

Ecological and evolutionary dynamics of mycorrhizal networks



CENTRE DE RECHERCHE SUR LA
BIODIVERSITE ET L'ENVIRONNEMENT



September 2025

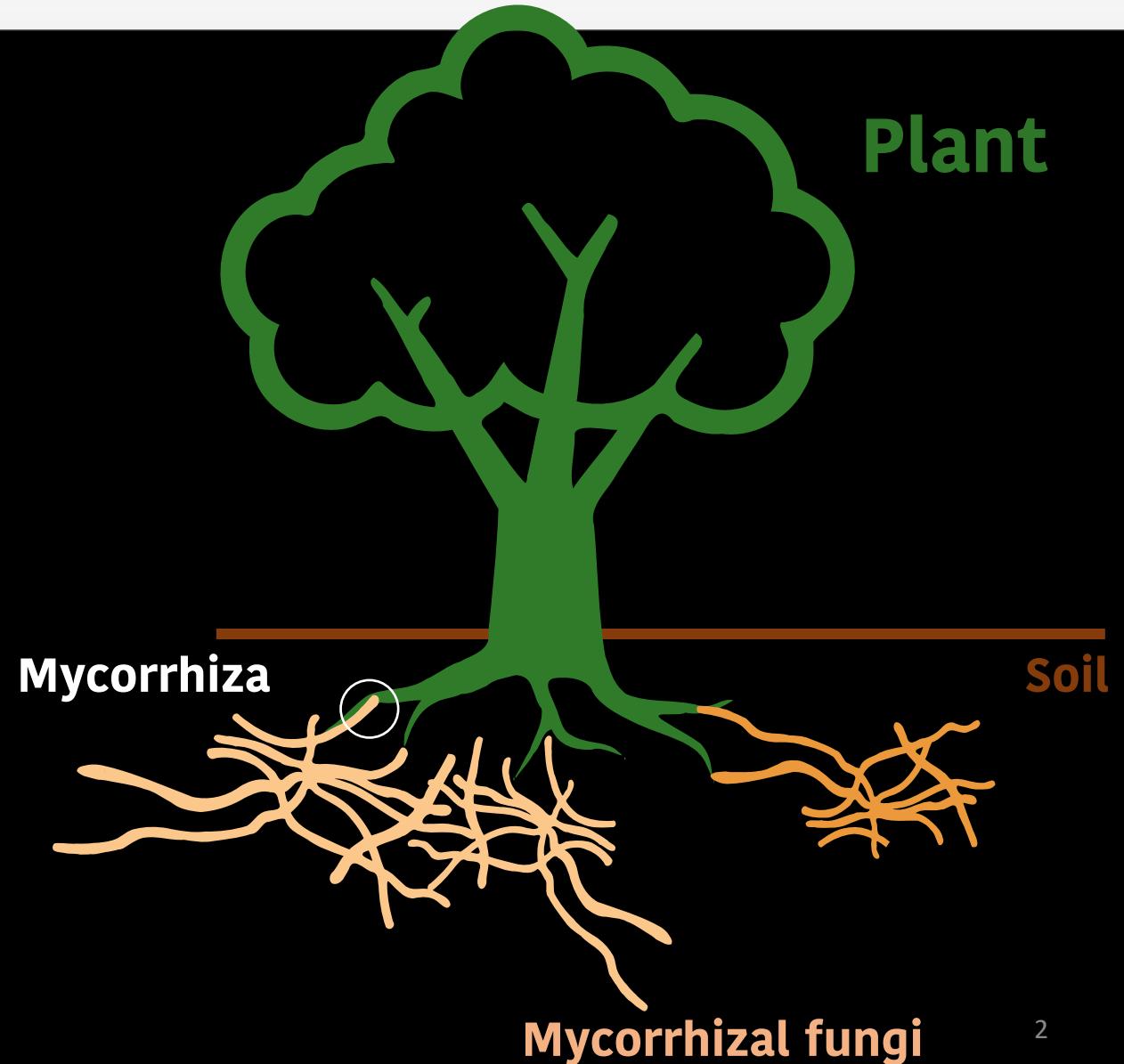
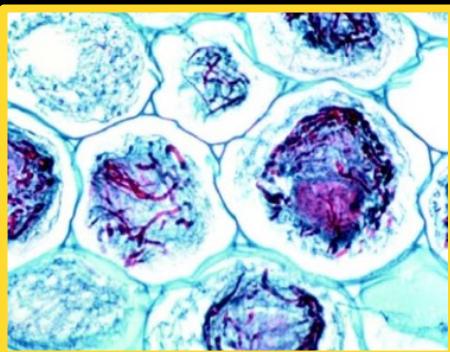
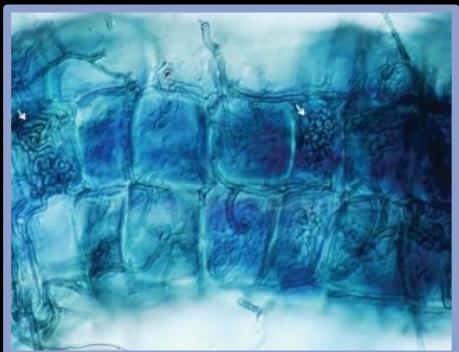
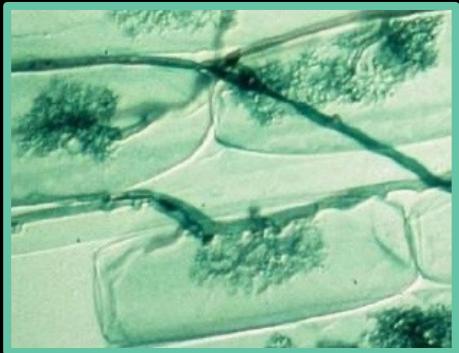
Benoît Perez-Lamarque

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Maître de conférences, CRBE, Université de Toulouse

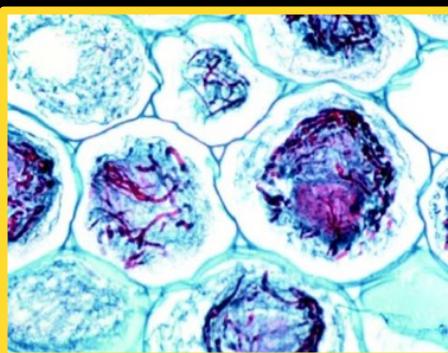
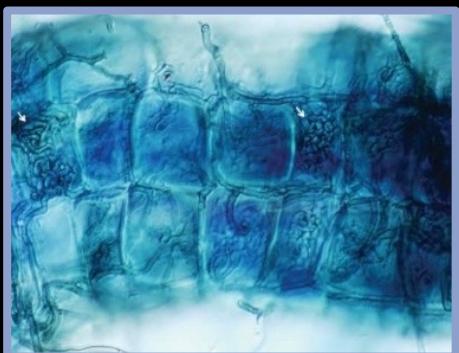
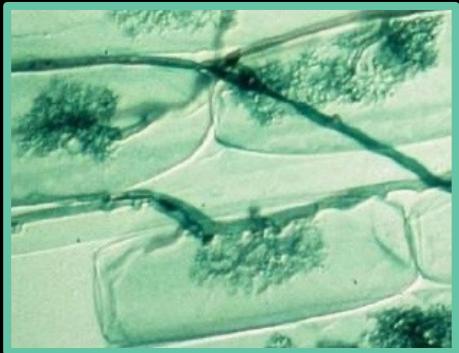
Mycorrhizal communities

Mycorrhizae: plant-fungus symbiotic interactions in the roots



Mycorrhizal communities

Mycorrhizae: plant-fungus symbiotic interactions in the roots

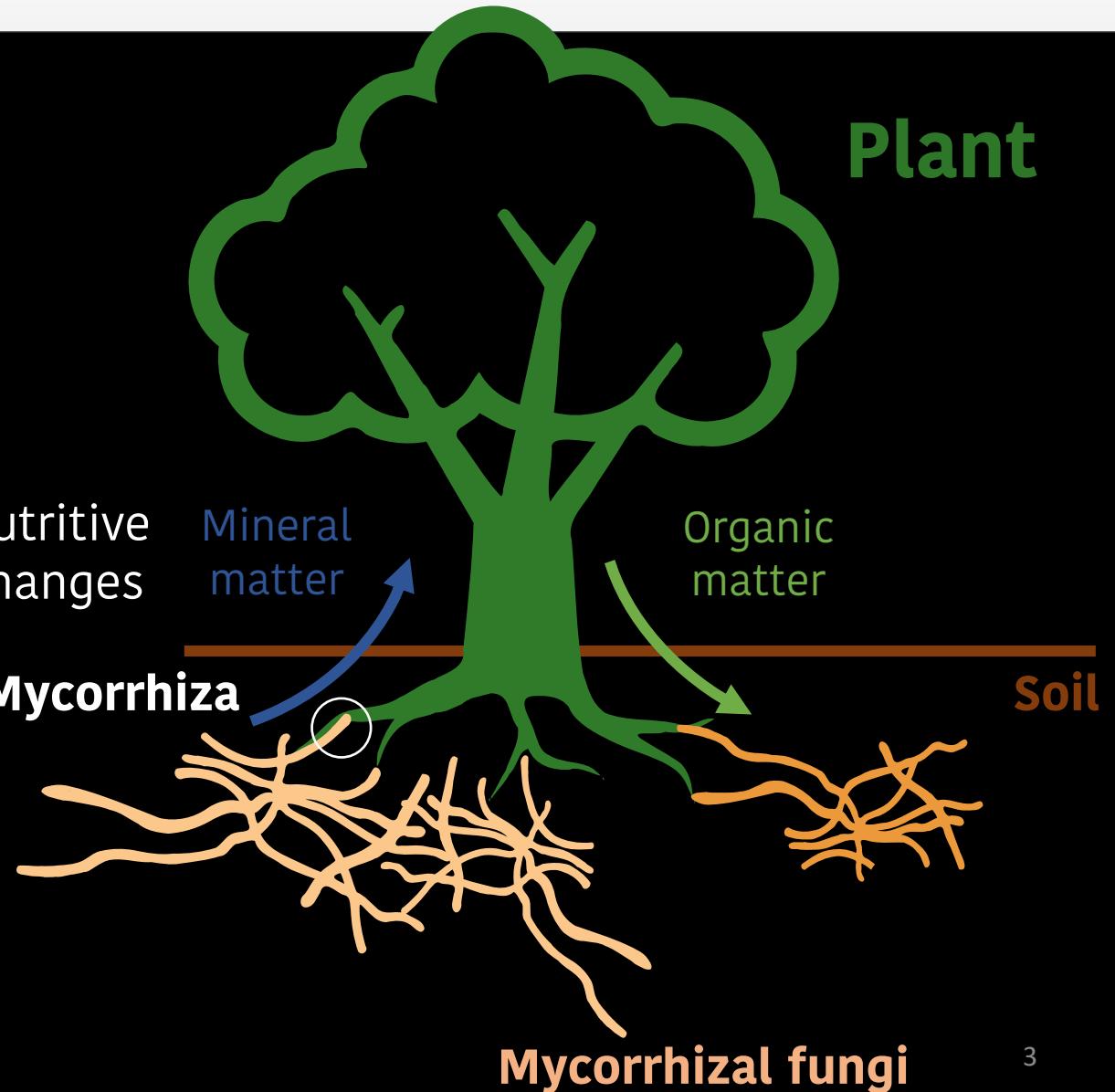


1) Nutritive exchanges

Mycorrhiza

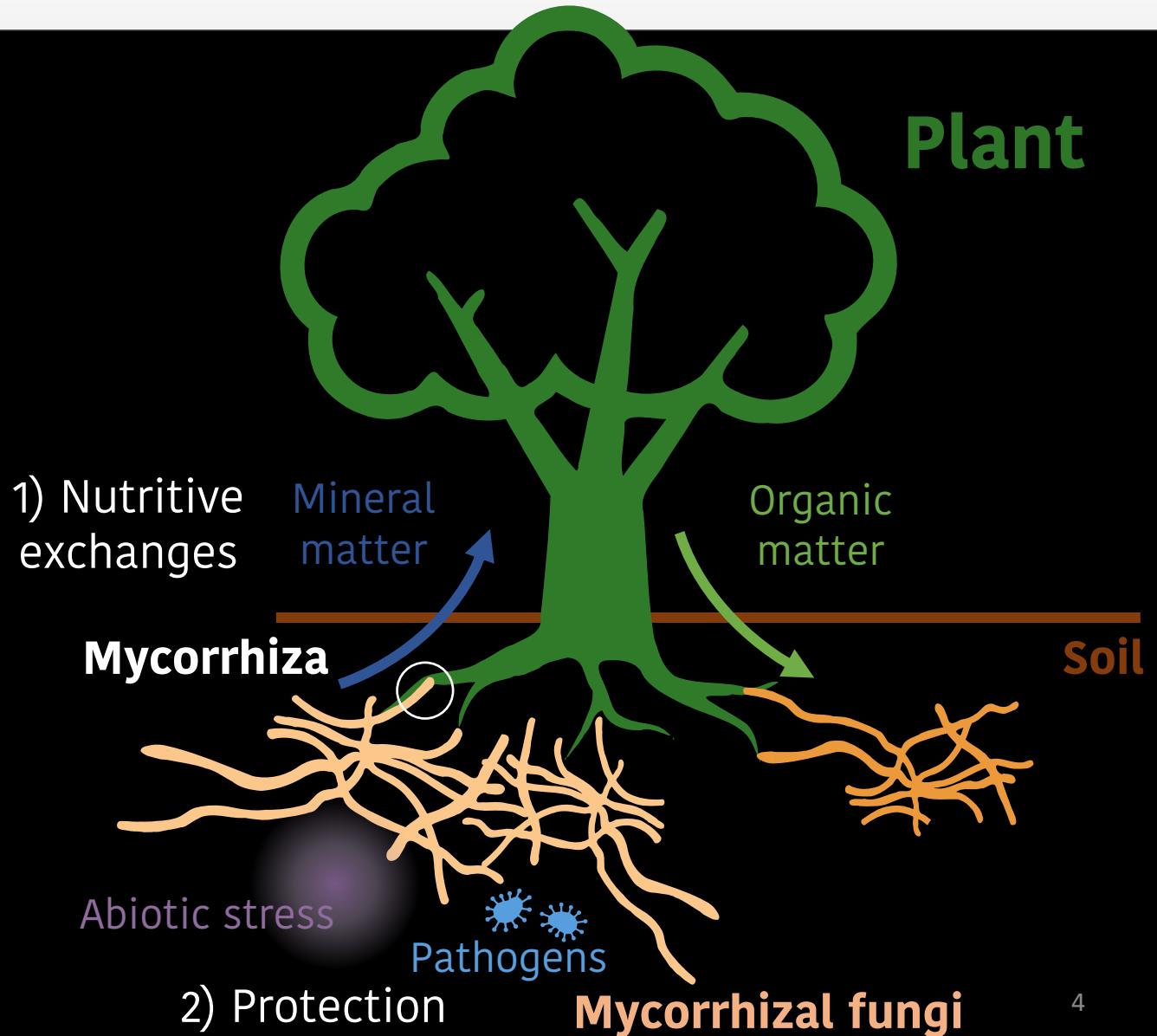
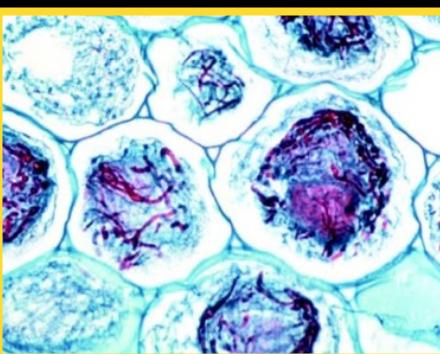
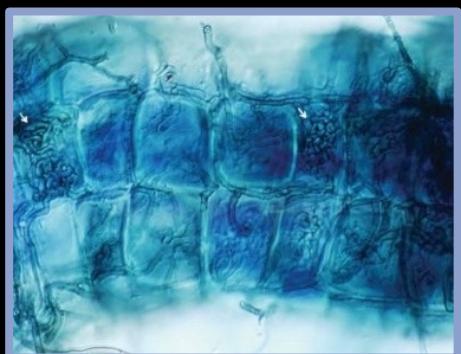
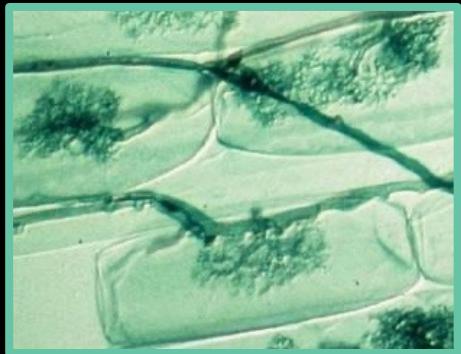
Mineral matter

Organic matter



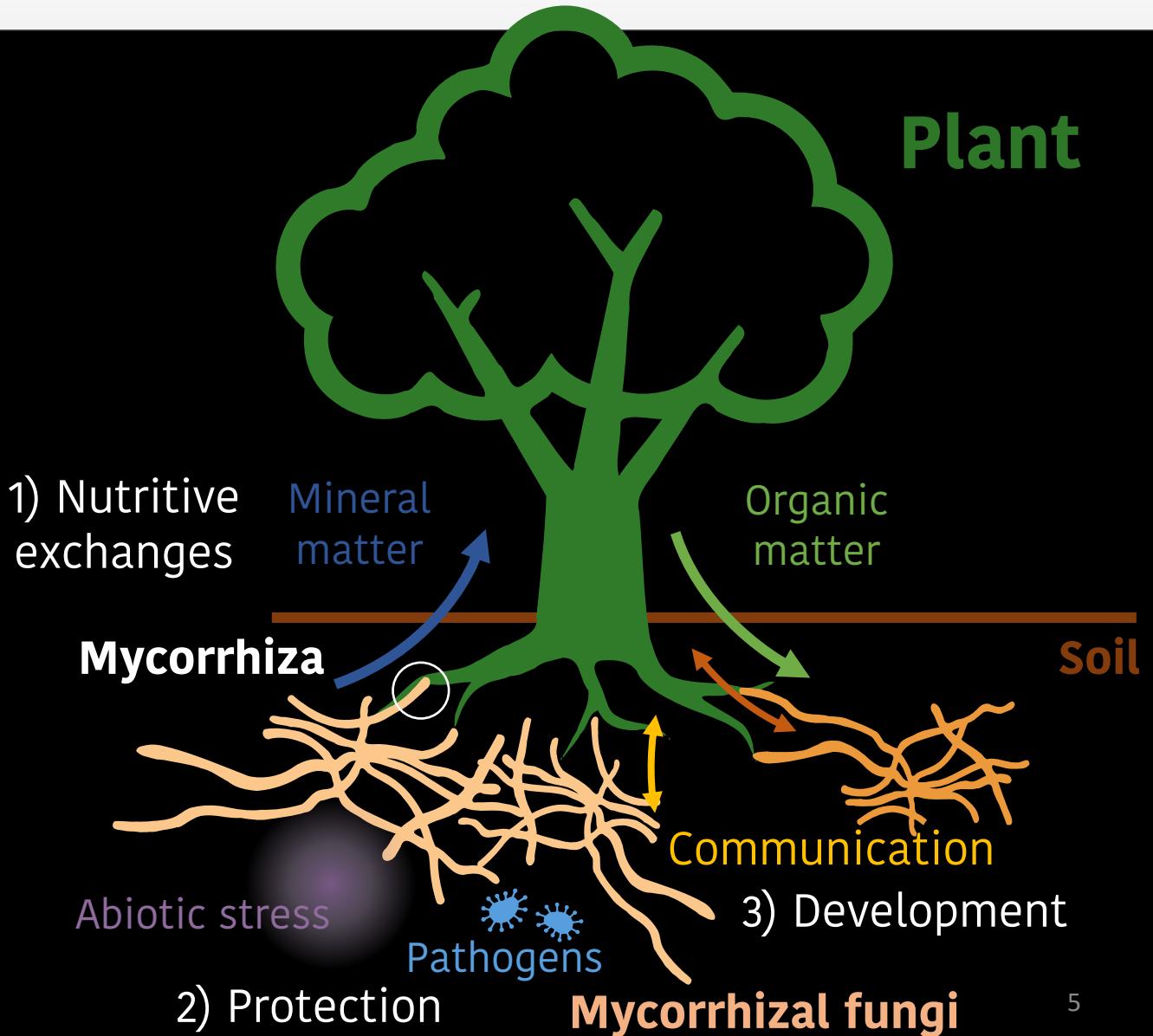
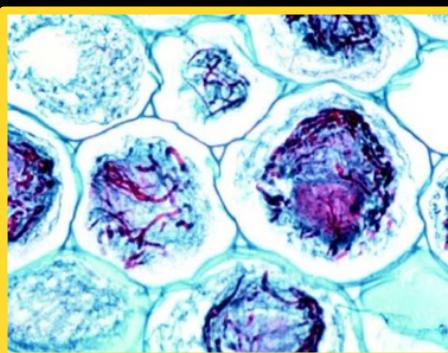
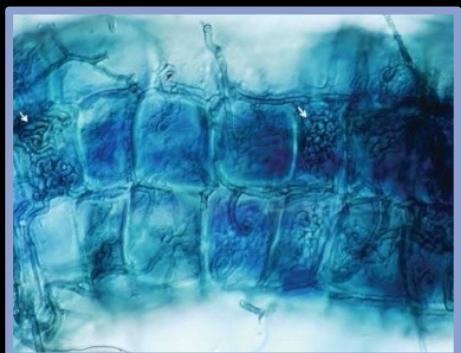
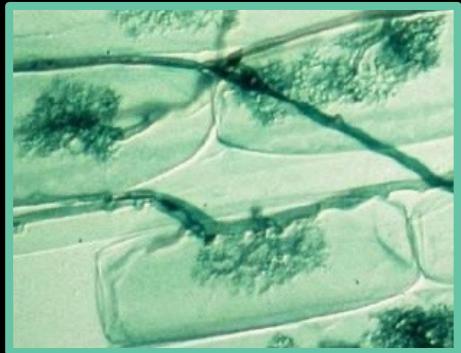
Mycorrhizal communities

Mycorrhizae: plant-fungus symbiotic interactions in the roots



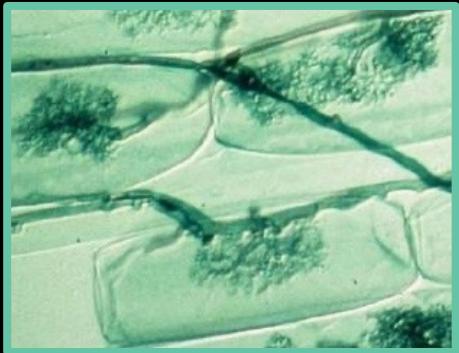
Mycorrhizal communities

Mycorrhizae: plant-fungus symbiotic interactions in the roots



Mycorrhizal communities

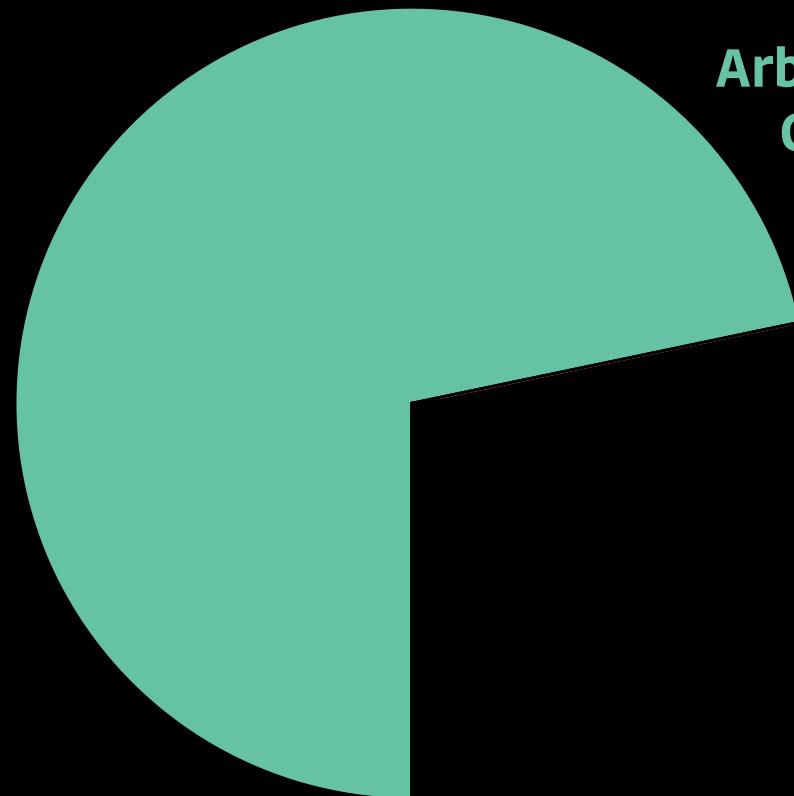
**Mycorrhizae: plant-fungus
symbiotic interactions in the roots**



