

# *Mycorrhizae for a sustainable world*

Article

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1 **Mycorrhizae for a sustainable world**  
2 **The 10<sup>th</sup> International Conference on Mycorrhiza (ICOM10), Mérida, Mexico, June 30 –**  
3 **July 5 2019**

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27 mycorrhiza, conservation

28  
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30 **Meeting report**

31  
32 More than 80% of plant species exchange resources with mycorrhizal fungi and these  
33 associations impact both partners at multiple scales, from individuals to ecosystems. 172  
34 participants from 33 countries and 160 institutions met at the 10<sup>th</sup> International Conference on  
35 Mycorrhiza in the city of Mérida in the Yucatan peninsula in Mexico – an area famous for its  
36 Mayan archaeological sites, cenotes, and the Chicxulub impact crater that marks the end of the  
37 Cretaceous period. They discussed latest advances on mycorrhizal research across 125 talks  
38 and 111 posters in 14 sessions focused on the biology, physiology, ecology, evolution and  
39 conservation of these interactions from molecules to biomes (Fig. 1). In particular, the  
40 contribution of mycorrhizal research to sustainability in agriculture, conservation and  
41 ecosystem restoration (Fig. 2) emerged as a promising topic to address today’s challenges in  
42 the realm of human population growth, globalization and climate change.

43  
44 **1. Sustainability in agriculture (managed ecosystems)**

45  
46 Several speakers discussed the increasing abundance of commercial arbuscular mycorrhizal  
47 products for agriculture, from “biofertilisers” to advances in seed coating technology (i.e.  
48 adding mycorrhizal fungal spores directly to seeds along with nutrients and plant-helper  
49 bacteria), and the interest in these products from growers.

50  
51 A noticeable recurring theme was that commercial biofertilisers make rather dramatic claims  
52 about their effectiveness, without evidence of their application leading to direct improvements  
53 in crop yield or nutrition. Jan Jansa (Czech Academy of Sciences, Prague, Czech Rep.)’s  
54 keynote presentation made the point that biofertilisers do not *create* nutrients per se; however,  
55 they may help plants to access existing nutrient sources, and may provide non-nutritional  
56 benefits. Examples of non-nutritional mycorrhizal benefits include increased soil glomalin  
57 inputs, tolerance of microplastics inputs, and alteration of the soil microbiome (Svenningsen *et*  
58 *al.*, 2018; de Souza Machado *et al.*, 2019; Hestrin *et al.*, 2019). Marcel van der Heijden  
59 (Agroscope, Zurich, Switzerland) and Ashleigh Elliott (University of Leeds, Leeds, UK)  
60 presented data on the application of commercial inoculants in field and glasshouse trials; crops  
61 grown with a commercial arbuscular mycorrhizal (AM) fungal inoculant exhibited higher root  
62 colonisation but there were few benefits to growth. Notably, the quality (in terms of active AM  
63 fungal propagules) and effectiveness of different commercial products was highly variable.

64 Miranda Hart (University of British Columbia, Kelowna, Canada) made the case that the  
65 variable responses of AM fungal inoculum in field trials are like those observed in the case of  
66 plant species invasions (Thomsen & Hart, 2018), and that current practices were too focused on  
67 establishing the most vigorous AM fungi. Some important questions arose from the workshop  
68 discussion on the topic: how can we, as a research community, contribute to ensuring that  
69 mycorrhizal fungal inoculum products are a) appropriate, e.g. are we selecting the most  
70 suitable fungi for a given system, rather than good invaders?; and b) successful, e.g. would a  
71 “certificate of effectiveness” be required?

72  
73 In terms of alternative approaches to agriculture, Rillig & Lehmann (2019) identified  
74 approximately 285,000 combinations of agricultural practices. In his keynote, Jan Jansa  
75 emphasised the need to rigorously quantify the AM symbiosis and its effects in the field, to  
76 enable the production of equations and models that make useful predictions, so that we can  
77 best make use of the AM symbiosis as a valuable biological resource. Jansa also highlighted  
78 the potential to look further down the production chain not only to crop productivity but to the  
79 quality of the food product (e.g. do mycorrhizas affect food nutritional content, taste, or  
80 spoilage), such as lowered pest impacts, postharvest disease reduction, and thus reduction of  
81 food waste (e.g. AM fungi for food security).

