing helpful suggestions and improvement.

Author affiliations

[A]Hawkesbury Institute for the Environment, Western Sydney University, Locked Bag 1797, Penrith, NSW 2751, Australia.

[B]School of Agriculture and Environmental Science, University of Southern Queensland, Toowoomba, Qld 4350, Australia.

[C]Centre for Crop Health, University of Southern Queensland, Toowoomba, Qld 4370, Australia.

Biographies

Meike Katharina Heuck is a PhD candidate at the Western Sydney University and passionate about food security in times of climate change. Her main focus is the interaction between arbuscular mycorrhizal fungi and plants to facilitate a sustainable agriculture.

Dr Christina Birnbaum is a lecturer in terrestrial ecology at the University of Southern Queensland. She uses field observations, combined with experimental manipulations and molecular tools to explore questions pertaining plant–microbe interactions to inform invasive plant species management, restoration ecology and plant–microbial dynamics.

Dr Adam Frew is a Lecturer and ARC DECRA fellow at the Hawkesbury Institute for the Environment and Adjunct Senior Research Fellow at the University of Southern Queensland. His research explores interactions between soil microbiota and plants, and how these relationships interact with herbivory.