→ **Glomeromycotina fungi:
obligate symbionts**

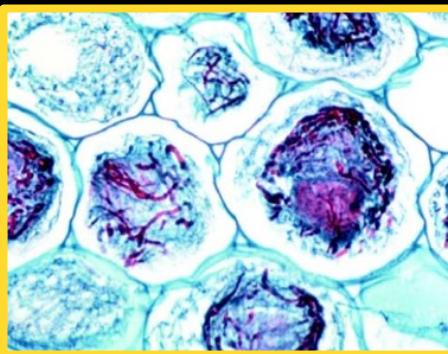
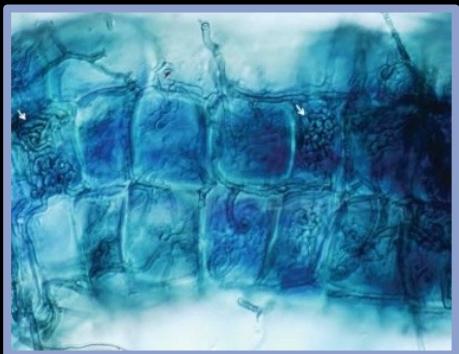
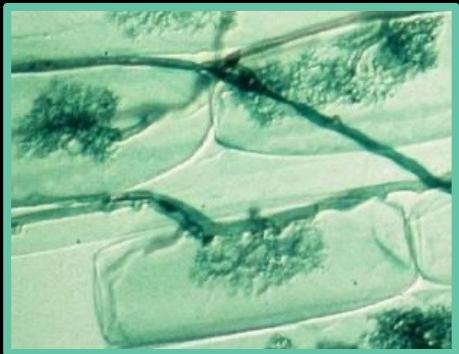
Land plant species

**Arbuscular mycorrhiza with
Glomeromycotina (71%)**

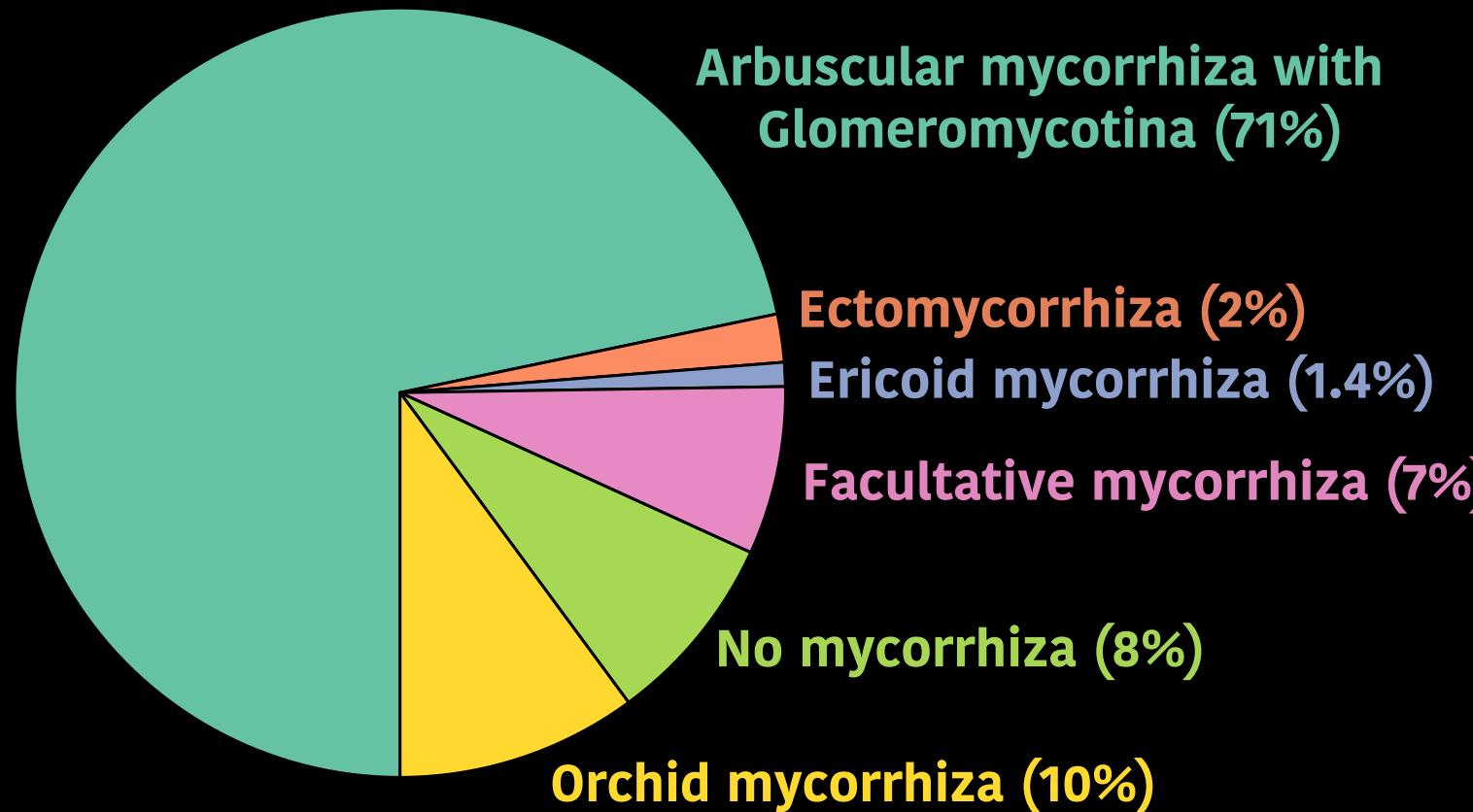


Mycorrhizal communities

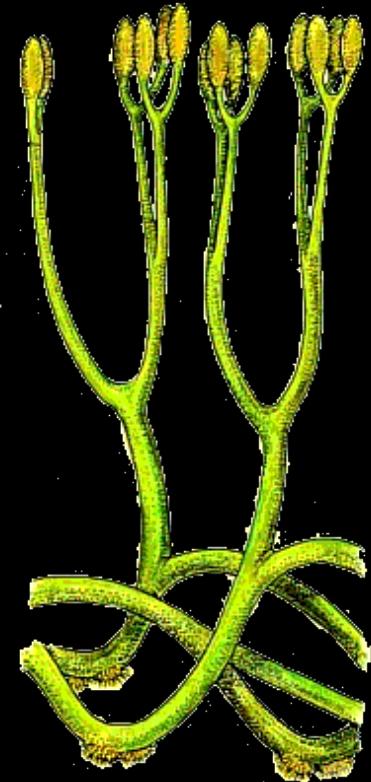
Mycorrhizae: plant-fungus symbiotic interactions in the roots



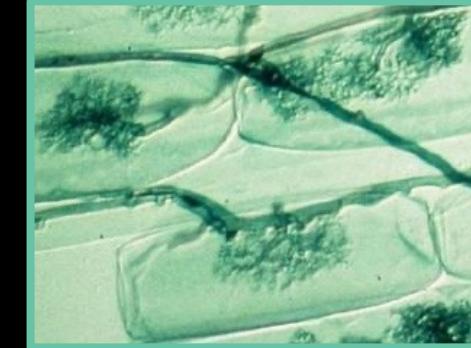
Land plant species



Arbuscular mycorrhizae contributed to land plant emergence



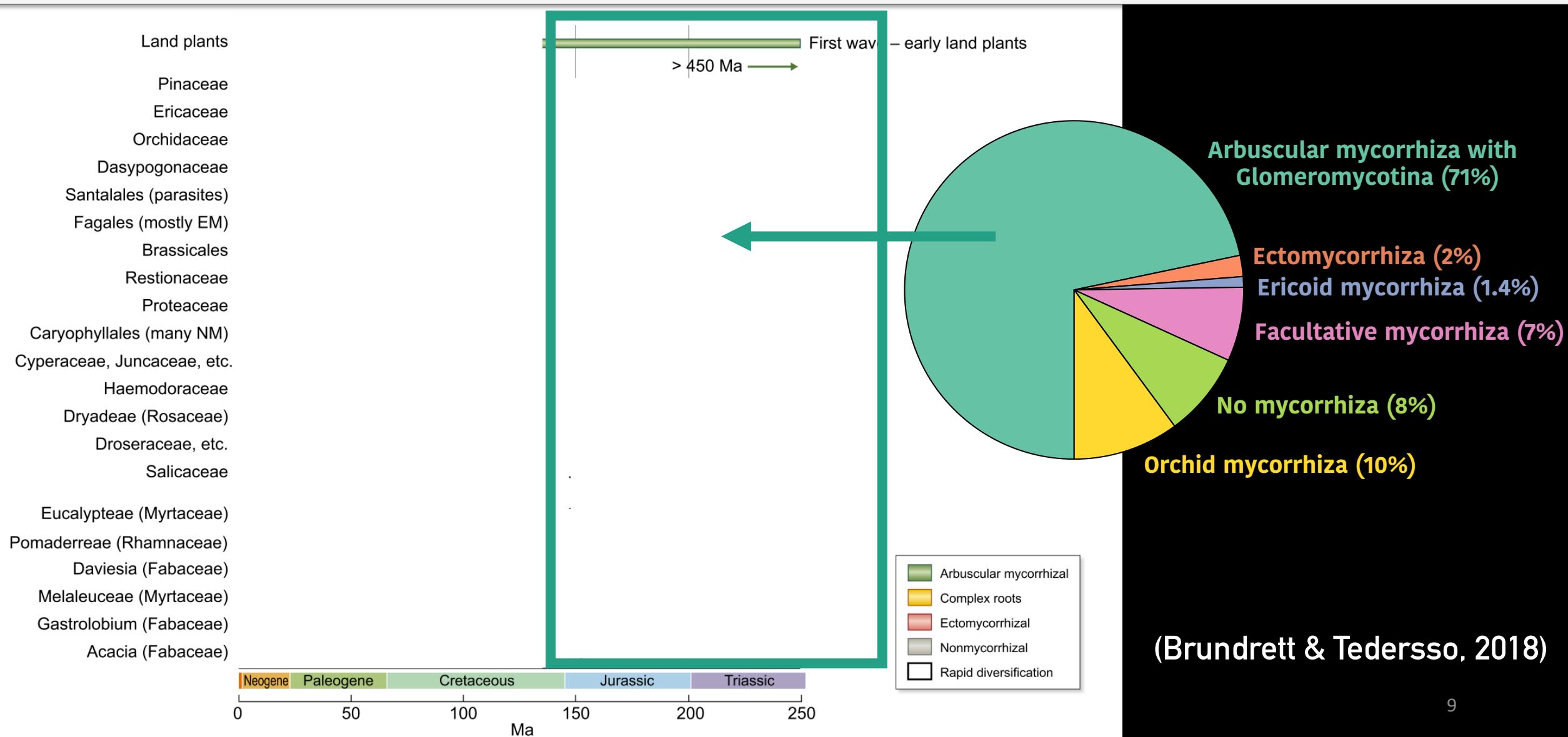
Fossil evidences of
mycorrhizal associations
with Glomeromycotina



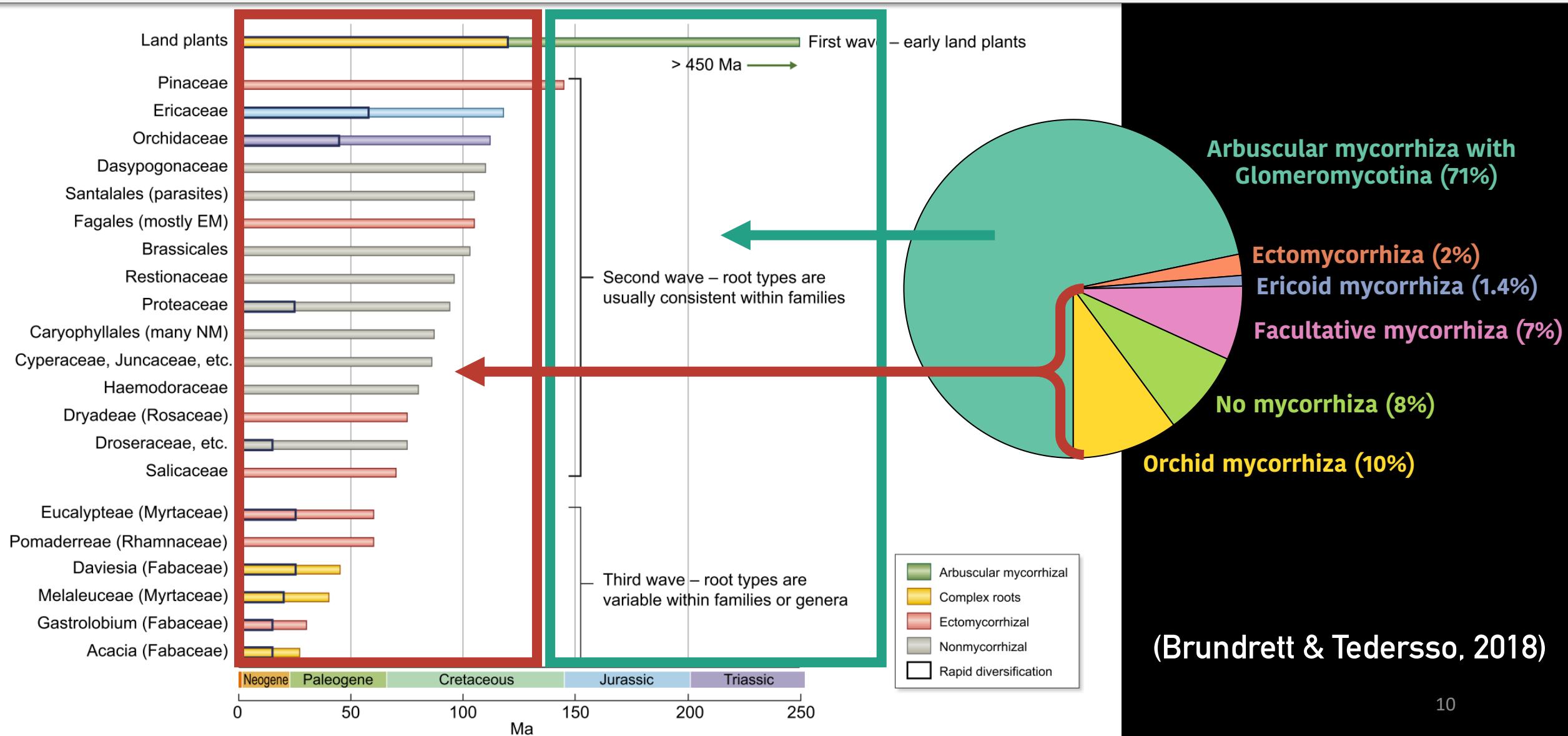
Aglaophyton major, one of the most common plants in the Rhynie Chert

(Kerp, 2017)

Emergence of new mycorrhizal symbioses



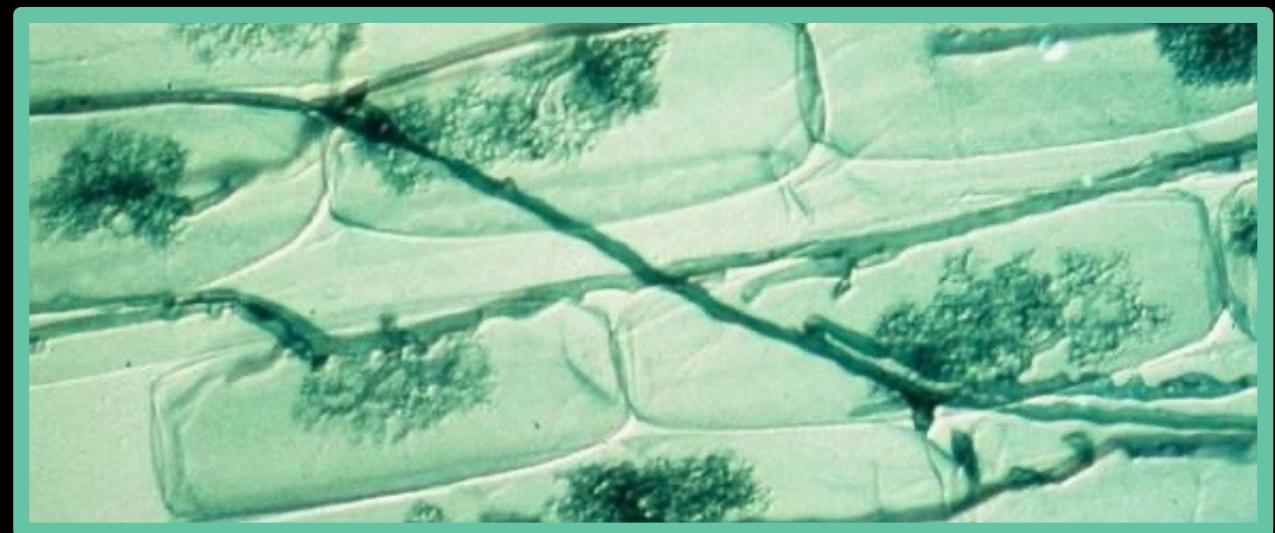
Emergence of new mycorrhizal symbioses



How to identify mycorrhizal fungal species?



Land plant root



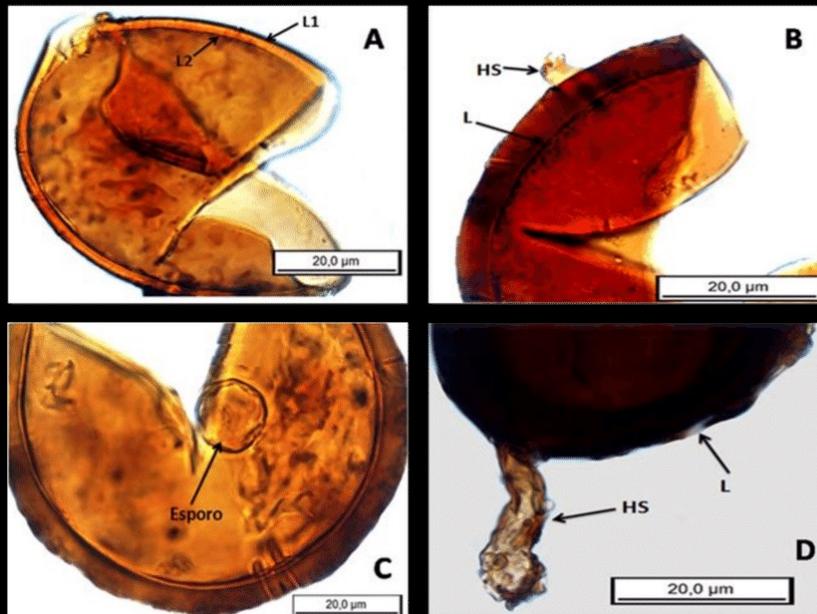
(Larry Peterson)

(Yoshihiro Kobae)

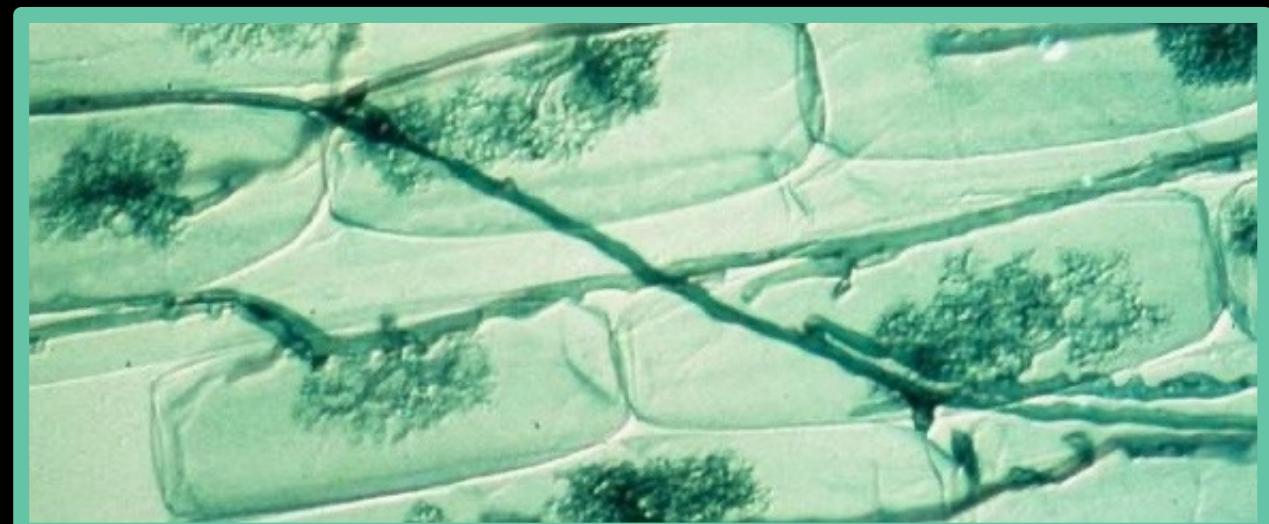
Glomeromycotina fungi forming arbuscular mycorrhizae

How to identify mycorrhizal fungal species?