82

## 83 **2. Sustainability in conservation and restoration (natural ecosystems)**

84

85 Effective use of the mycorrhizal symbiosis for restoration and conservation requires a deeper  
86 understanding of mycorrhizal functionality and related ecosystem processes, and how these  
87 processes and functions are altered through interactions with other actors and changing  
88 conditions. For instance, several talks (e.g. Heike Bücking, South Dakota State University,  
89 Brookings, USA; Ricardo Arraiano Castilho, Kew Gardens, London, UK) highlighted the  
90 importance of local soil factors and host nutrient demand in shaping mycorrhizal fungal  
91 communities, and whether changes in local environmental conditions associated with climate  
92 change (i.e. drought) or nutrient deposition (i.e. soil fertility) may disrupt the structure of these  
93 communities. Many speakers discussed the contribution of mycorrhizas in low impact,  
94 sustainable approaches to ecosystem restoration (e.g. Brian Pickles, University of Reading,  
95 Reading, UK; Cameron Egan, University of Hawai‘i, Mānoa, USA) and species conservation  
96 (e.g. Nicole Hynson, University of Hawai‘i, Mānoa, USA; Louise Egerton-Warburton,  
97 Chicago Botanic Garden, Glencoe, USA). Still, other mechanisms related to the activities of

98 mycorrhizal fungi, such as carbon sequestration (i.e. priming effect discussed by María Pozo,  
99 EEZ-CSIC, Granada, Spain; and Johanna Pausch, University of Bayreuth, Bayreuth, Germany)  
100 or the outcome of interactions among important actors, such as signaling pathways for kin  
101 recognition (e.g. Monika Gorzelak, Agriculture and Agri-Food Canada, Lethbridge, Canada),  
102 need to be accounted for when considering mycorrhizal applications in conservation and  
103 ecosystem restoration.

104  
105 A key theme is that different ecosystems may well need different approaches (i.e. there is no  
106 “silver bullet” for restoration or conservation). For example, Louise Egerton-Warburton found  
107 that “cedar” (*Widdringtonii wrighteii*) seedlings grew well in nursery conditions but  
108 experienced drastic mortality following transfer to the field in Malawi. In turn, Nicole Hynson  
109 and Cameron Egan’s work showed that incomplete recovery of Hawaiian native fungal  
110 communities following successful growth of planted native host trees may compromise forest  
111 restoration. However, the presence of diverse mycorrhizal fungal communities is not the only  
112 requirement for a successful restoration plan. For instance, when comparing the performance of  
113 AM fungal species on high- and low-quality (determined by associated fungal biomass) native  
114 plant hosts in tallgrass prairie, Ylva Lekberg (MPG Ranch, Missoula, USA) found that AM  
115 fungal identity and abundance influenced plant performance, while AM fungal species  
116 diversity was unimportant in this regard. Similar results were found in a successional plant-  
117 feedback study where only the appropriate late successional AM fungi with their corresponding  
118 plant species grew faster and larger (Koziol & Bever, 2019). In the North American Southwest,  
119 Catherine (Kitty) Gehring (Northern Arizona University, Flagstaff, USA) found that  
120 intraspecific drought tolerance of pinyon pine was strongly associated with root-colonising  
121 ECM fungal species composition. Here, drought-tolerant pinyons tended to associate with  
122 *Geospora* spp., which increased water flow velocity in drought-tolerant seedling lineages and  
123 reduced it in intolerant lineages. A related study revealed that after successive droughts, ECM  
124 fungal species composition and abundance in roots of pinyon pines were responsive to tree  
125 mortality, with *Geospora* increasing and *Tuber* spp. decreasing in response to pine death  
126 (Mueller *et al.*, 2019). These studies indicate that the identity of mycorrhizal fungi and their  
127 interaction with certain host traits are critical for achieving restoration aims.