(Pereira et al., 2017)



Land plant root

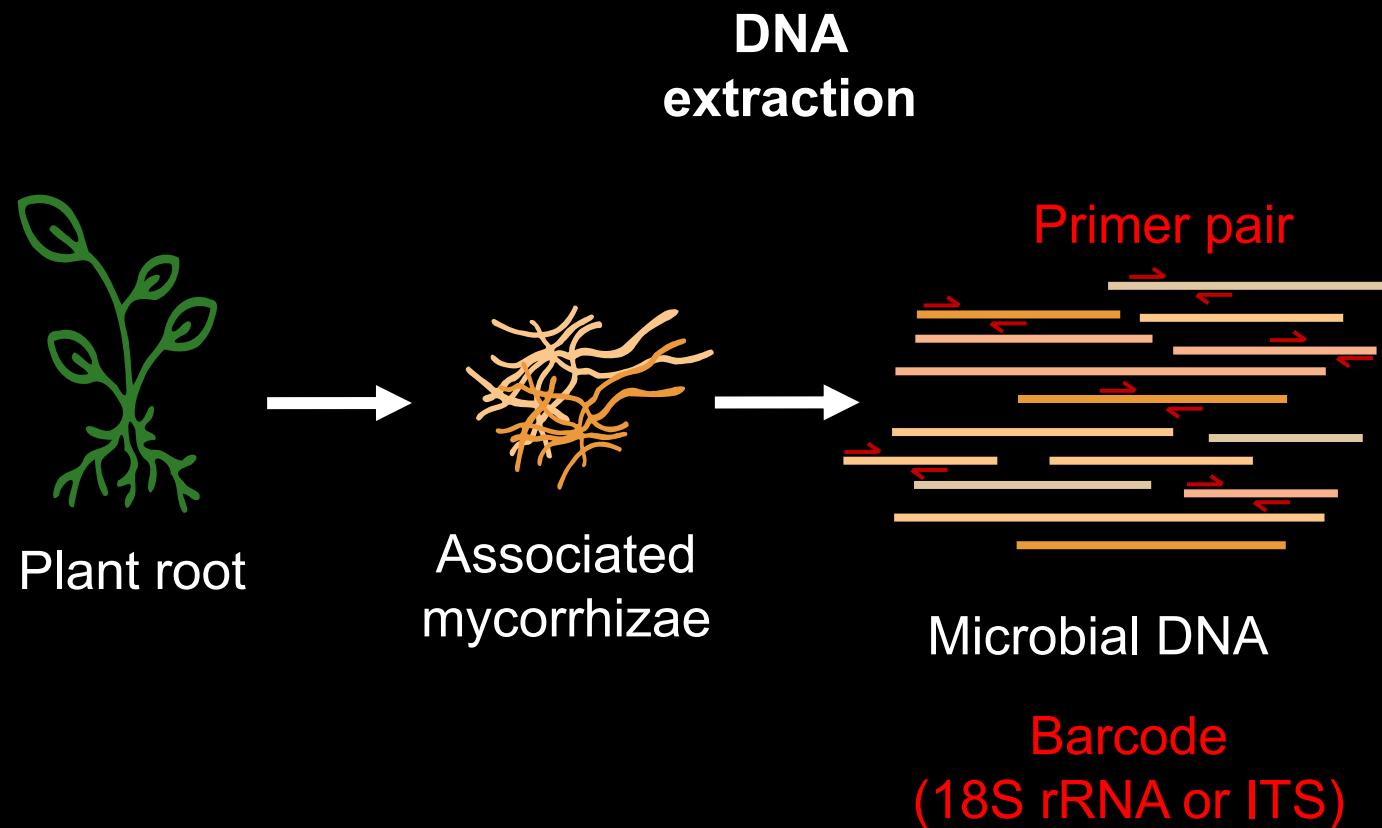


(Larry Peterson)

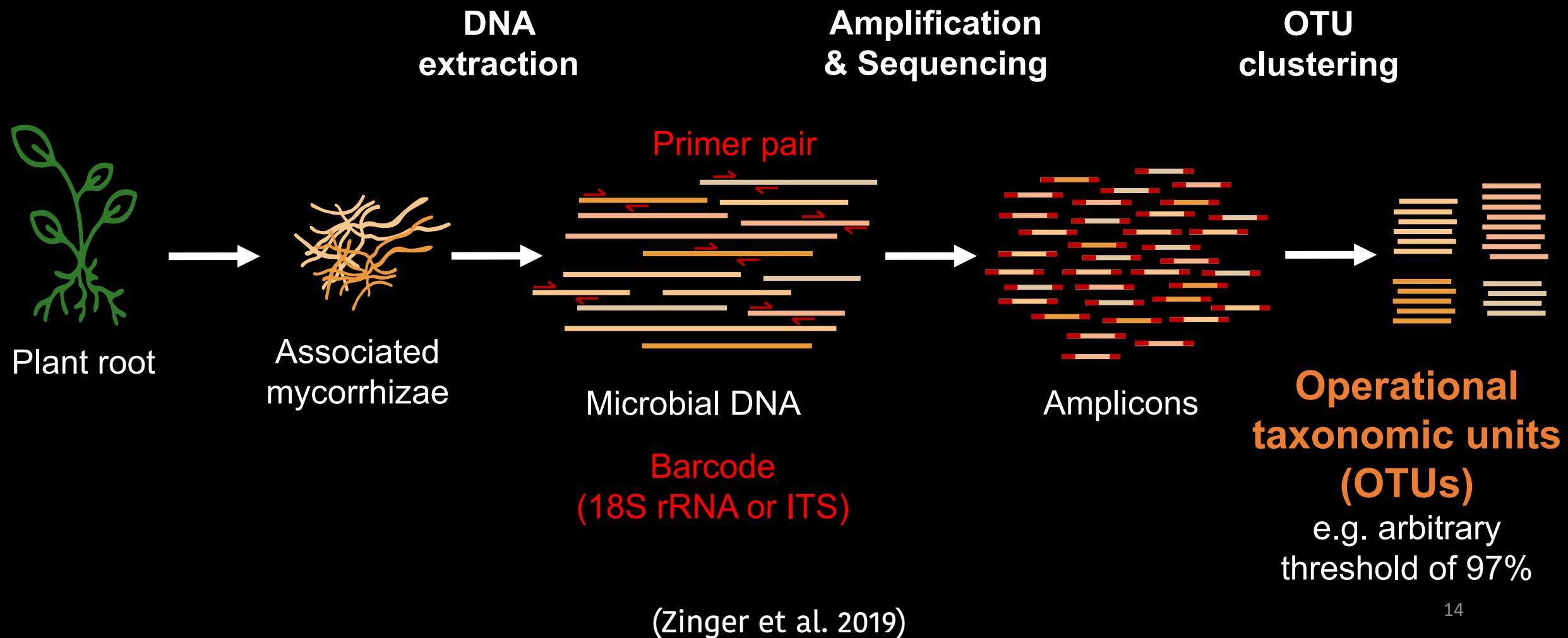
Previous morphological species
delineation based on spores

Glomeromycotina fungi forming arbuscular mycorrhizae

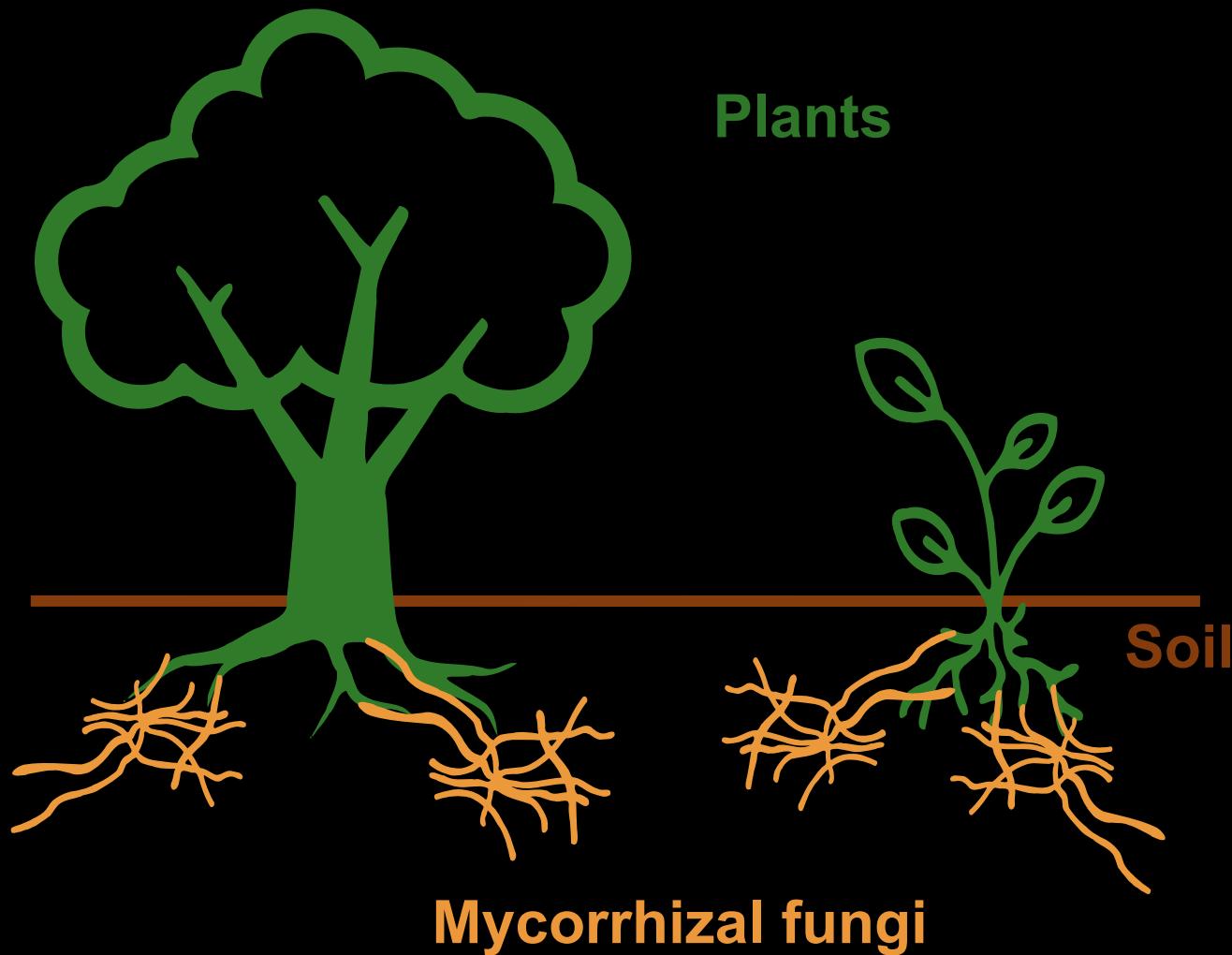
“Species delimitation” using metabarcoding



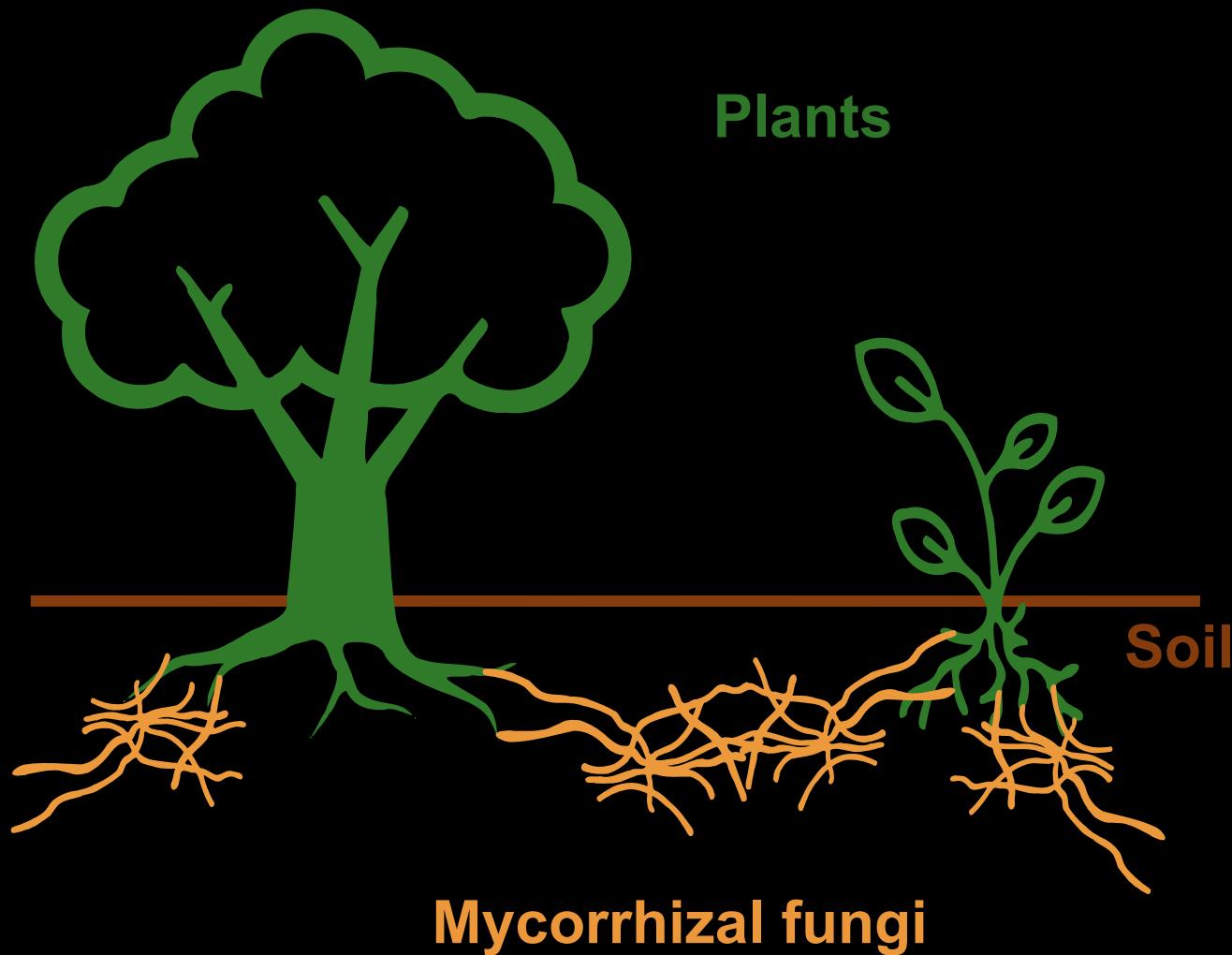
“Species delimitation” using metabarcoding



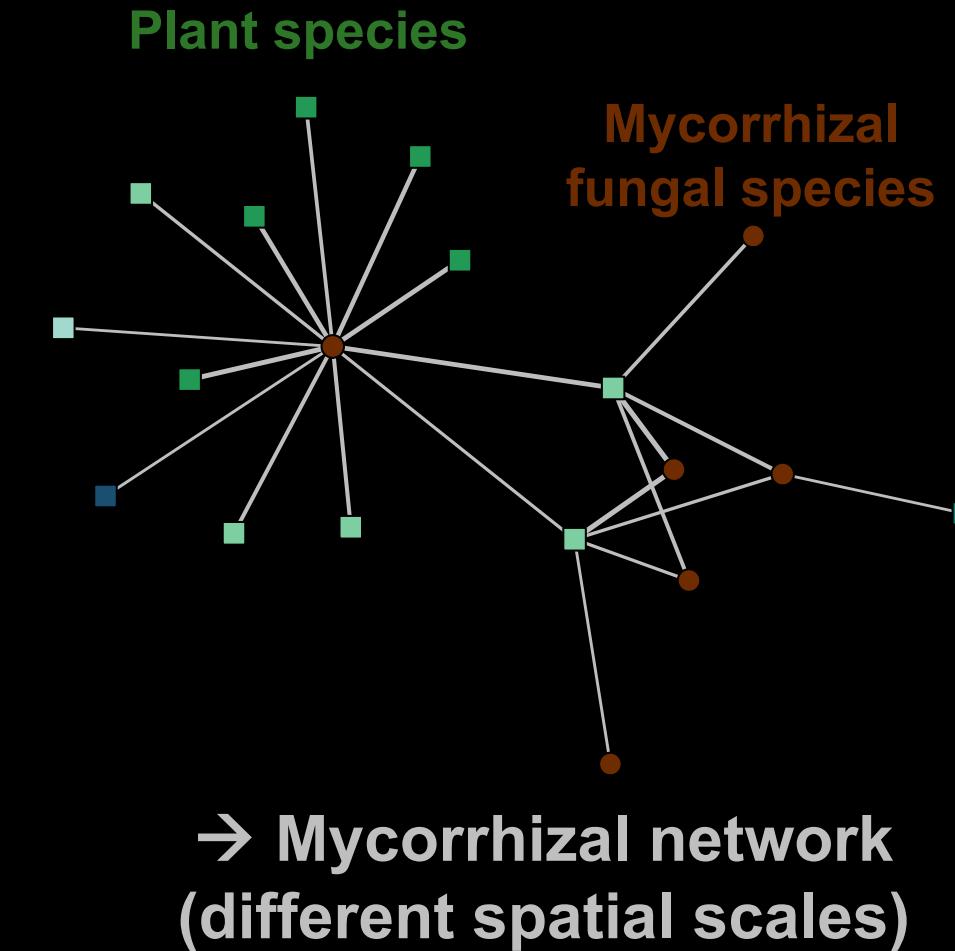
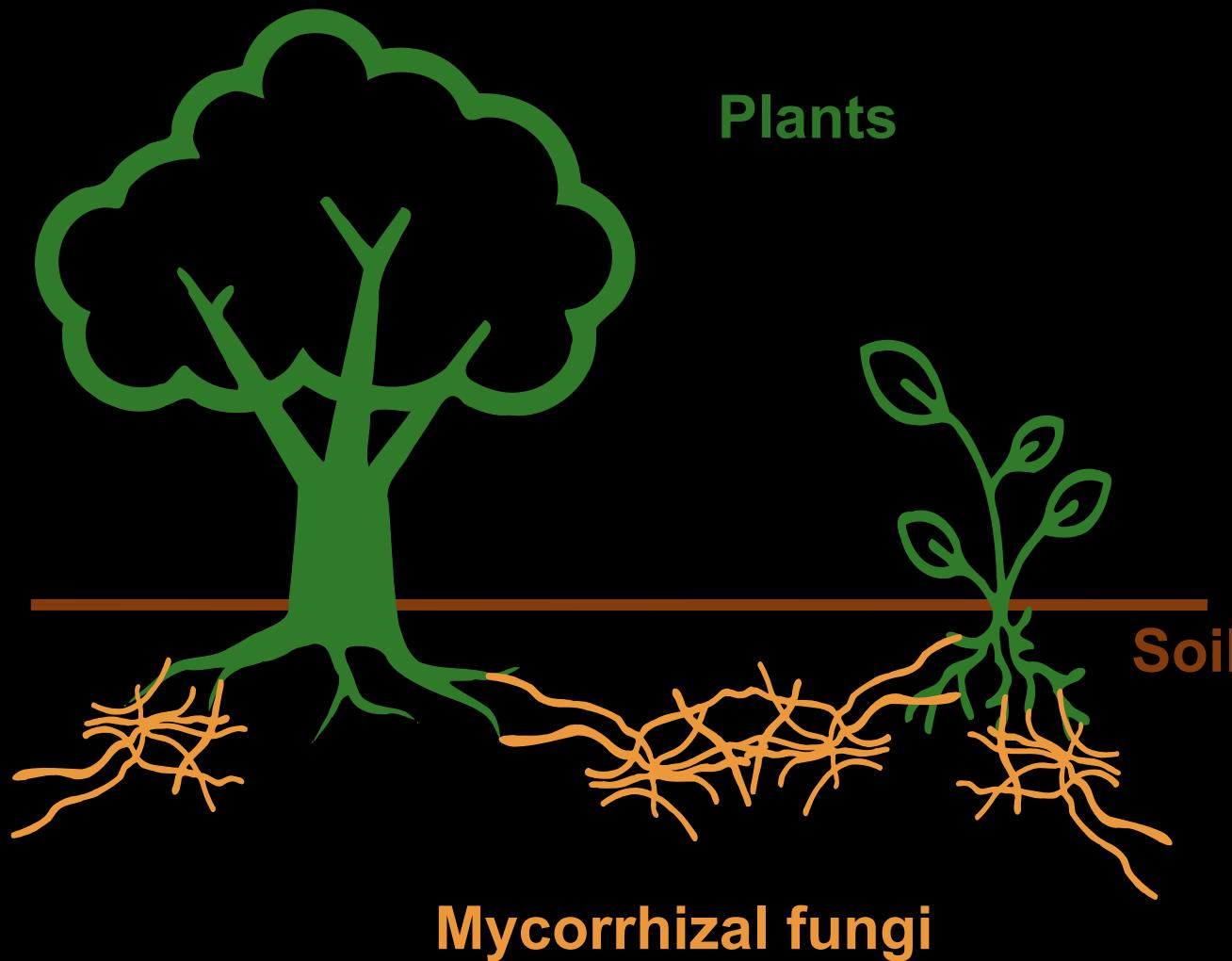
Mycorrhizal networks



Mycorrhizal networks

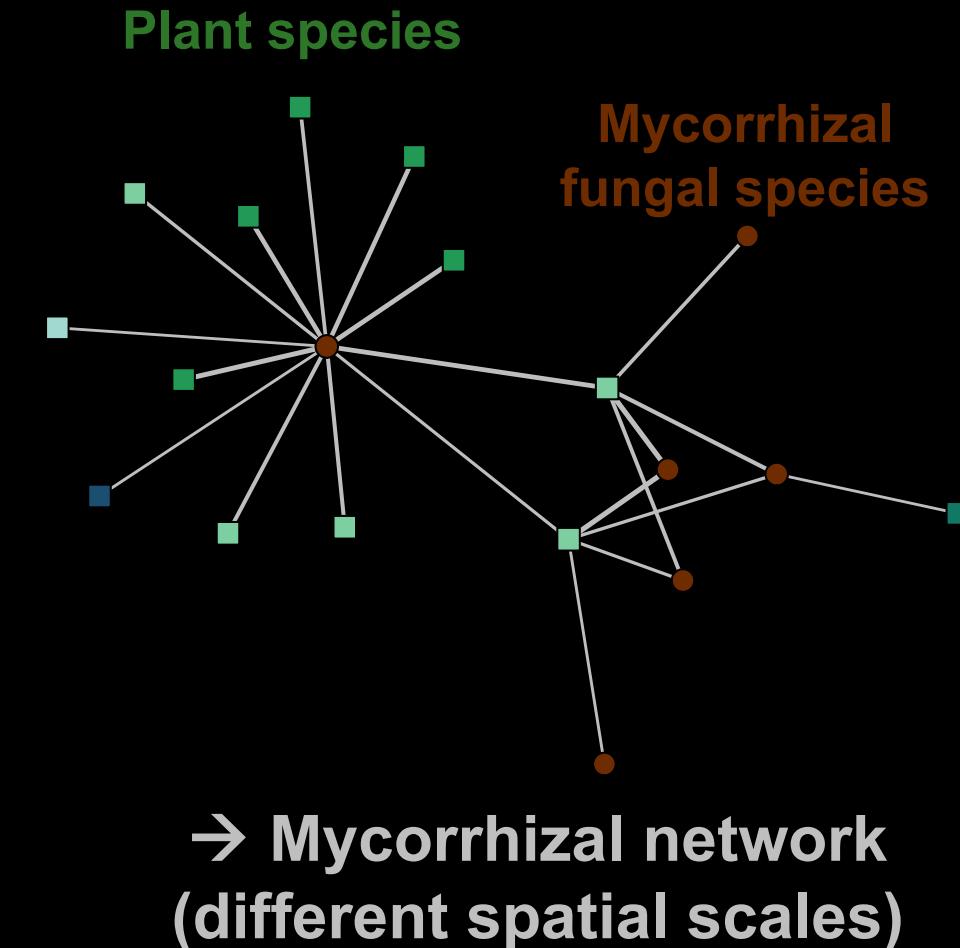


Mycorrhizal networks



Dynamics of mycorrhizal networks

How do mycorrhizal networks assemble and evolve?



Dynamics of mycorrhizal networks

Research seminar: 1 hour

Research project: 2 hours

Dynamics of mycorrhizal networks

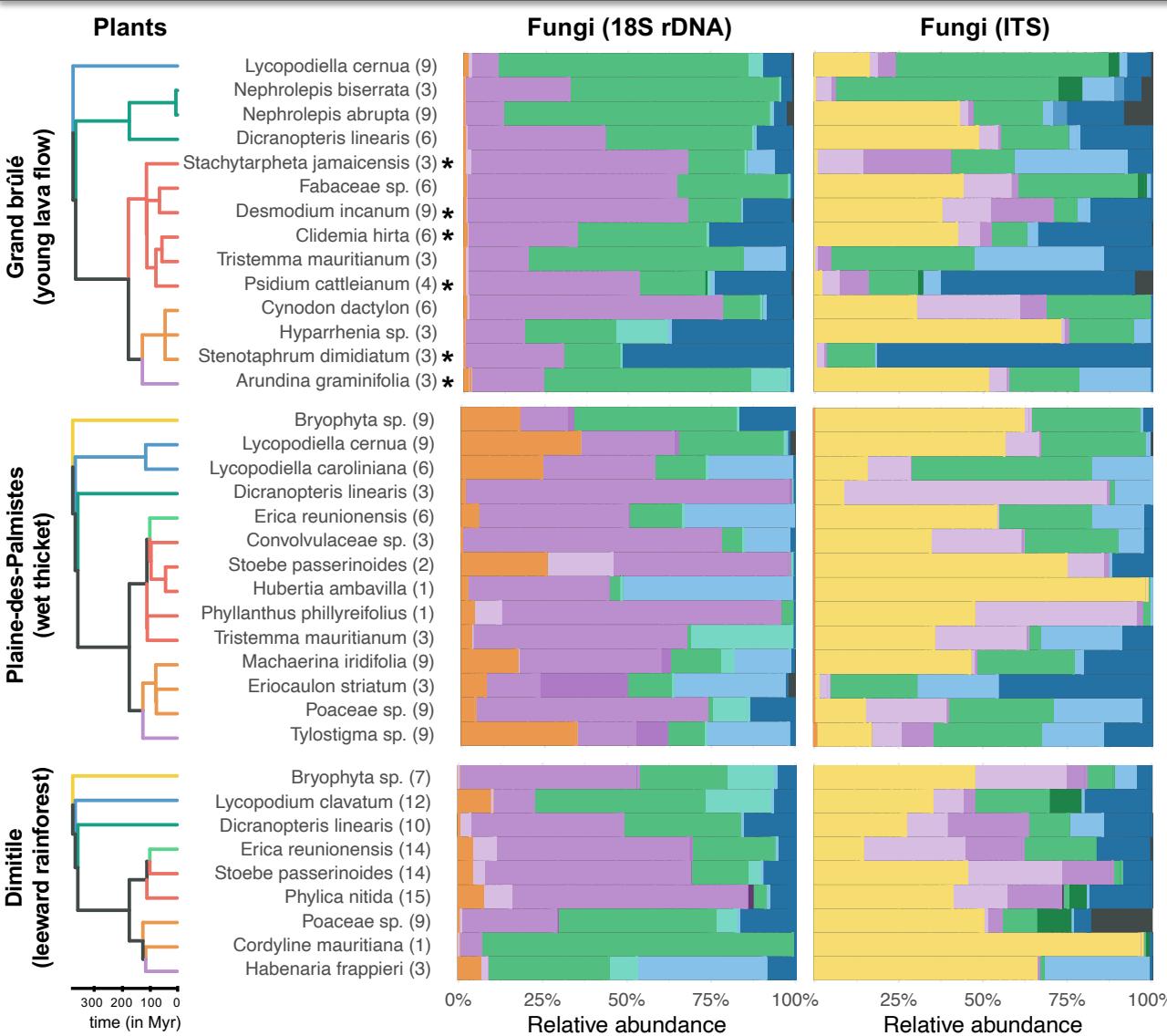
- 1) The arbuscular mycorrhizal symbiosis: a symbiosis with low specificity**
- 2) Toward more specialized and competitive mycorrhizal symbioses**
- 3) The evolution of mycoheterotrophy**

1) The arbuscular mycorrhizal symbiosis: a symbiosis with low specificity

Characterizing mycorrhizal networks in natural communities



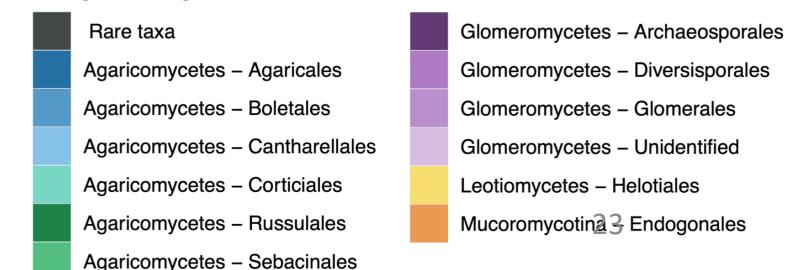
Characterizing mycorrhizal networks in natural communities



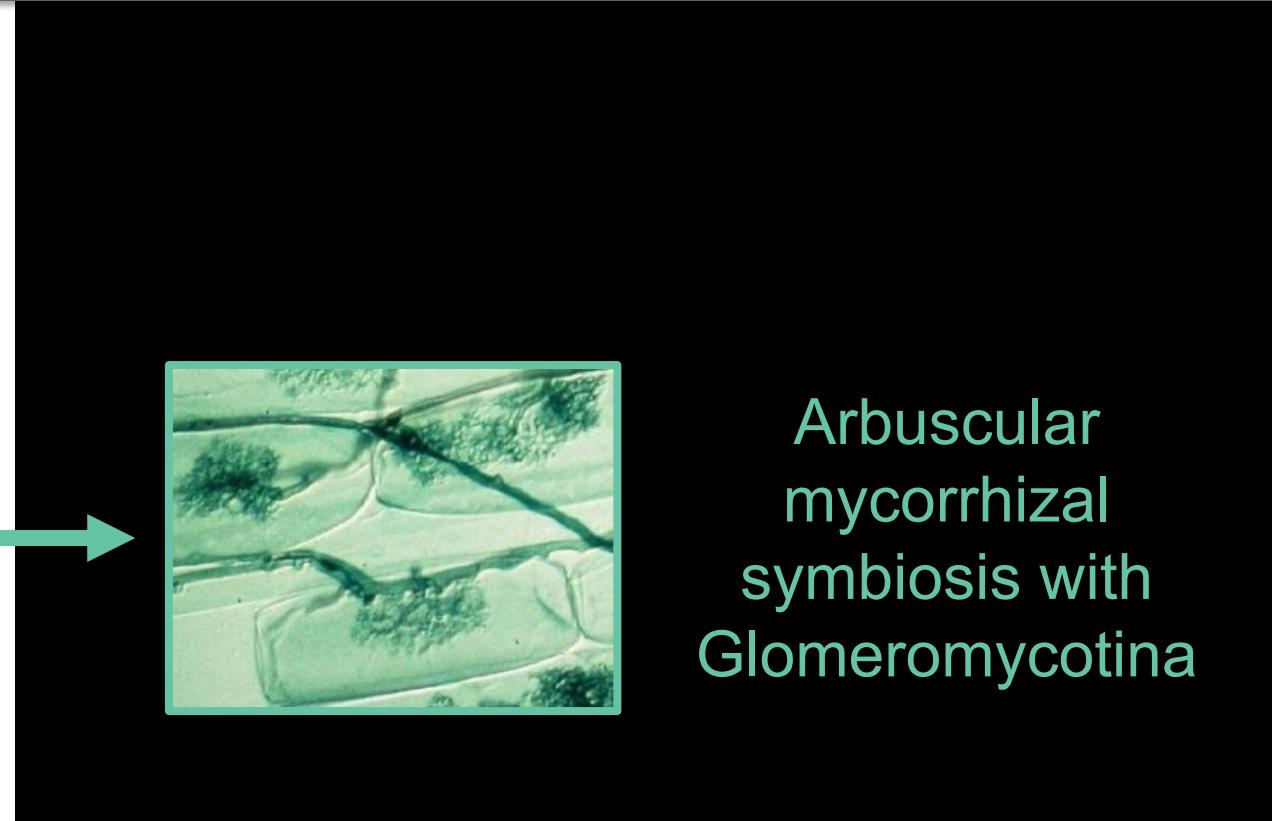
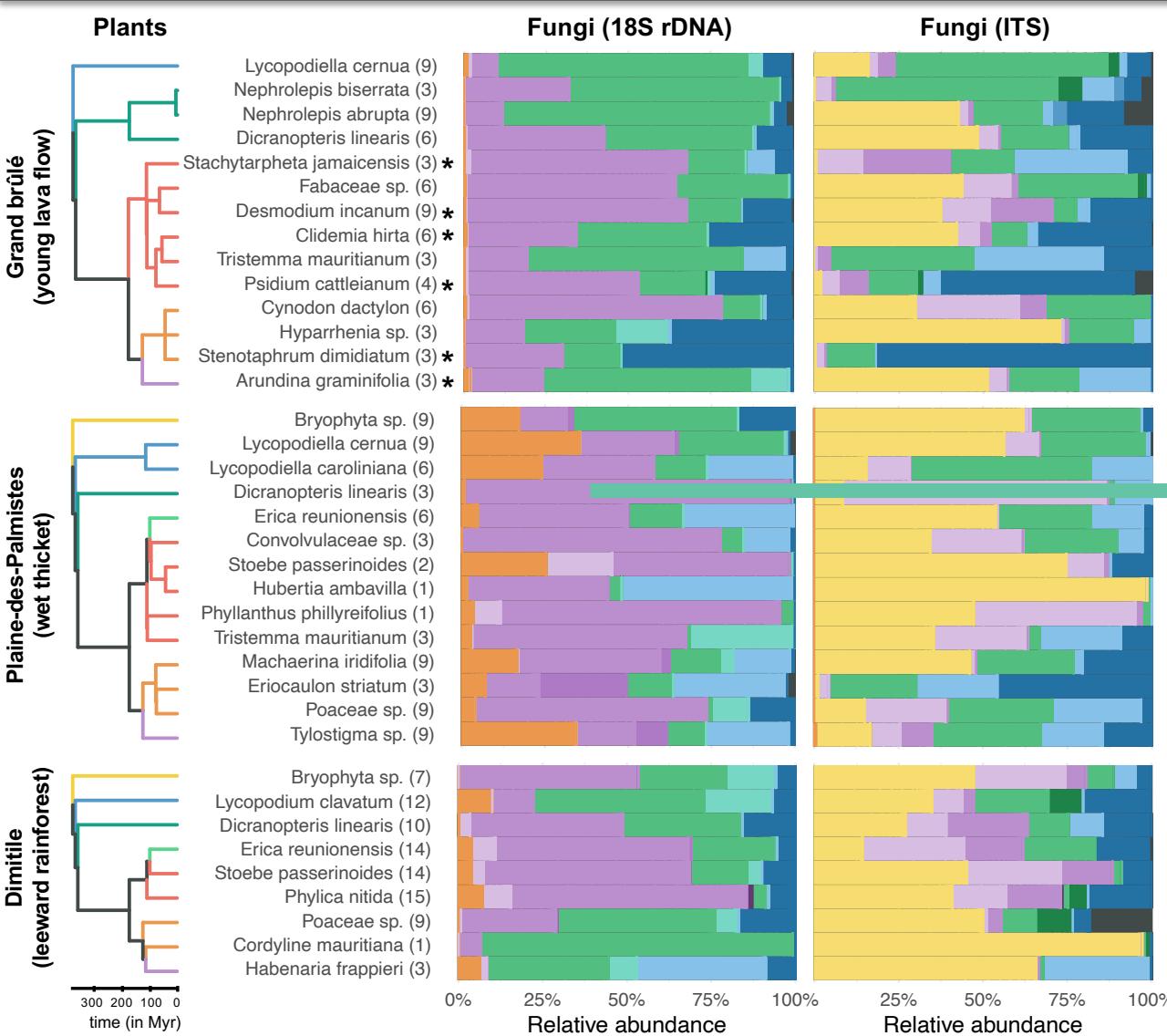
Plant lineages:

- Bryophytes
- Lycopods
- Ferns
- Ericaceae
- Other dicots
- Orchids
- Other monocots

Fungal lineages:



Characterizing mycorrhizal networks in natural communities



Plant lineages:

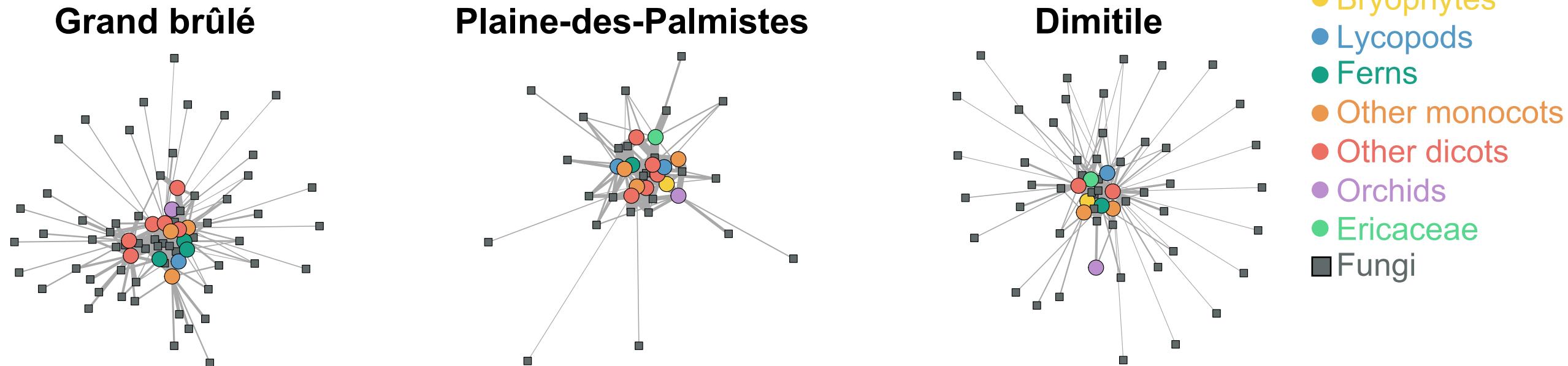
Bryophytes
Lycopods
Ferns
Ericaceae
Other dicots
Orchids
Other monocots

Fungal lineages:

Rare taxa
Glomeromycetes – Archaeosporales
Glomeromycetes – Diversisporales
Glomeromycetes – Glomerales
Agaricomycetes – Boletales
Agaricomycetes – Cantharellales
Agaricomycetes – Corticiales
Agaricomycetes – Russulales
Agaricomycetes – Sebacinales
Leotiomycetes – Helotiales
Mucromycotina – Endogonales

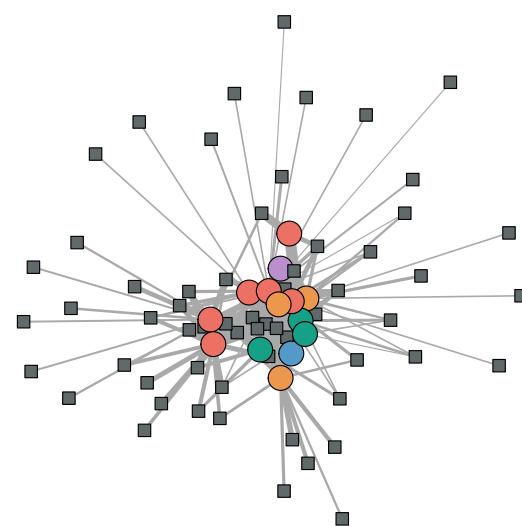
Arbuscular
mycorrhizal
symbiosis with
Glomeromycotina

Plant-Glomeromycotina networks at local scale

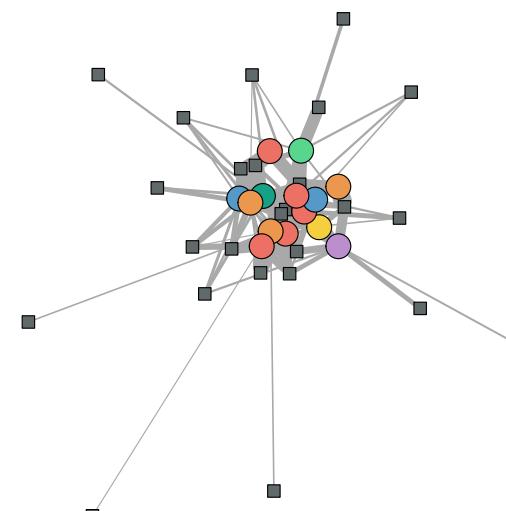


Plant-Glomeromycotina networks at local scale

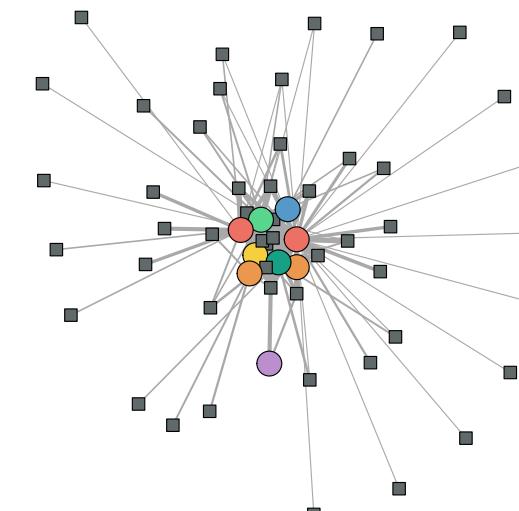
Grand brûlé



Plaine-des-Palmistes



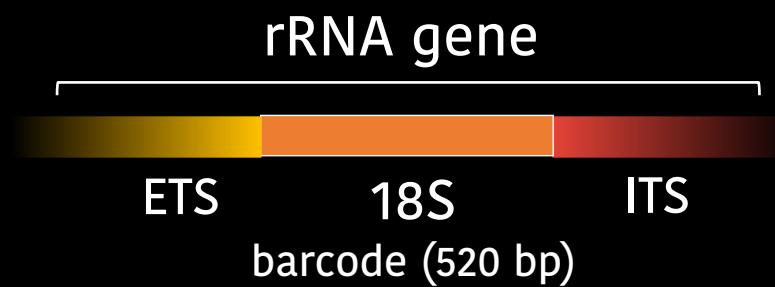
Dimitile



→ Low specificity
→ Nested structure

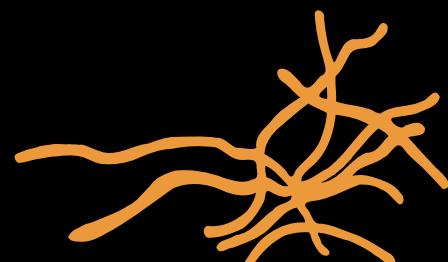
Plant-Glomeromycotina network at global scale

MaarjAM database



> 41,000 18S rRNA sequences

> 25,000 interactions in natural environments



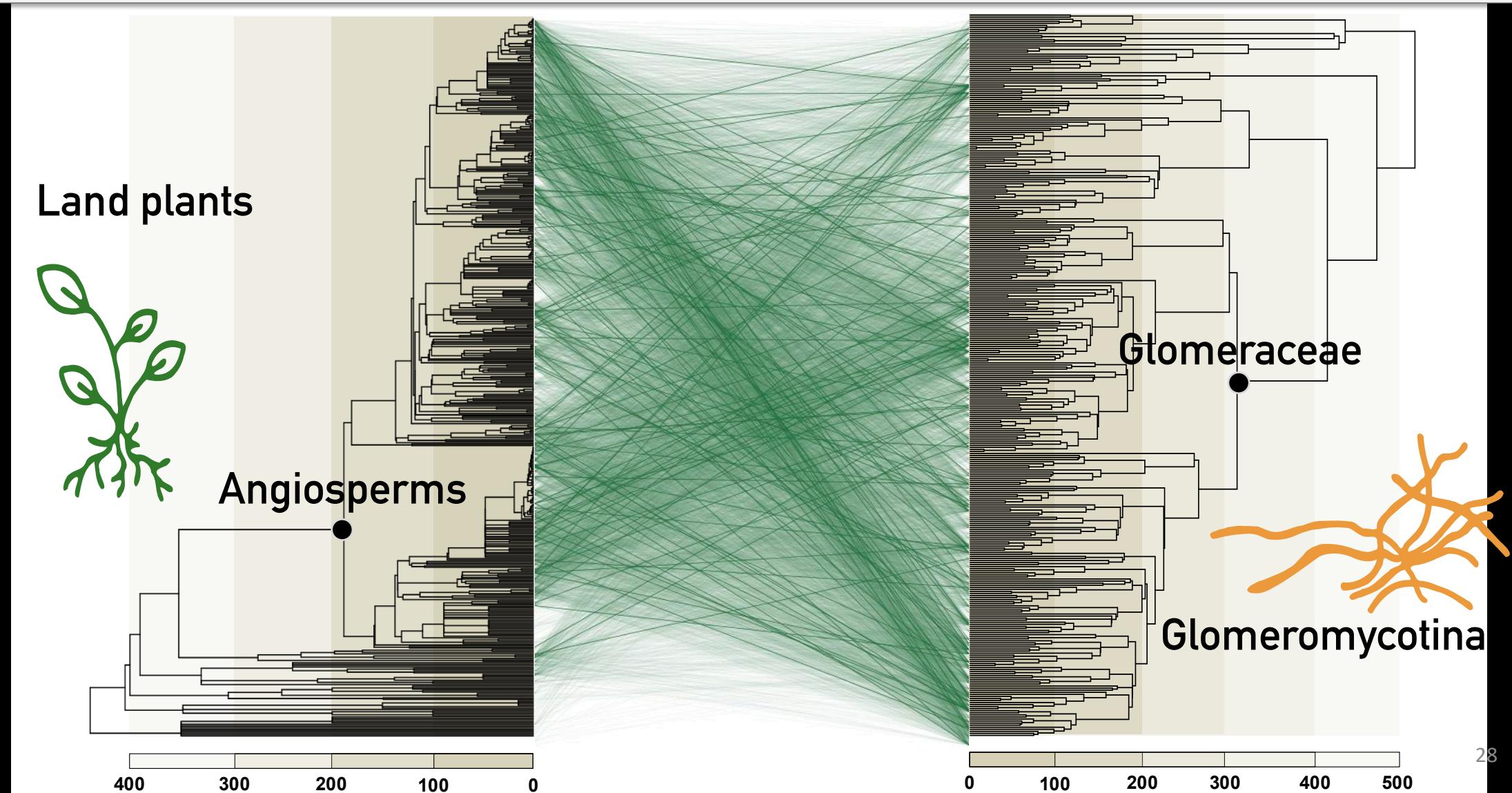
384 Glomeromycotina OTUs

(Öpik et al. 2010)