128

### 129 **3. Advances in mycorrhizal research with sustainability applications**

130

131 Understanding patterns of plant mycorrhizal type dominance, for instance in highly protected  
132 and valuable ecosystems, is key to understanding many ecosystem processes and their  
133 dynamics, and hence predicting limiting factors and environmental risks. In his keynote  
134 presentation, Richard Phillips (Indiana University, Bloomington, USA) presented a plethora of  
135 works describing differences in functioning between forests dominated by AM and ECM trees  
136 in similar climatic conditions (e.g. Zhang *et al.*, 2018). It had long been hypothesised that  
137 ECM-dominated forests accumulate more soil carbon, due in part to visibly greater production  
138 of recalcitrant organic matter. Yet when soils from ECM- and AM-dominated forests in  
139 proximity were compared to a depth of 1 m, greater accumulation of soil organic matter was  
140 found in AM-dominated forests (Craig *et al.*, 2018). Several talks presented at ICOM10  
141 highlighted how processes such as C storage, soil enzymatic activities, nutrient cycling, and  
142 ecosystem-level sensitivity to global changes may vary (in part) because of mycorrhizal  
143 interactions (e.g. Haley Dunleavy Northern Arizona University, Flagstaff, USA; Tom Thirkell,  
144 University of Leeds, Leeds, UK; Melanie Jones, University of British Columbia, Kelowna,  
145 Canada). These results clearly stress the need to consider how the dominance of different  
146 mycorrhizal types may impact ecosystem function, and the consequences of host changes for  
147 broader ecosystem dynamics, management, and restoration. Nonetheless, subdominant plant  
148 species such as herbs and grasses in the forest understory can also play significant roles in  
149 ecosystems. For example, Rebecca Bunn (Western Washington University, Bellingham, USA)  
150 revisited the ‘direct mineral cycling hypothesis’ from the 1960’s and showed that AM fungal  
151 hyphae are active in forest leaf litter through cooperation with other microorganisms (e.g. Lin  
152 Zhang, China Agricultural University, Beijing, China), even in ecosystems dominated by ECM  
153 trees (Bunn *et al.* 2019). Despite these recent advances in using plant mycorrhizal type to  
154 investigate ecosystem processes, distinguishing between the plant mycorrhizal types (such as  
155 AM, ECM, or dual AM and ECM) is not always easily solved and different approaches coexist  
156 (Brundrett & Tedersoo, 2019; Bueno *et al.* 2019). ICOM10 facilitated an interesting debate in  
157 this respect, discussing possibilities for merging functional, morphological, and experimental  
158 approaches to tackle this important issue.

159  
160 Studies of the functions of symbioses in the presence of their closest neighbours are also  
161 warranted. Marco Cosme (Université Catholique de Louvain, Louvain-la-Neuve, Belgium)  
162 illustrated the role that mycorrhizal fungi can play in ‘non-mycorrhizal’ plant functional  
163 responses, in which a presumed non-host species (*Arabidopsis thaliana*) in the presence of a  
164 mycorrhizal plant (*Medicago truncatula* colonised by the AM fungus *Rhizophagus* sp.)

165 exhibited root cortex colonisation. No nutrient exchange (via arbuscules) was observed, but the  
166 non-host plant exhibited activation of AM fungal-induced resistance to pathogens (Fernández  
167 *et al.*, 2019), indicating a functionally beneficial colonisation of the presumed non-host  
168 species. All in all, examining the multifunctional effects of the entire root mycobiome,  
169 including non-mycorrhizal and “fine root endophyte” fungi (Hoysted *et al.*, 2019) across  
170 plants, may be crucial to predicting the effect of global changes in natural and managed  
171 ecosystems.

172

#### 173 **4. Challenges**

174 During the conference, key challenges facing mycorrhizal research (and researchers) in the  
175 coming decades were addressed:

176

##### 177 *Global change*

178 Mycorrhizal symbioses are already highly complex, so how do we decipher mycorrhizal effects  
179 in systems subjected to multiple simultaneous pressures? Many speakers discussed  
180 mycorrhizal responses to climate change impacts such as drought, fire, and insect outbreaks  
181 (e.g. Philip Brailey, University of York, York, UK; Jean Carlos Rodríguez-Ramos, University  
182 of Alberta, Edmonton, Canada; Yong Zheng, Fujian Normal University, Fuzhou, China).

183 Restoration of ecosystems exposed to pollutants (e.g. microplastics) was another common  
184 theme, as exemplified by Matthias Rillig (Freie Universität Berlin, Berlin, Germany)’s keynote  
185 talk. Species introductions of exotic fungi and/or exotic hosts are another important topic that  
186 potentially leads to fungal invasions. For example, global patterns in native vs introduced  
187 island floras revealed a strong tendency towards introduced mycorrhizal plants compared to  
188 non-mycorrhizal natives (Delavaux *et al.*, 2019), with some notable exceptions to the general  
189 pattern (e.g. Hawaii). Anne Pringle (University of Wisconsin-Madison, Madison, USA)’s  
190 research on *Amanita muscaria* (fly agaric) invasions in North America revealed that the  
191 population structure of this invasive fungus differed dramatically compared to its native range.  
192 The interactive effects of global change processes on mycorrhizal fungi and their hosts will  
193 undoubtedly provoke significant research effort from the mycorrhizal research community.