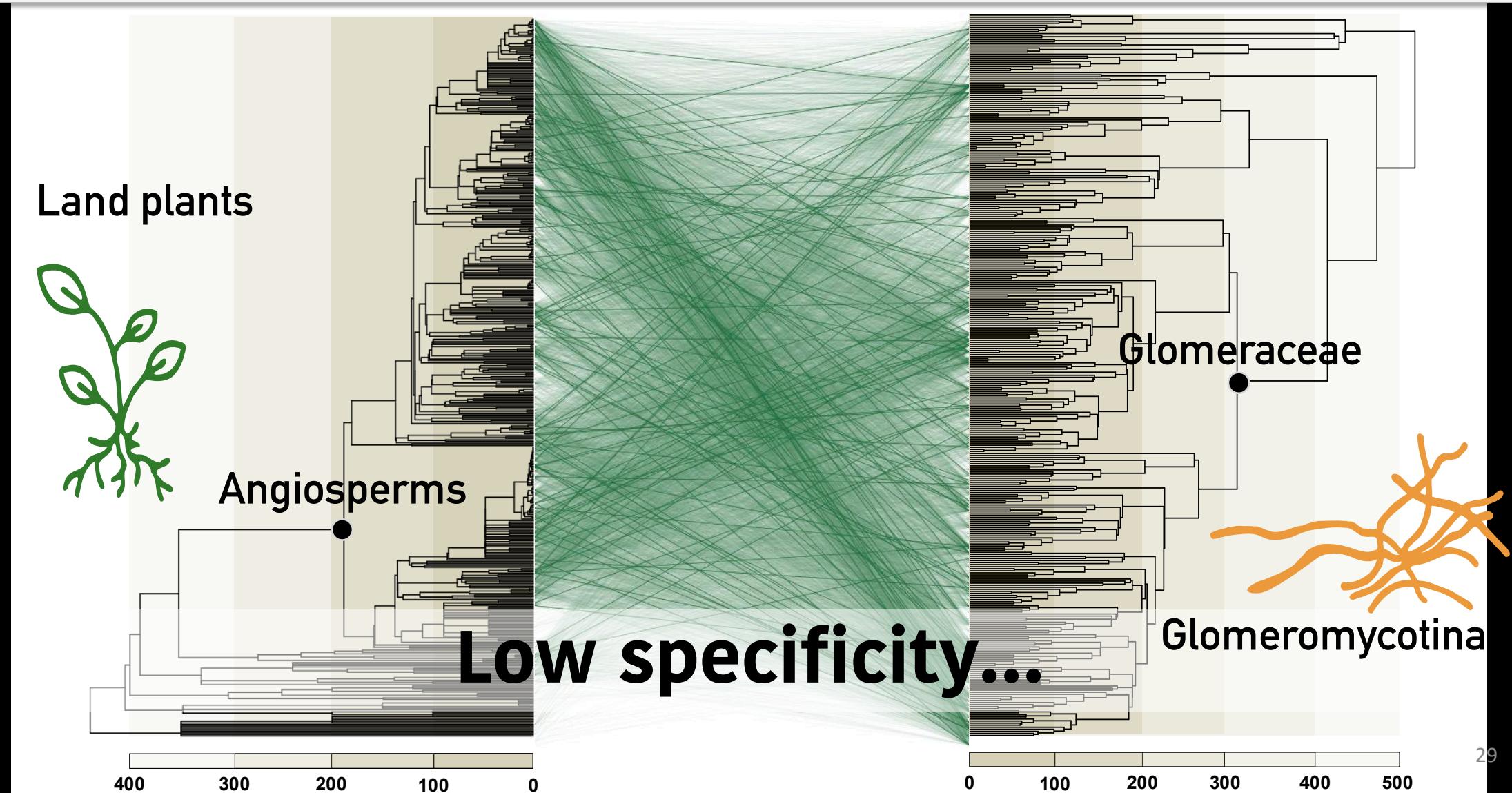


490 plant species

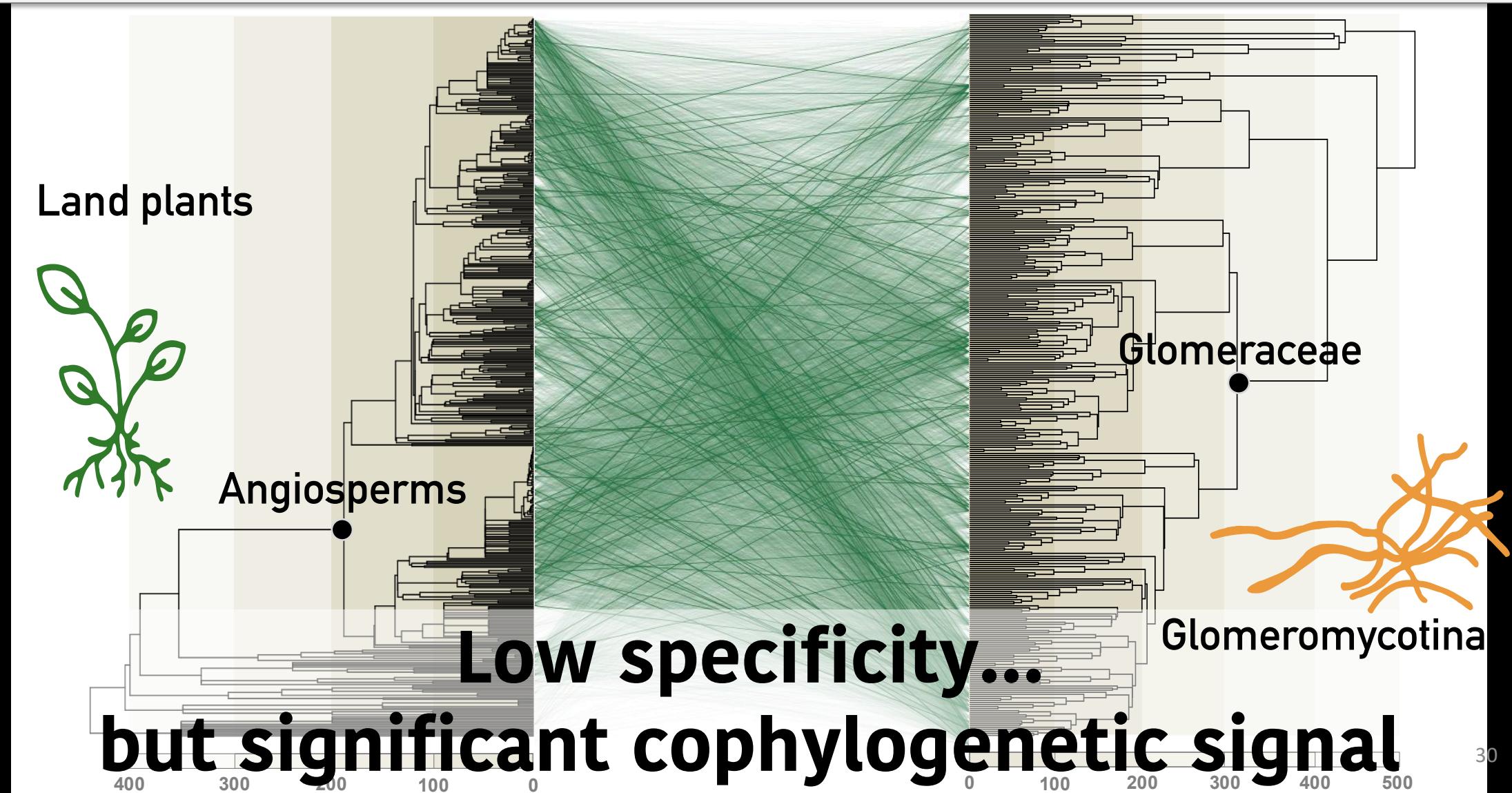
Plant-Glomeromycotina network at global scale



Plant-Glomeromycotina network at global scale



Plant-Glomeromycotina network at global scale



How to explain this cophylogenetic signal?

How to explain this cophylogenetic signal?

PROCEEDINGS
OF
THE ROYAL
SOCIETY **B**



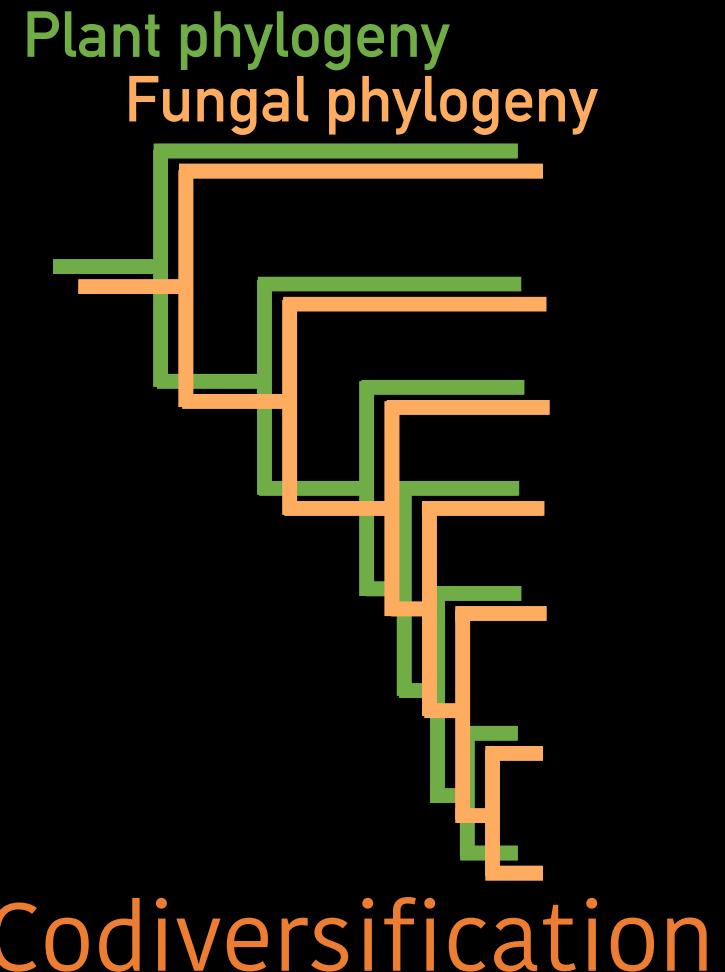
Proc. R. Soc. B
doi:10.1098/rspb.2007.1622
Published online

Breakdown and delayed cospeciation in the arbuscular mycorrhizal mutualism

Vincent Merckx^{1,*} and Martin I. Bidartondo^{2,3}

¹Laboratory of Plant Systematics, K. U. Leuven, Kasteelpark Arenberg 31, PO Box 2437, 3001 Leuven, Belgium

²Imperial College, London and ³Royal Botanic Gardens, Kew TW9 3DS, UK



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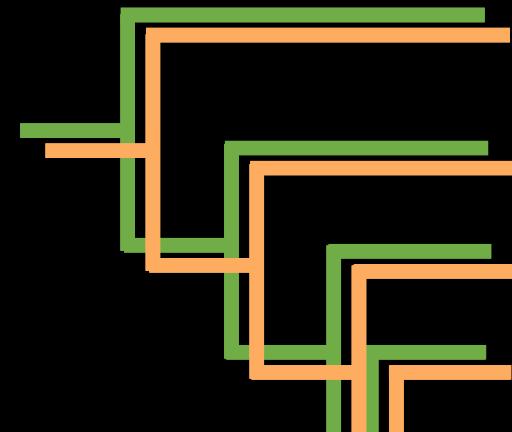
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Plant phylogeny
Fungal phylogeny



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<https://doi.org/10.1093/sysbio/syae013>

Advance Access Publication March 13, 2024

Distinguishing Cophylogenetic Signal from Phylogenetic Congruence Clarifies the Interplay Between Evolutionary History and Species Interactions

BENOÎT PEREZ-LAMARQUE^{1,2,*}, AND HÉLÈNE MORLON¹,

How to explain this cophylogenetic signal?

PROCEEDINGS
OF
THE ROYAL
SOCIETY **B**



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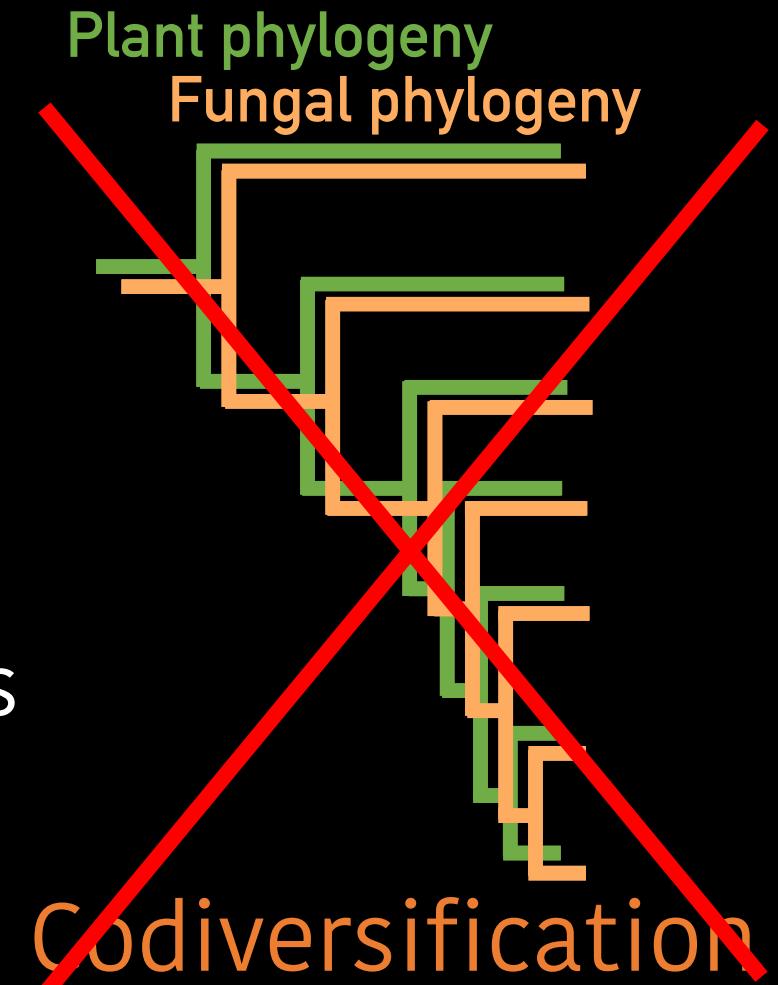
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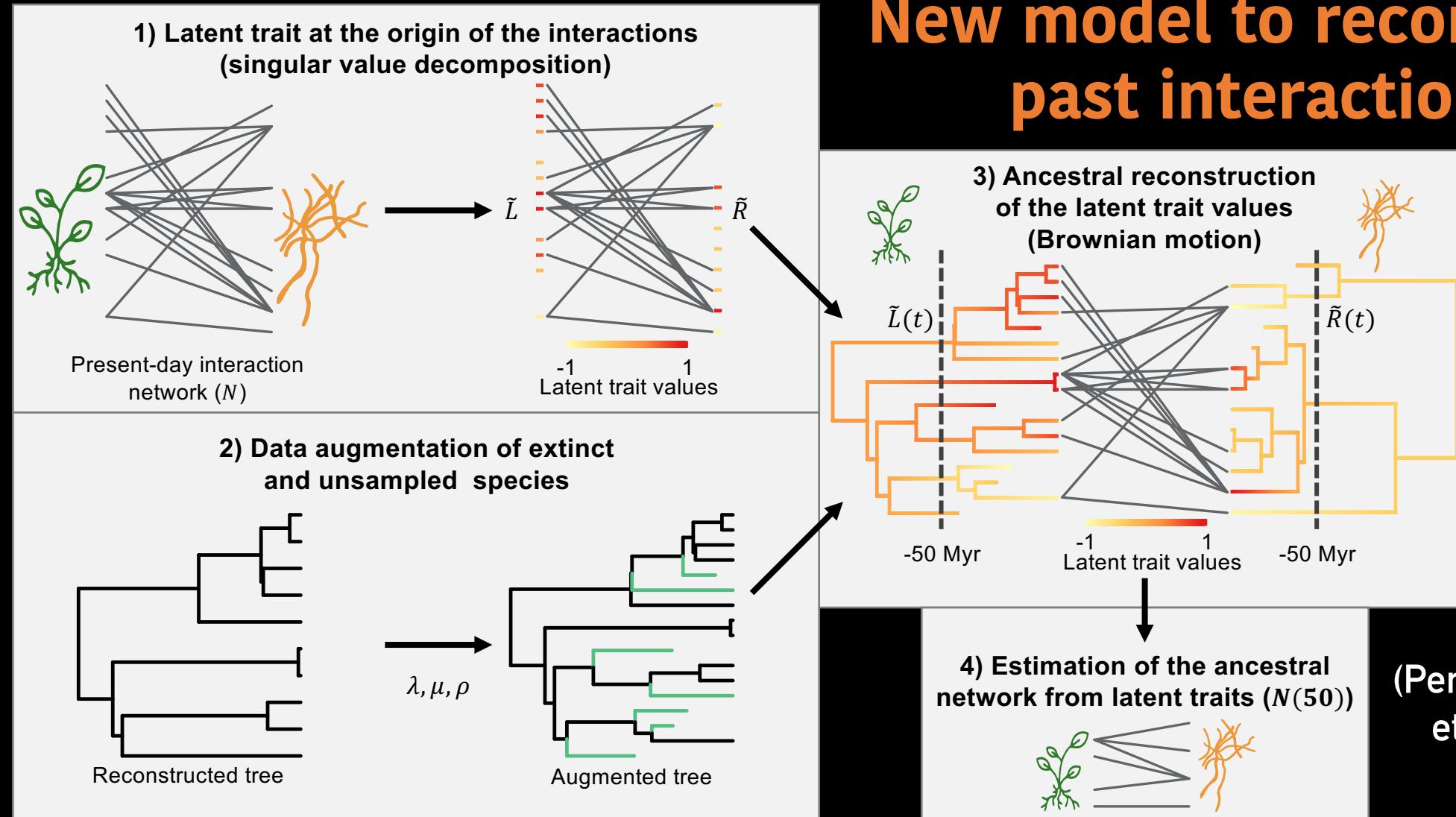
Meta-analysis of 30 mycorrhizal networks

→ No evidence of codiversification

(Bodin et al., in prep.)



How to explain this cophylogenetic signal?



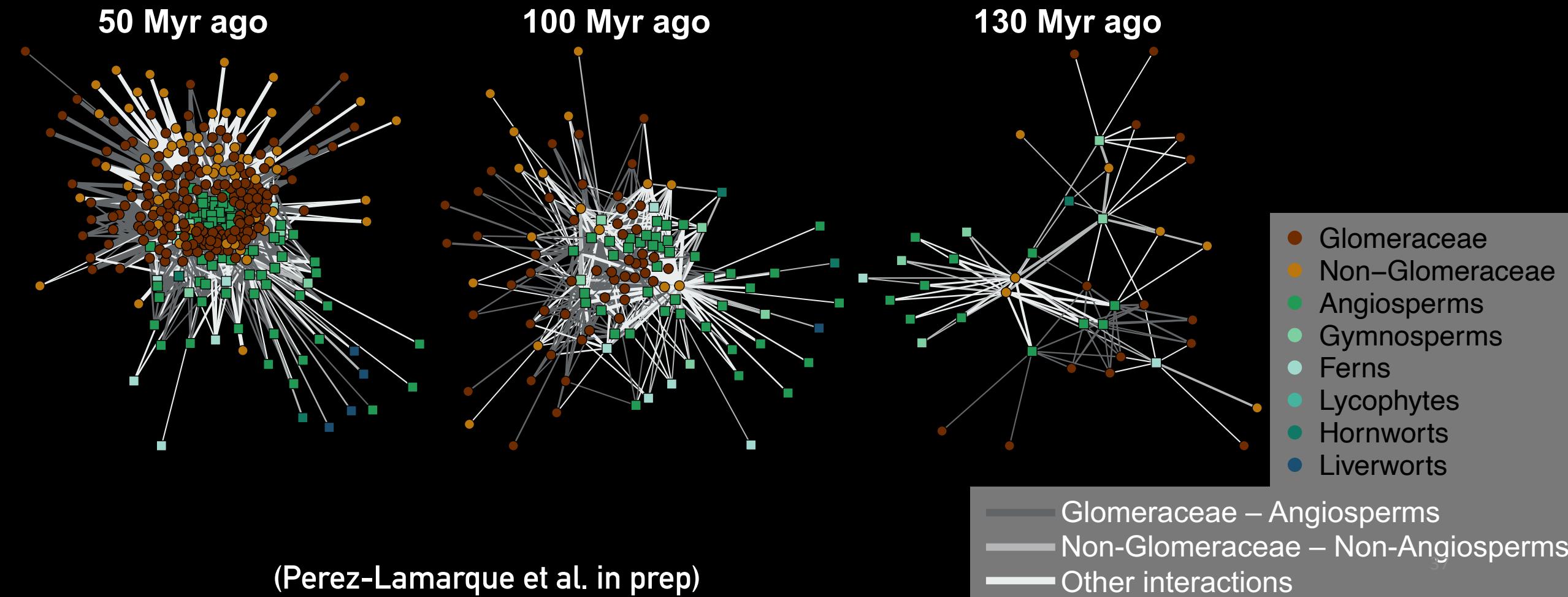
How to explain this cophylogenetic signal?

Ancestral plant-Glomeromycotina networks



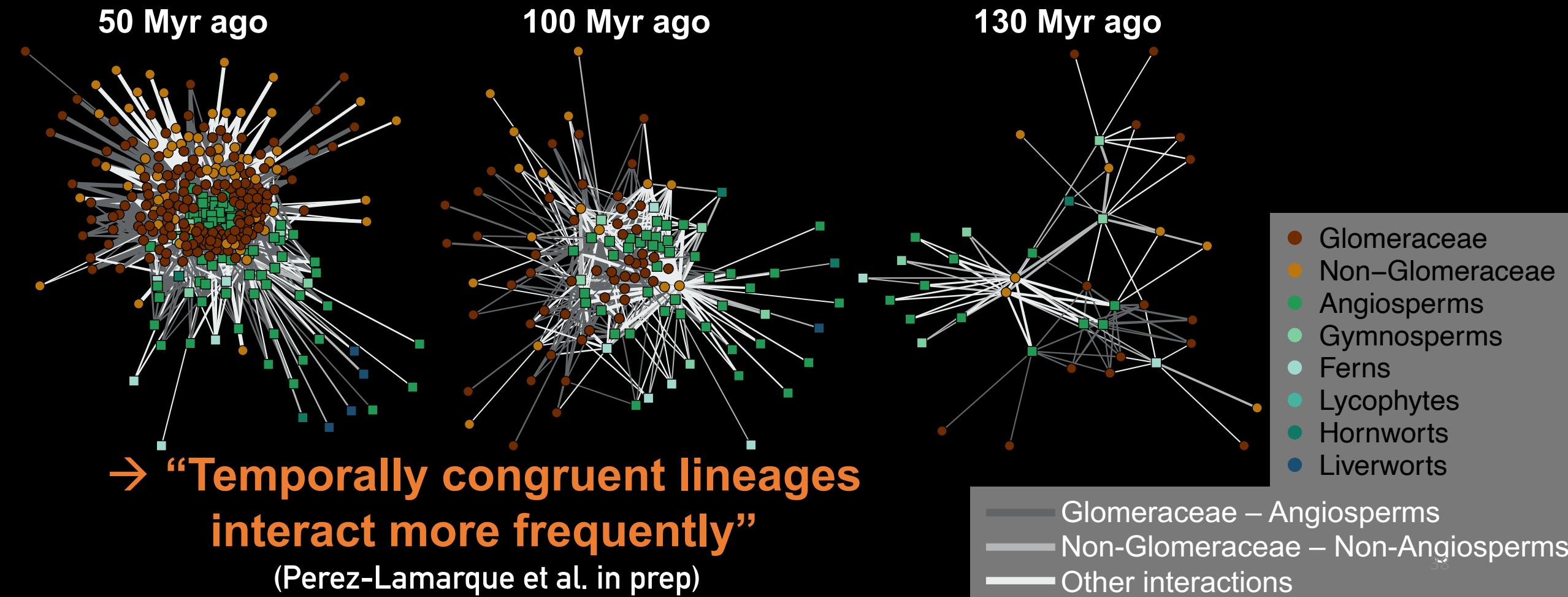
How to explain this cophylogenetic signal?

Ancestral plant-Glomeromycotina networks



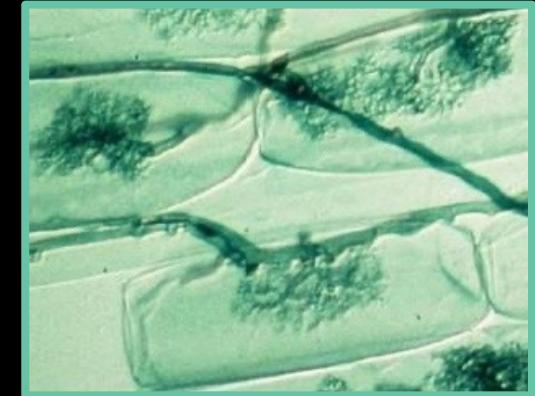
How to explain this cophylogenetic signal?