194

##### 195 *Methodological issues and advances*

196 Although this topic is not new, finding ecologically relevant control for, and measurement of,  
197 the mycorrhizal status of plants is still controversial. Is “non-mycorrhizal” really an appropriate  
198 control condition for plants, given the prevalence of mycorrhizal fungi in natural and



199 anthropogenic ecosystems (i.e., plants without mycorrhizal symbionts are rare), or would  
200 severing/restricting common mycorrhizal networks be more relevant experimental control (e.g.  
201 David Johnson, University of Manchester, Manchester, UK)?

202  
203 The advent of modern high-throughput plant phenotyping systems has allowed us to begin  
204 characterising mycorrhizal host plant (shoot) growth responses (positive through to negative)  
205 over time (Watts-Williams *et al.*, 2019), rather than just at the harvest time point. This  
206 technology will be especially useful when it extends to root phenotyping platforms that allow  
207 for high resolution screening, and analysis of the effects of mycorrhizal fungi on root growth  
208 and morphology over time.

209  
210 Several issues remain unresolved among the continual technological advances used for  
211 molecular work and interpretation of those data, as sequencing of mycorrhizal fungal  
212 communities becomes more commonplace. As Annegret Kohler (INRA, Nancy, France)'s  
213 keynote talk asked: What does gene copy number mean in terms of function? What does  
214 sequence abundance really mean in terms of species abundances? Many researchers  
215 uncritically present sequence abundances from NGS platforms as if they were equivalent to  
216 species relative abundances, although the ecological relevance of sequence abundance data  
217 needs to be cautiously addressed within the mycorrhizal (Nguyen *et al.*, 2015) and wider  
218 microbiome (Gloor *et al.*, 2017) research communities. Clearly, there needs to be more care  
219 with the use of metagenomic data and this may prove to be a suitable topic for a discussion  
220 session at a future ICOM.

221

## 222 **Acknowledgements**

223 This report is dedicated to the memory of the late Professor Sally E. Smith (1941 – 2019;  
224 <https://nph.onlinelibrary.wiley.com/doi/full/10.1111/nph.15569>). Sally's illustrious research  
225 career spanned more than 50 years and contributed important findings, particularly on the  
226 arbuscular mycorrhizal symbiosis. She inspired many young scientists to pursue careers in plant  
227 and mycorrhiza research, and she will be greatly missed by the mycorrhiza research community.  
228 Sally received the Eminent Mycorrhiza Researcher Award at ICOM10.

229

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235

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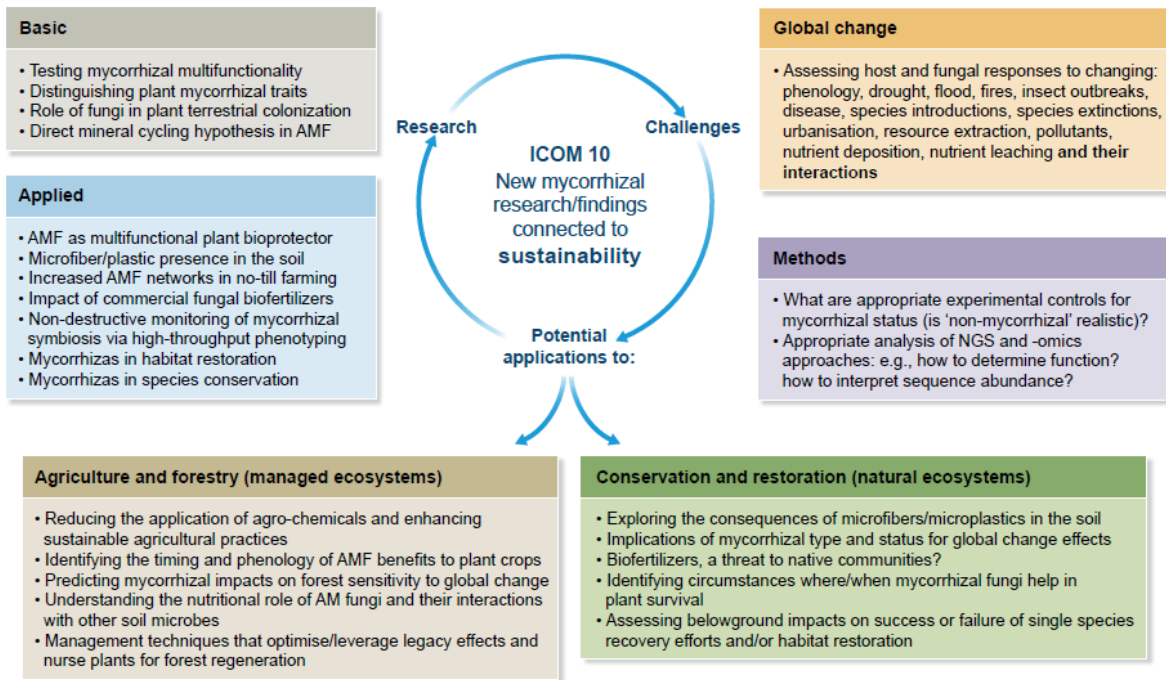
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- 286

287 **Figure legends**

288 **Figure 1.** ICOM10 covered a variety of recent basic and applied mycorrhizal research with a  
289 focus on topics that inform the sustainability of managed and natural ecosystems. Interactions  
290 between global change processes, and the interpretation of data from rapidly advancing  
291 sequencing technologies, emerged as common challenges for mycorrhizal researchers.

292 **Figure 2.** Planned and unplanned (in some cases unwanted) inputs into managed (e.g.,  
293 agricultural, silvicultural) and natural mycorrhizal systems, and potential or existing outputs,  
294 which can extend to ecosystem and socio-economic impacts.

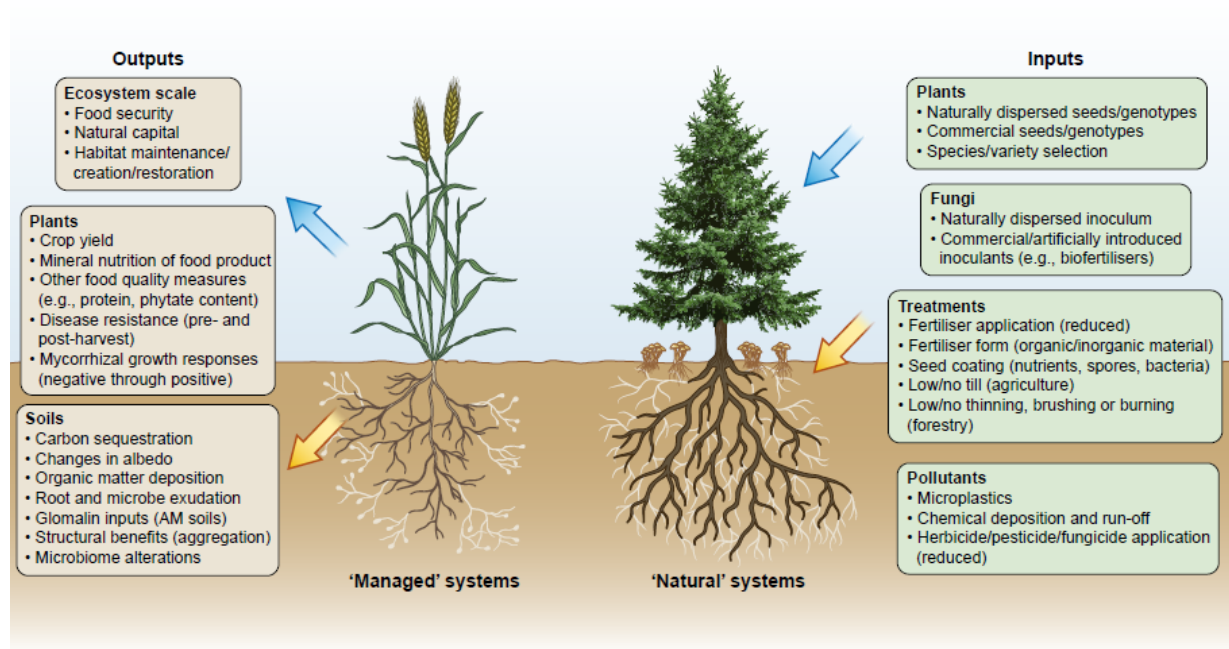
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296

297 **Figure 1.**

298



299

300 **Figure 2.**