Ancestral plant-Glomeromycotina networks



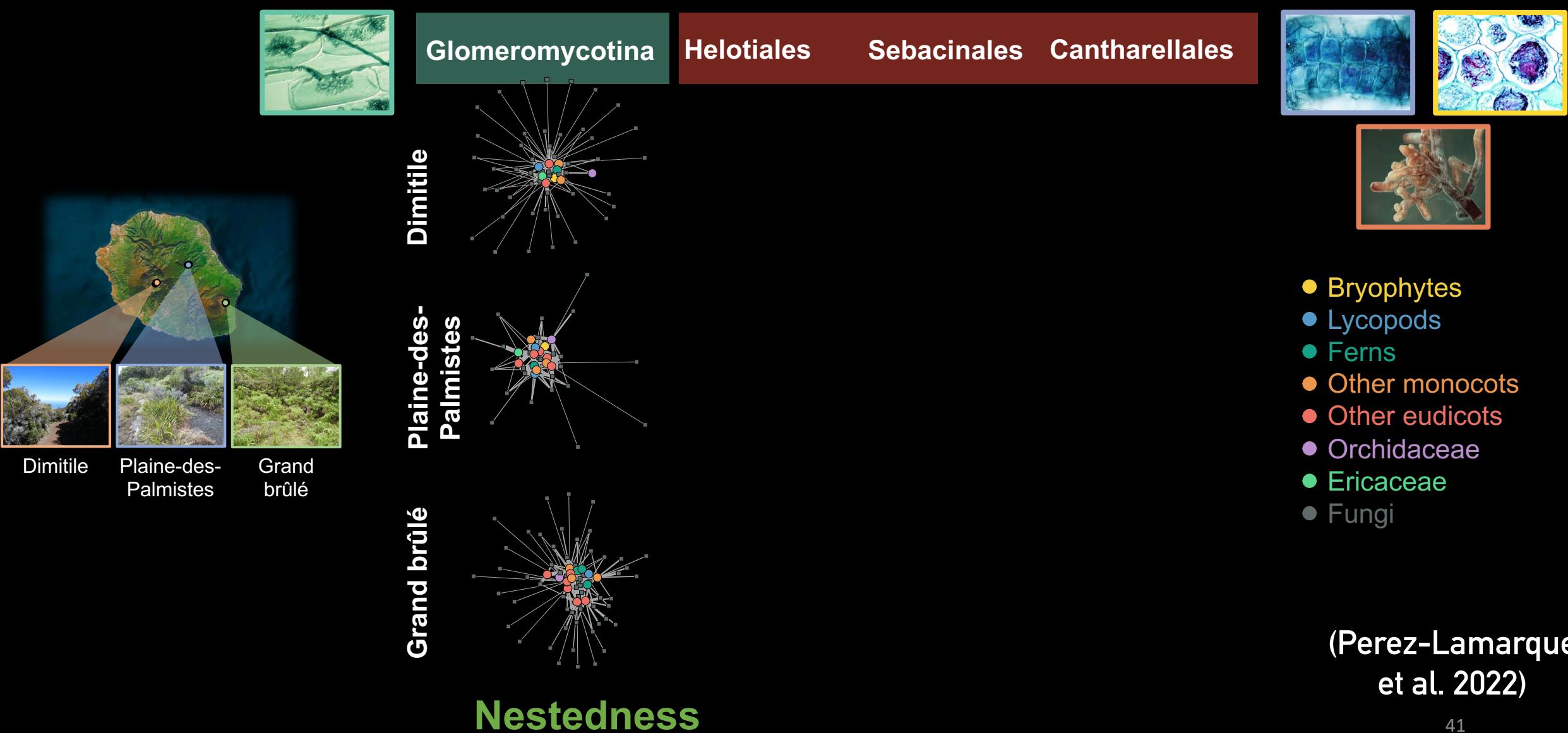
1) The arbuscular mycorrhizal symbiosis: a symbiosis with low specificity:

- **Low specificity**
- **Nested interaction networks**
- **But significant cophylogenetic signal:
“Temporally congruent lineages interact
together”.**

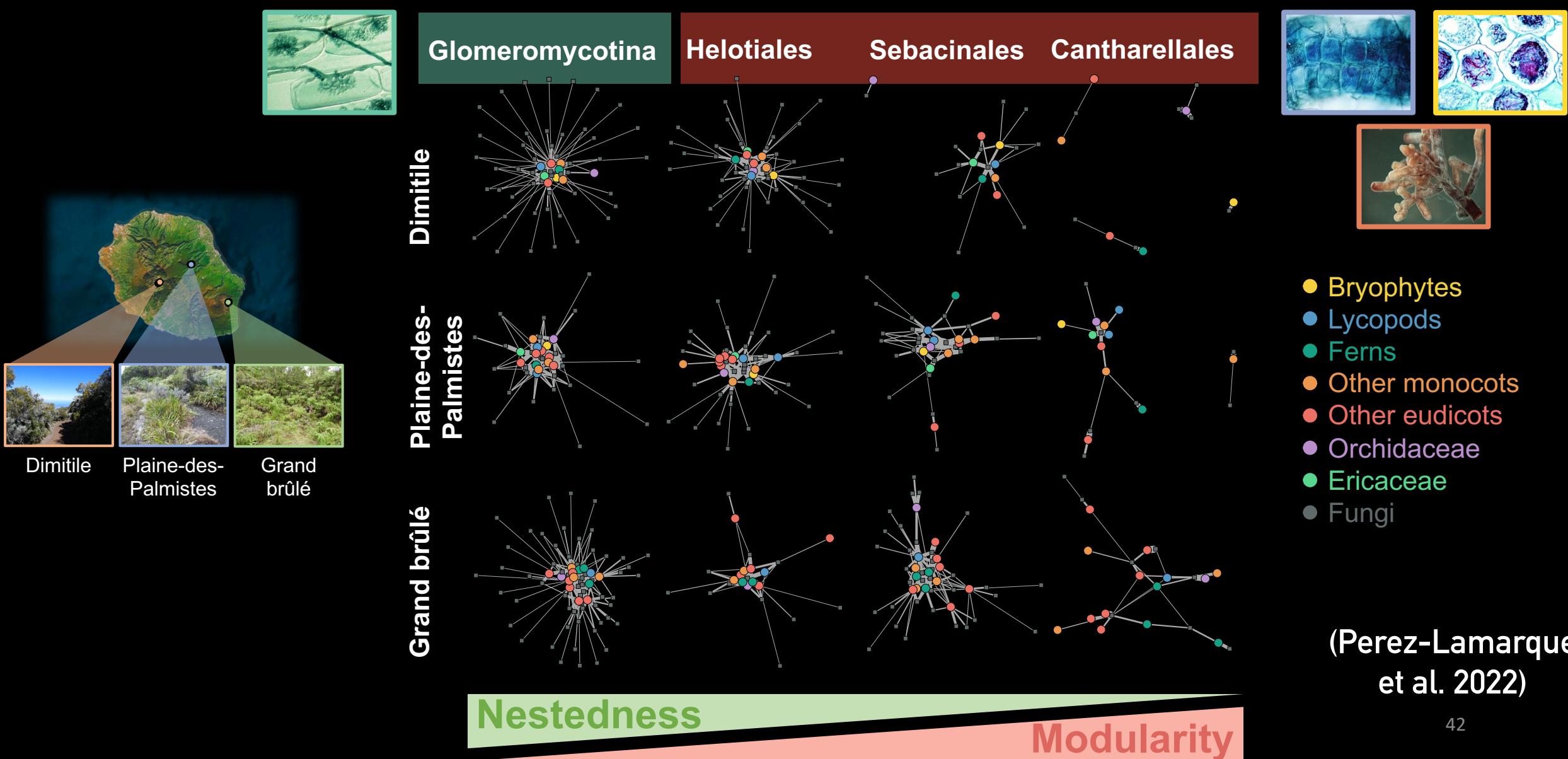


2) Toward more specialized and competitive mycorrhizal symbioses

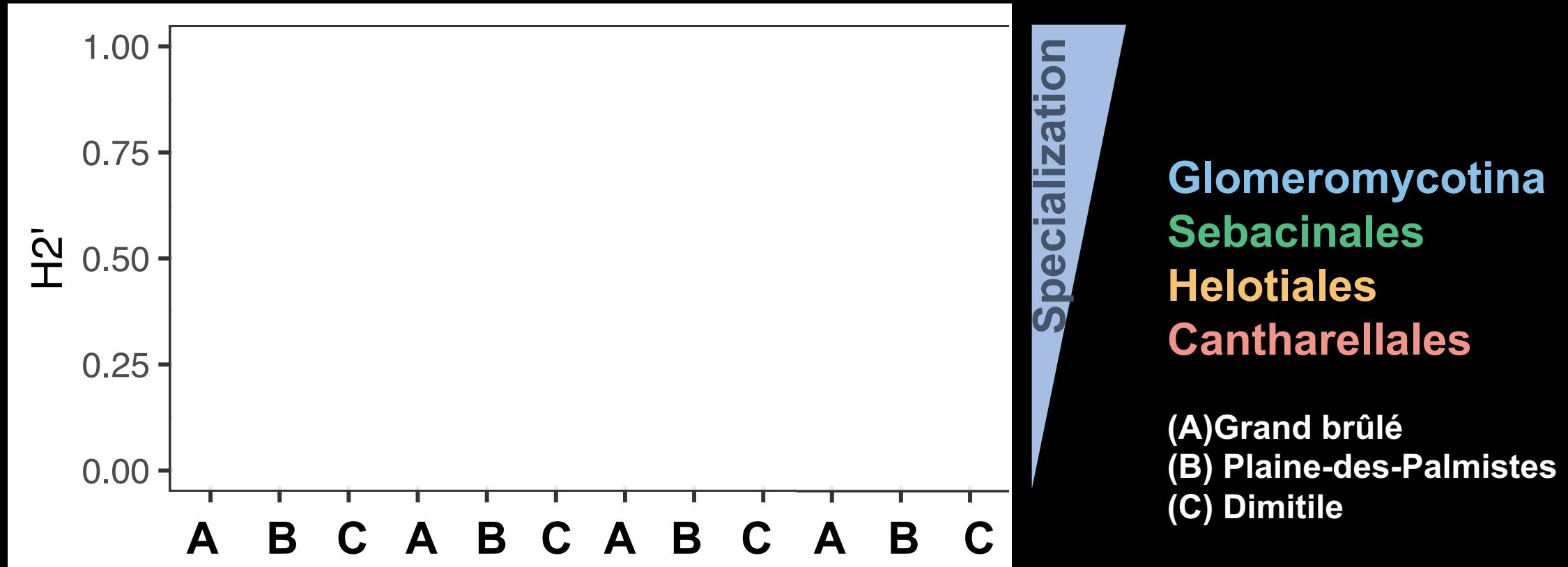
From nestedness to modularity



From nestedness to modularity

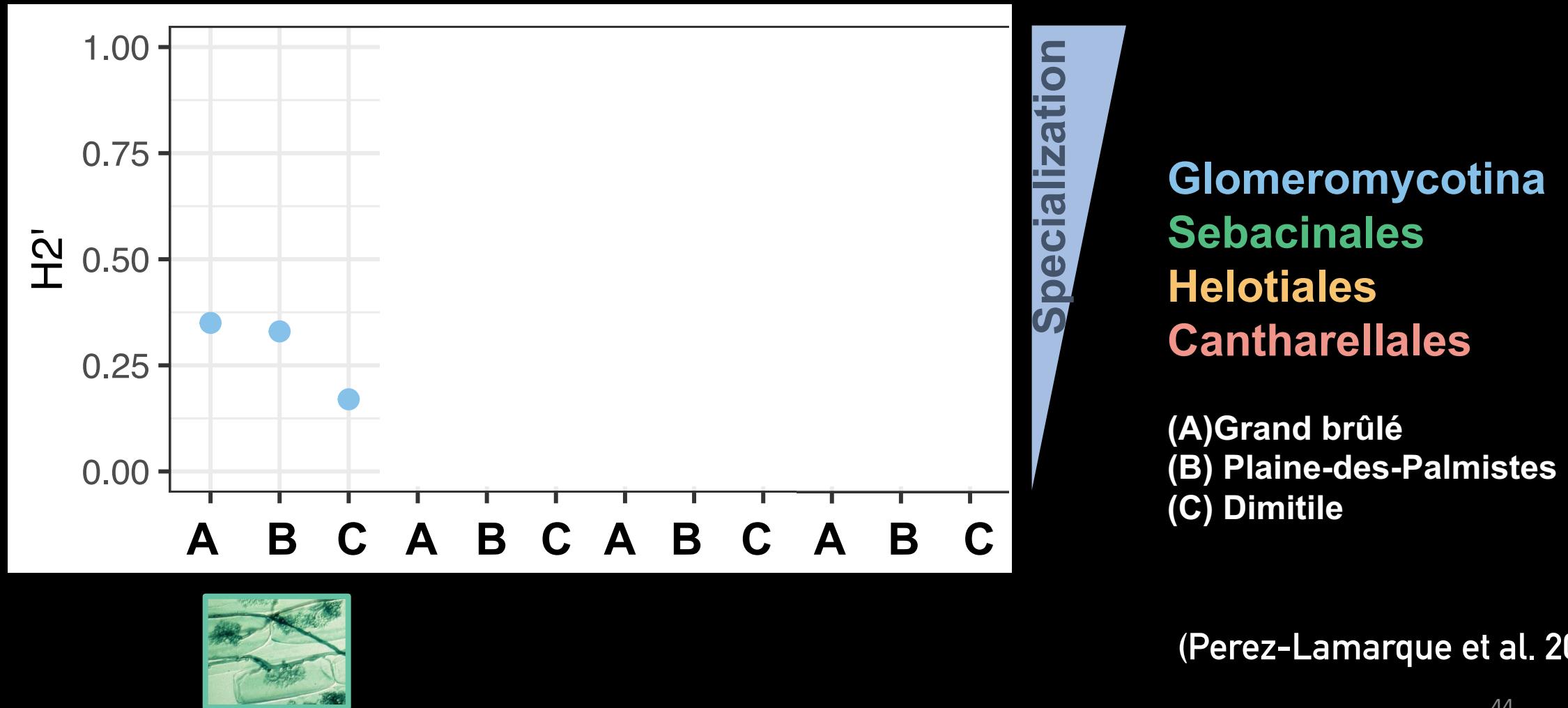


Stronger specificity in other types of mycorrhizal symbioses

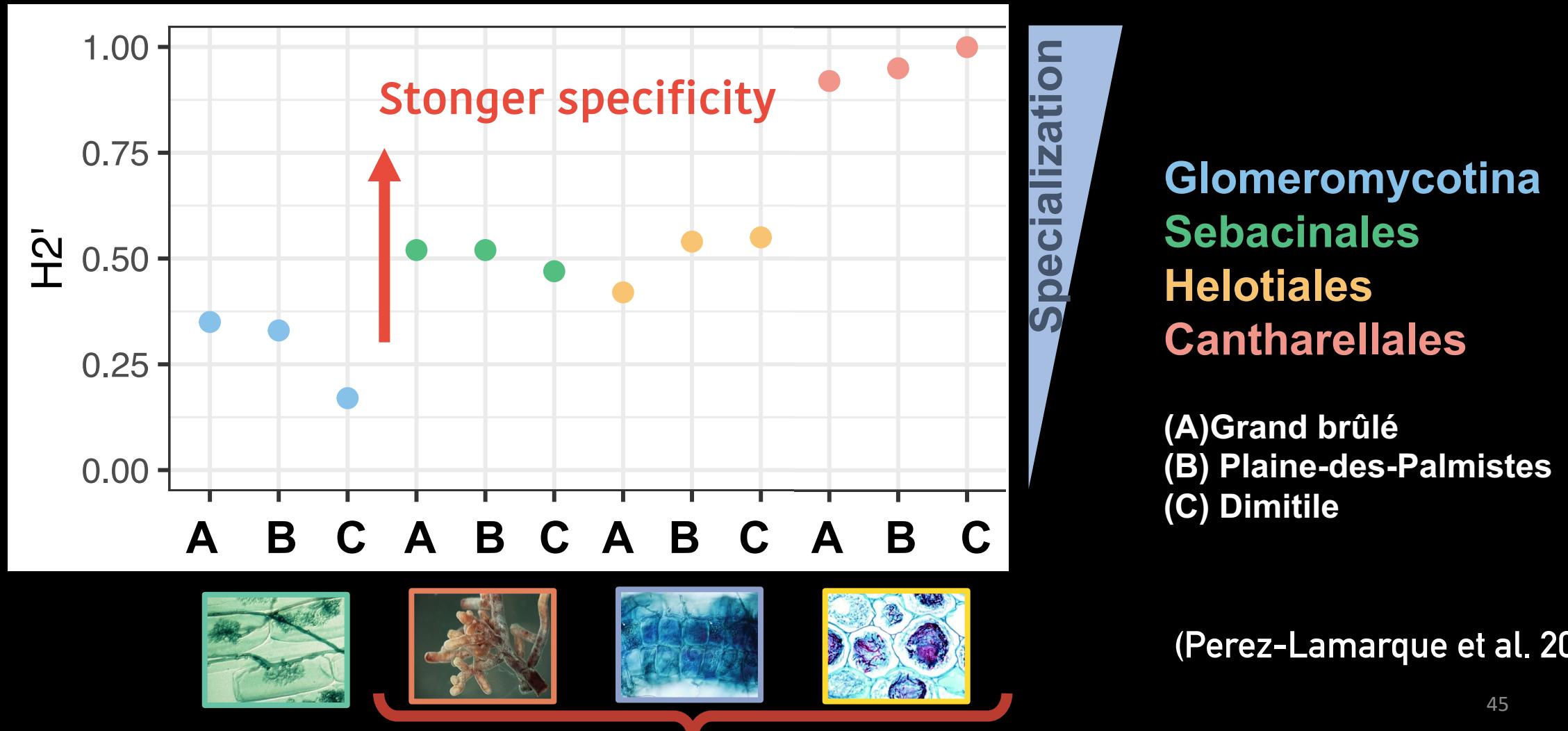


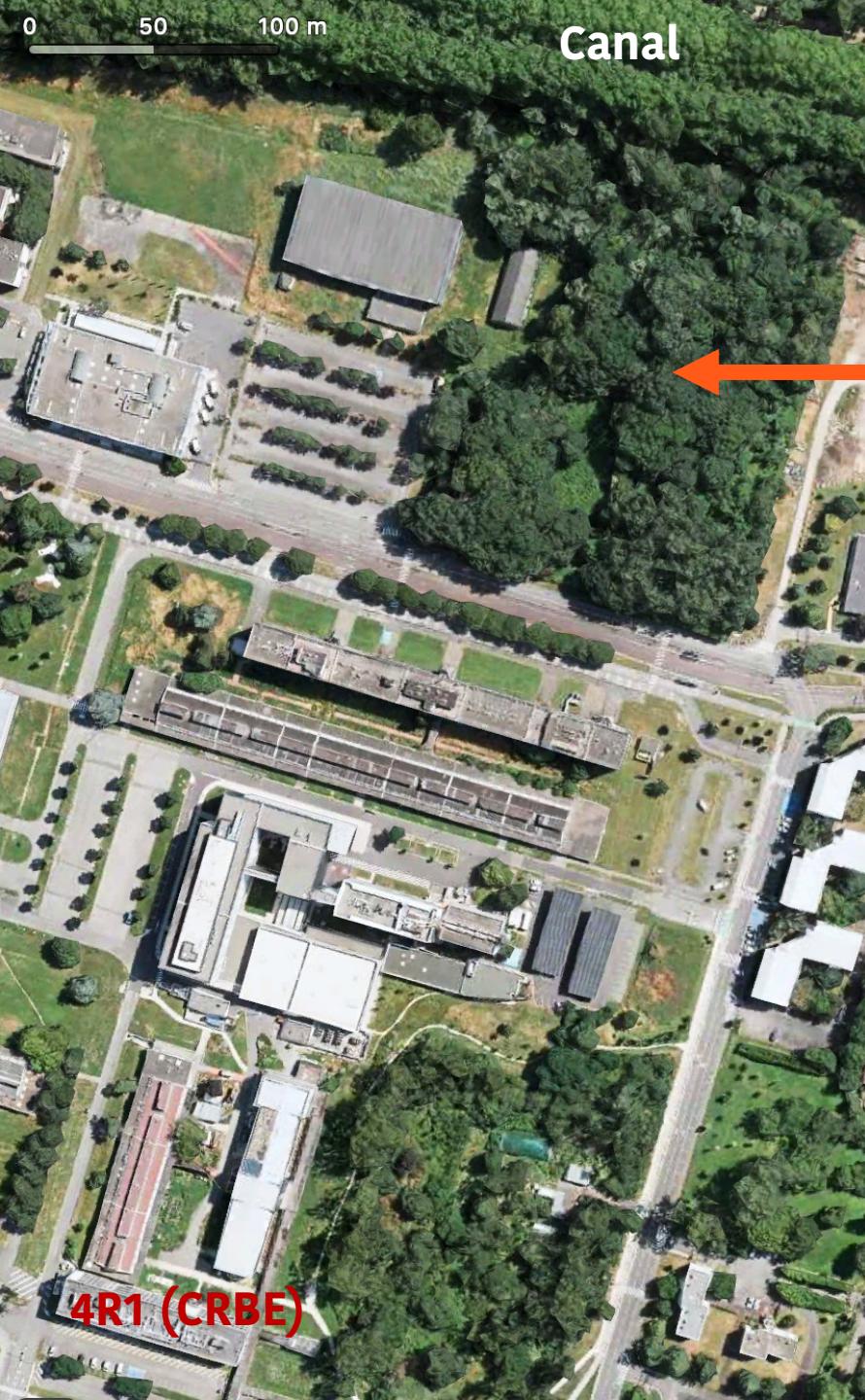
(Perez-Lamarque et al. 2022)

Stronger specificity in other types of mycorrhizal symbioses



Stronger specificity in other types of mycorrhizal symbioses



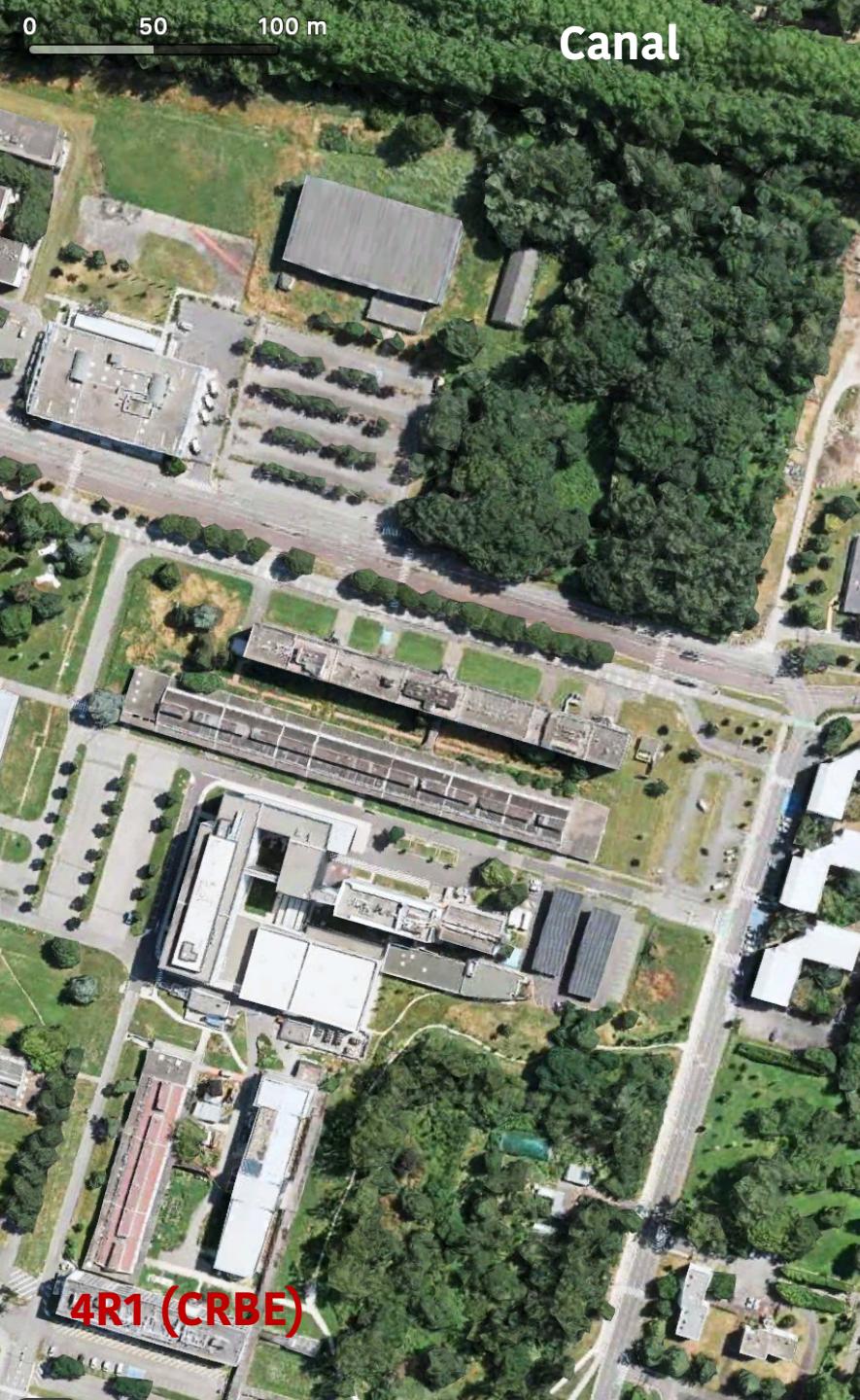


Strong specificity in the ectomycorrhizal symbiosis

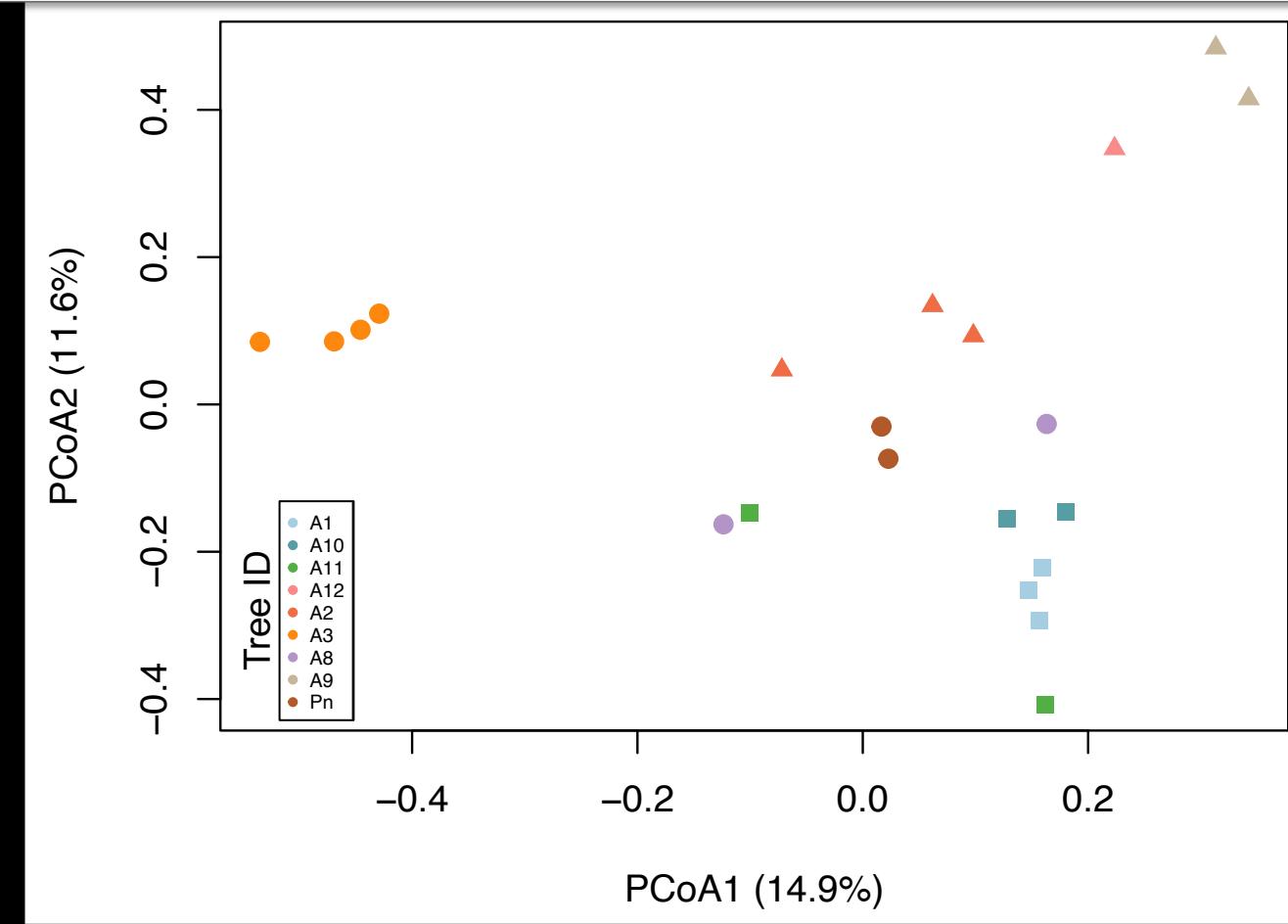
Bois de Pouciquot

Characterization of the ectomycorrhizal fungi associated with *Populus alba* since 2017

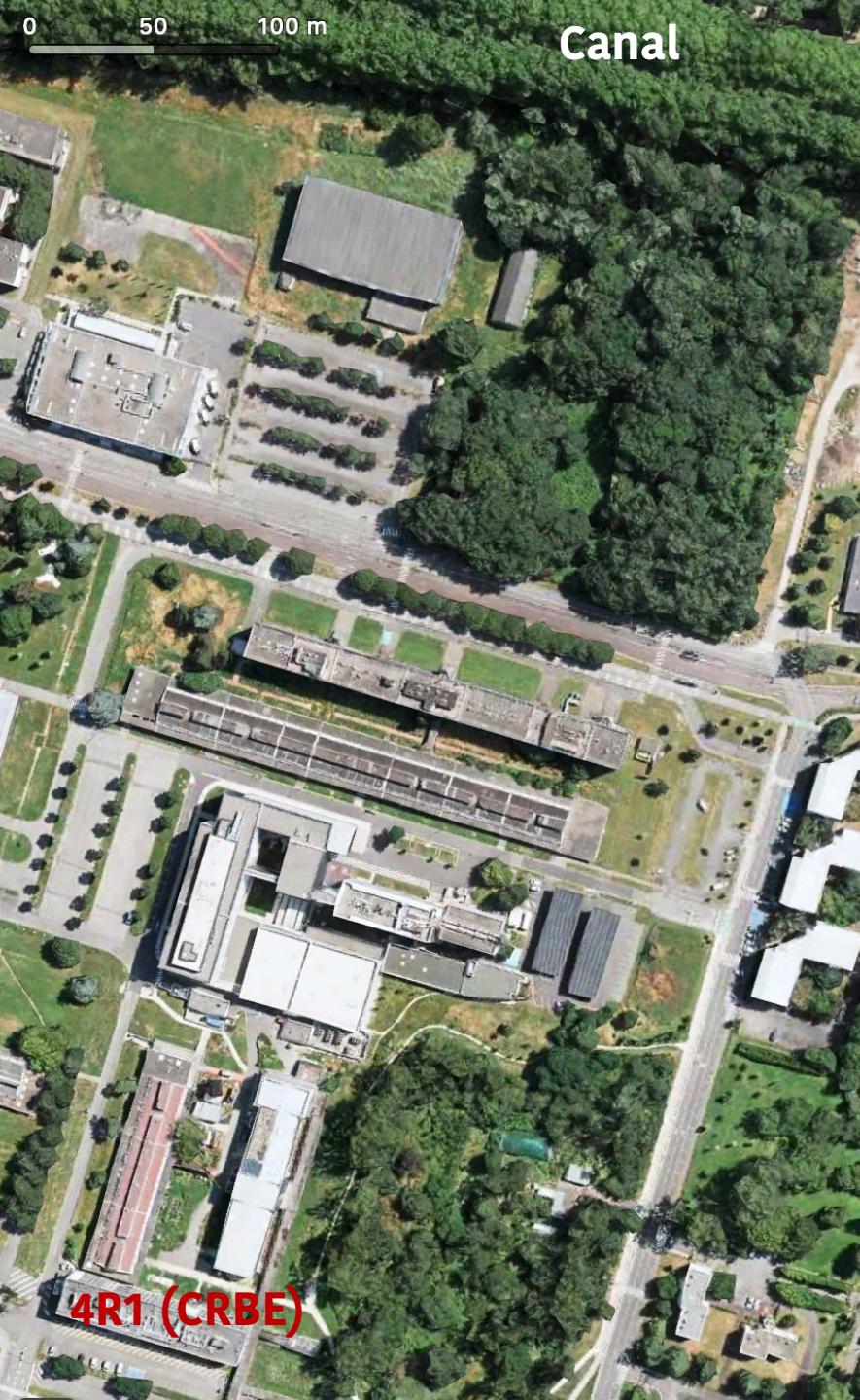
by Patricia Jargeat and the students from the M1 Biologie végétale (UT)



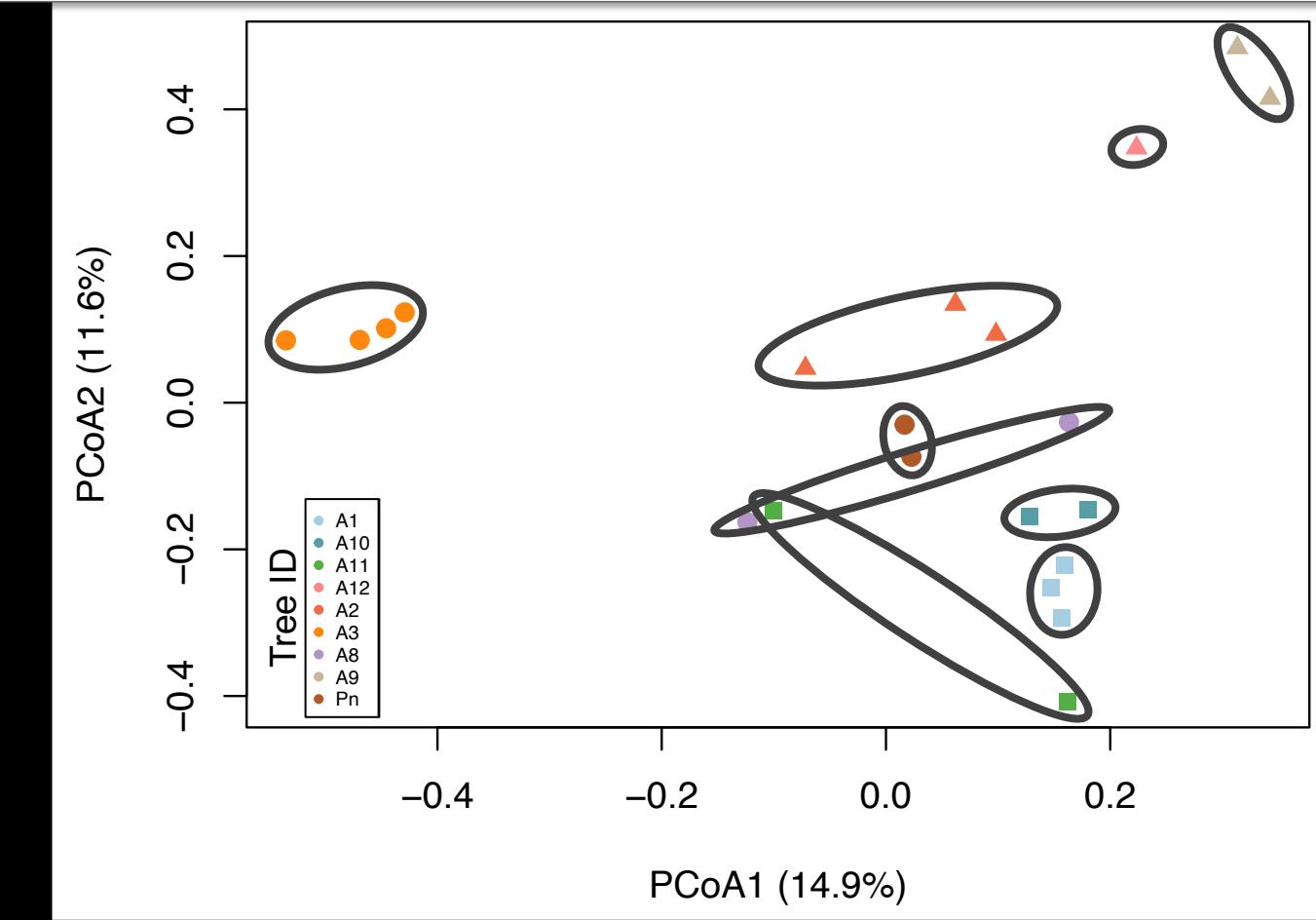
Strong specificity in the ectomycorrhizal symbiosis



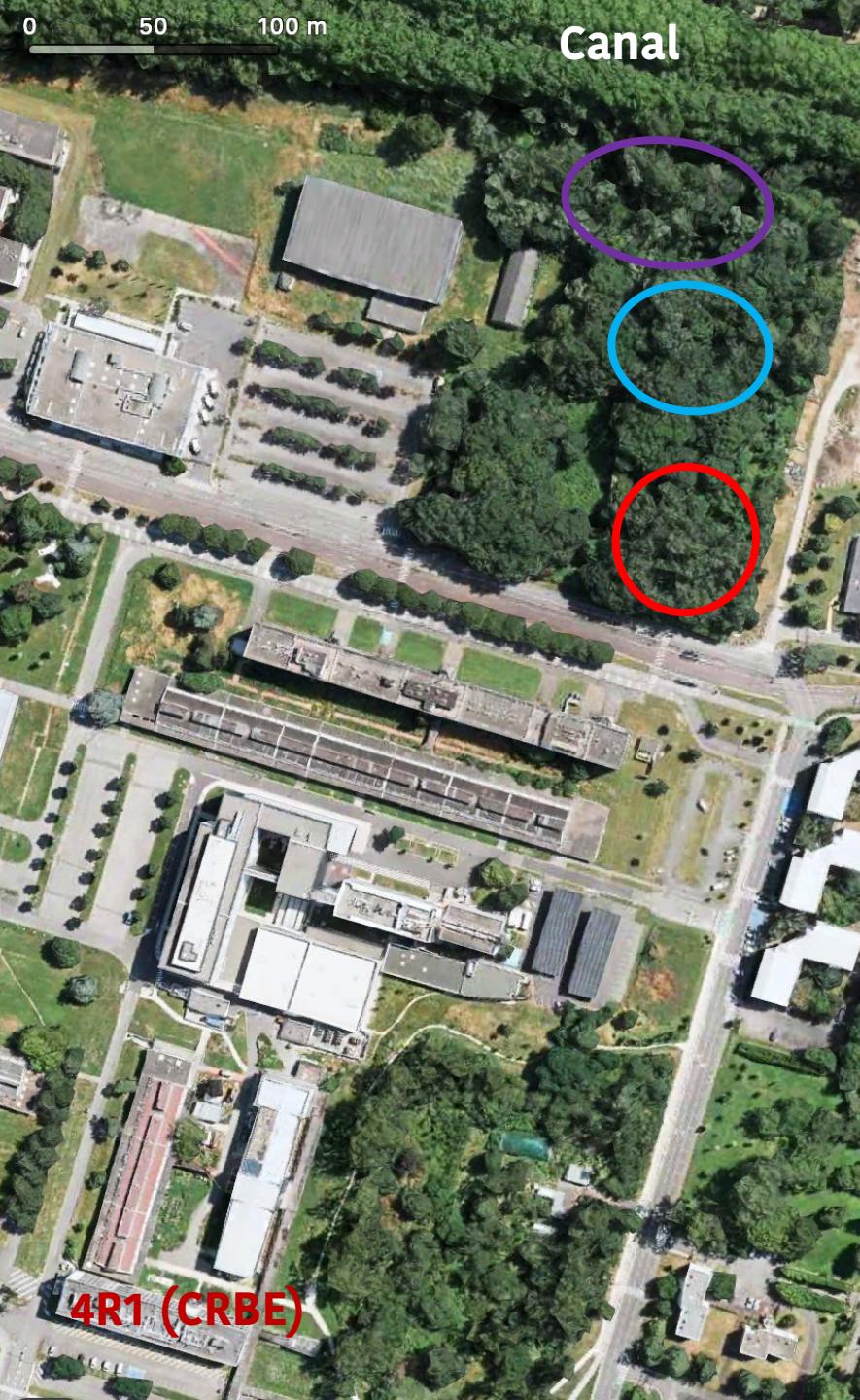
→ significant influence of the tree individual



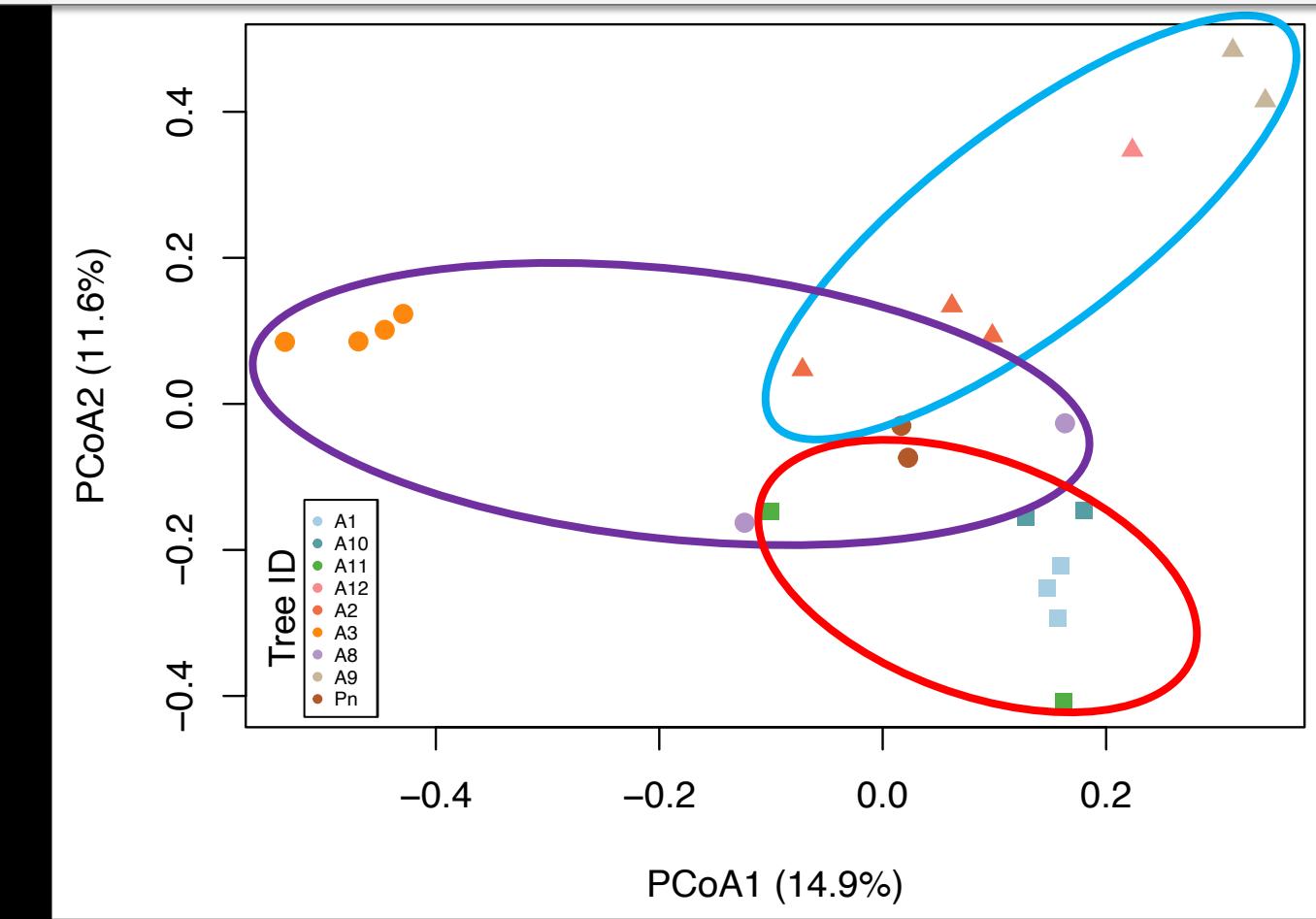
Strong specificity in the ectomycorrhizal symbiosis



→ significant influence of the tree individual

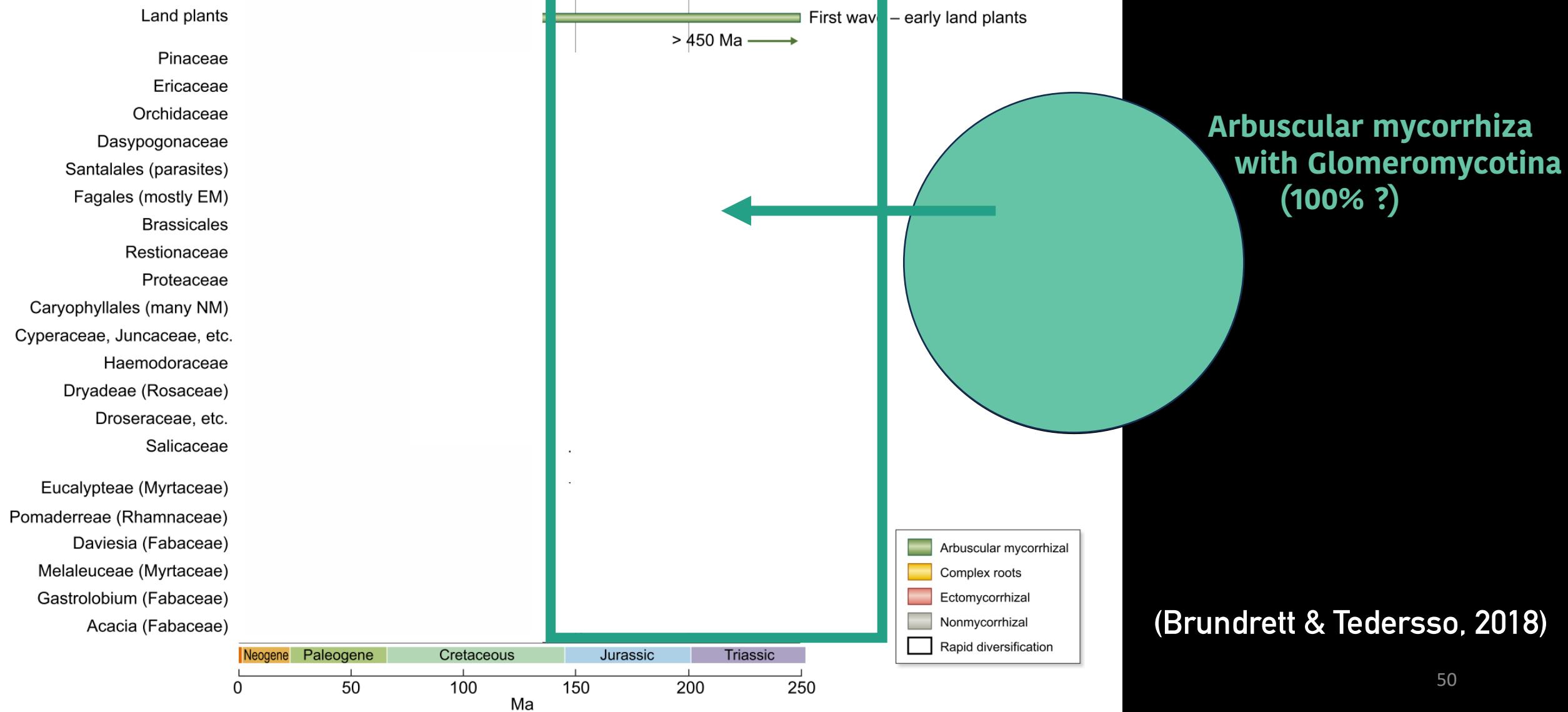


Strong specificity in the ectomycorrhizal symbiosis

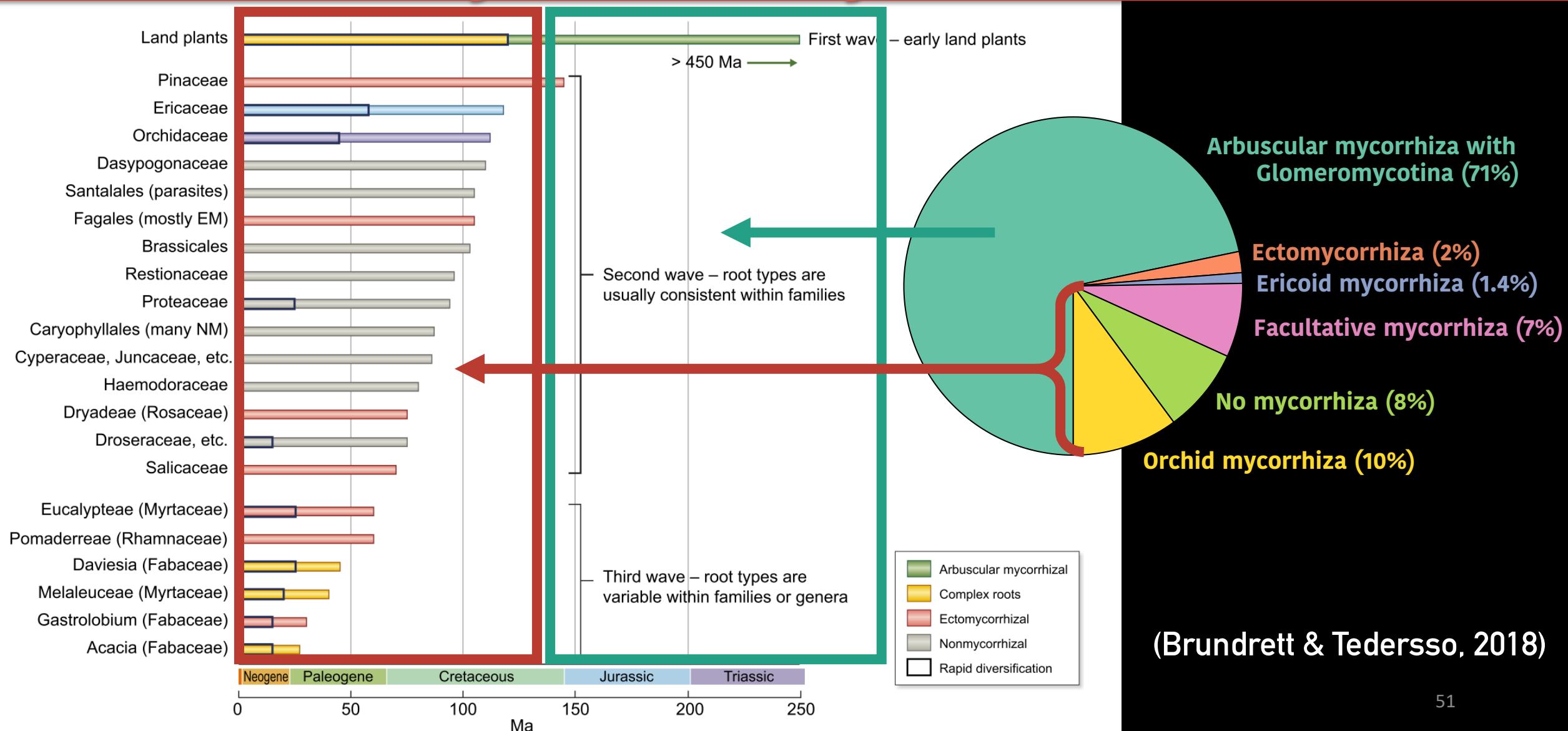


→ significant influence of the tree individual and the habitat

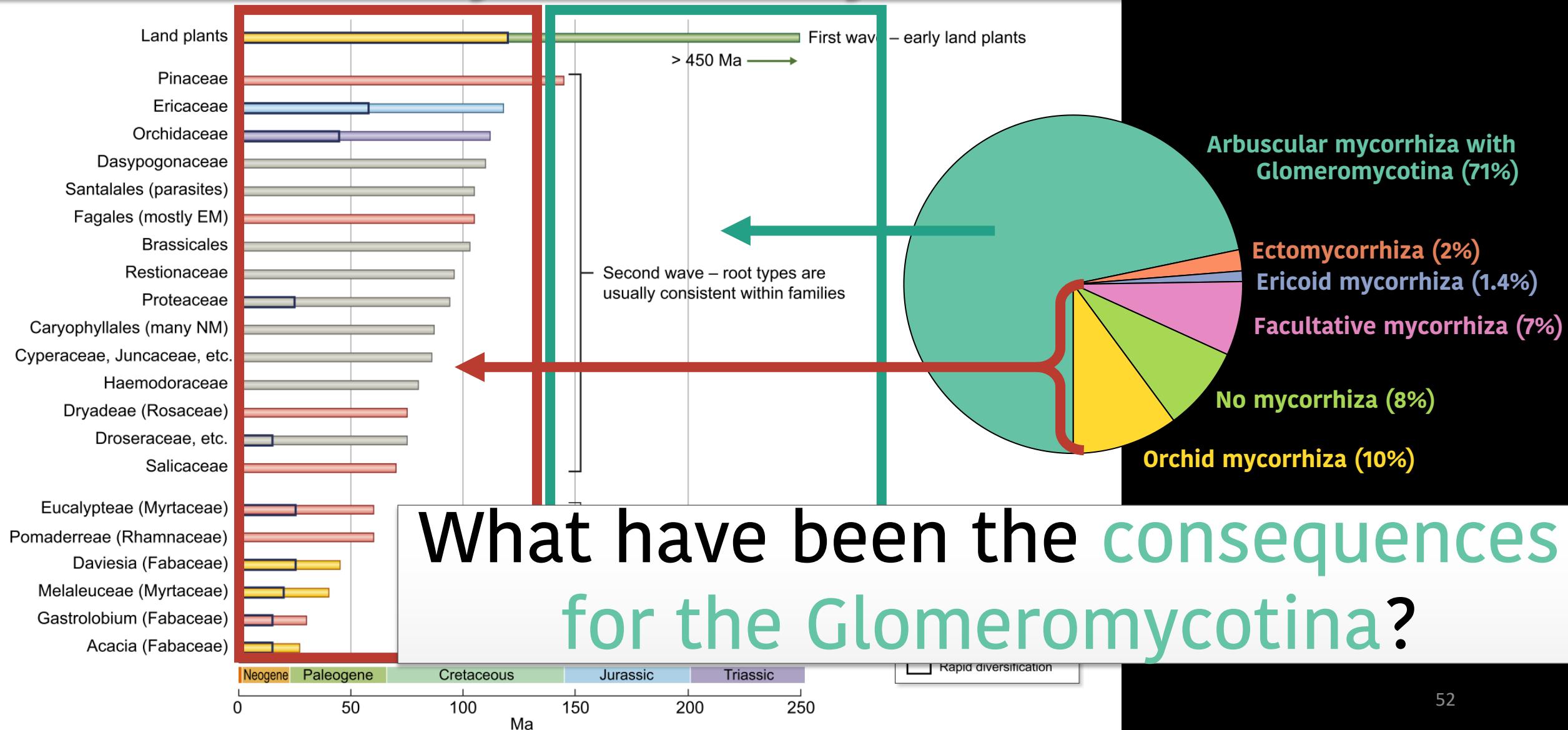
Emergence of more specialized mycorrhizal symbioses



Emergence of more specialized mycorrhizal symbioses

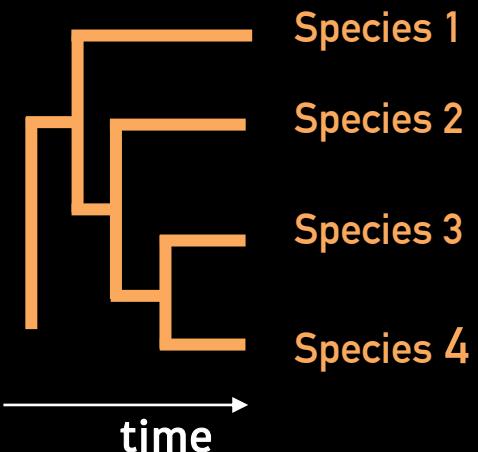


Emergence of more specialized mycorrhizal symbioses



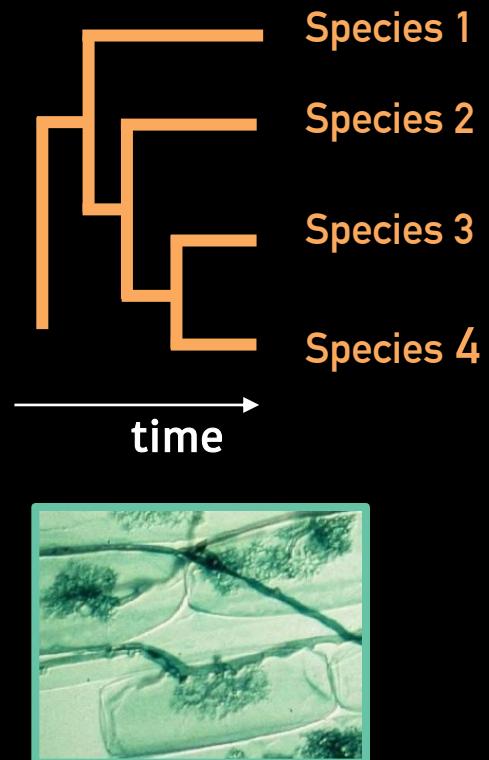
What have been the consequences of the emergence of more specialized mycorrhizal symbioses for Glomeromycotina ?

Glomeromycotina
species
diversification
= speciation +
extinction

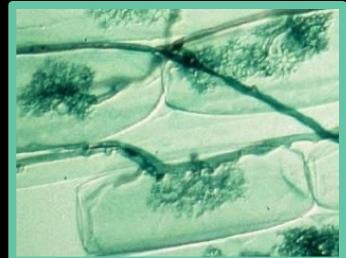


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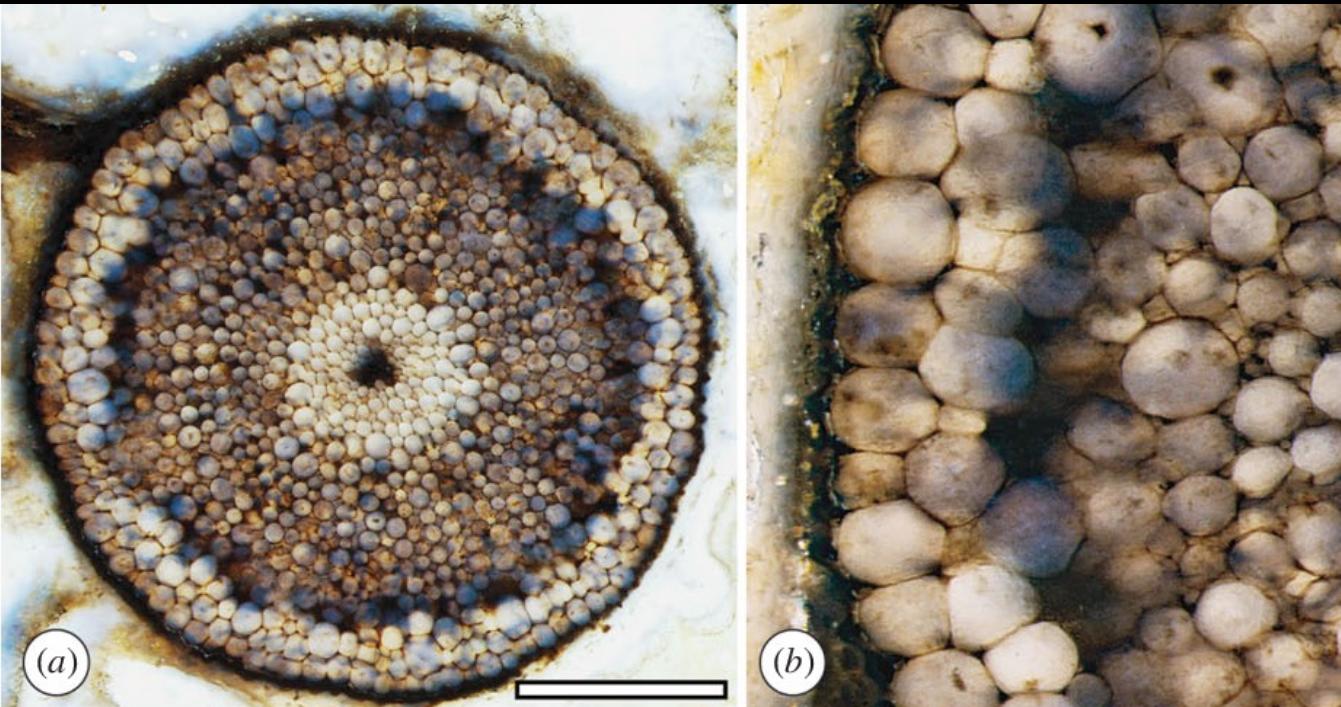
What have been the drivers
of Glomeromycotina
diversification?



What have been the drivers of Glomeromycotina diversification?

Lack of measures of past diversity

Microbial fossils cannot delineate “species”

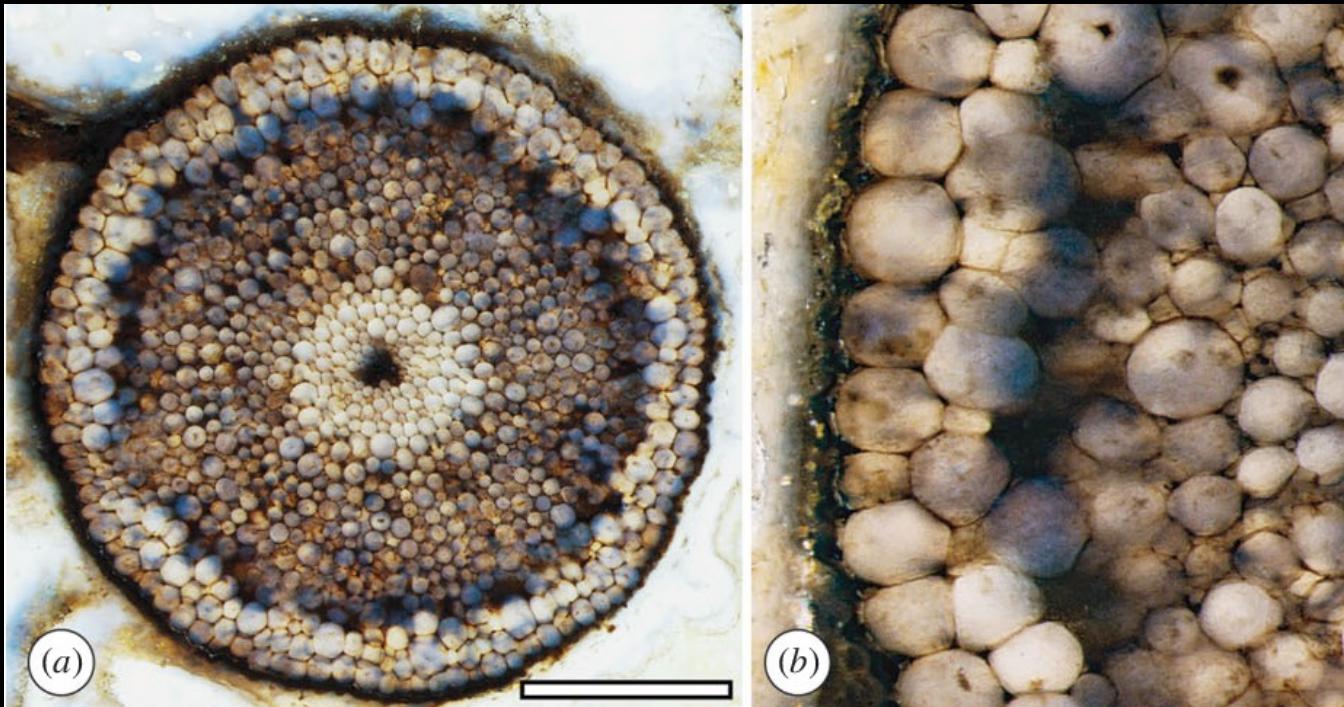


(Kerp et al. 2017)

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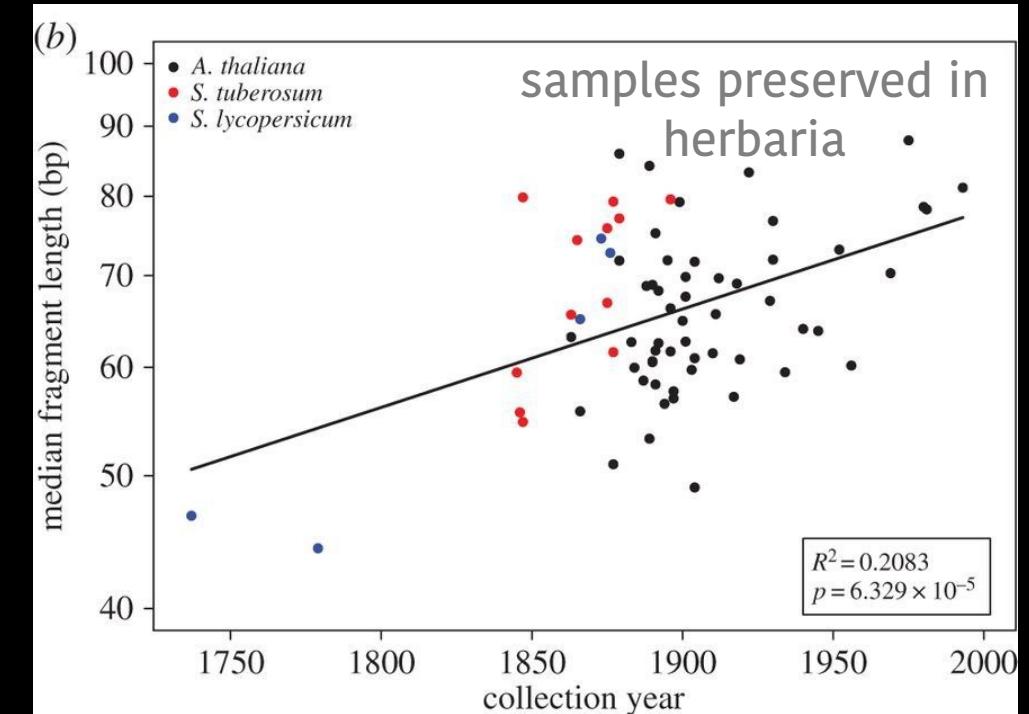
Lack of measures of past diversity

Microbial fossils cannot delineate “species”



(Kerp et al. 2017)

Fast DNA degradation



(Weiβ et al. 2016)

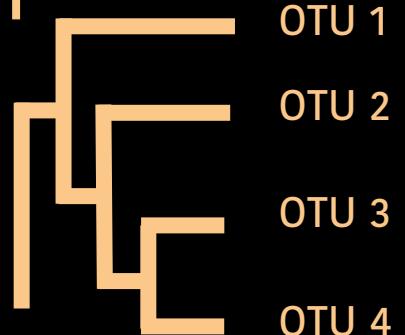
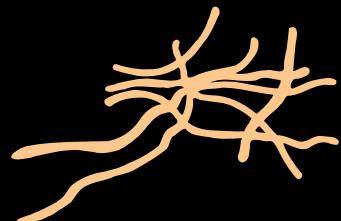
What have been the drivers of Glomeromycotina diversification?

MaarjAM database

rRNA gene

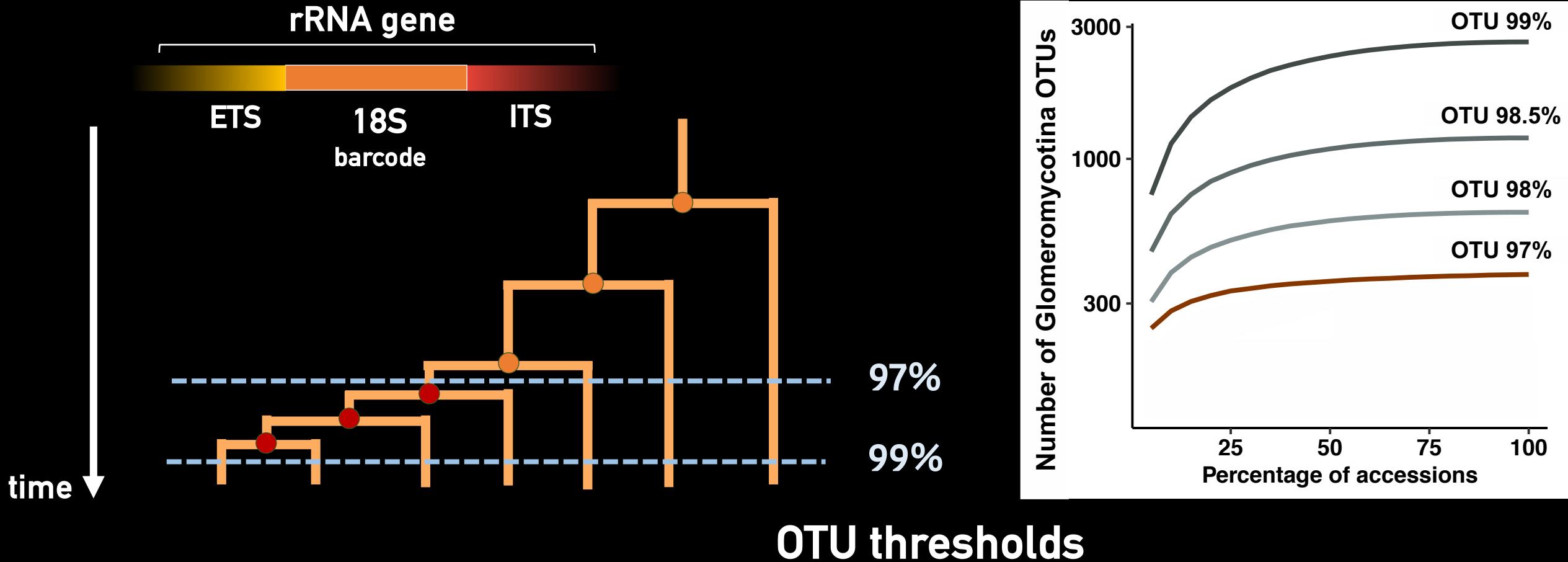
ETS 18S ITS
barcode

Glomeromycotina diversification

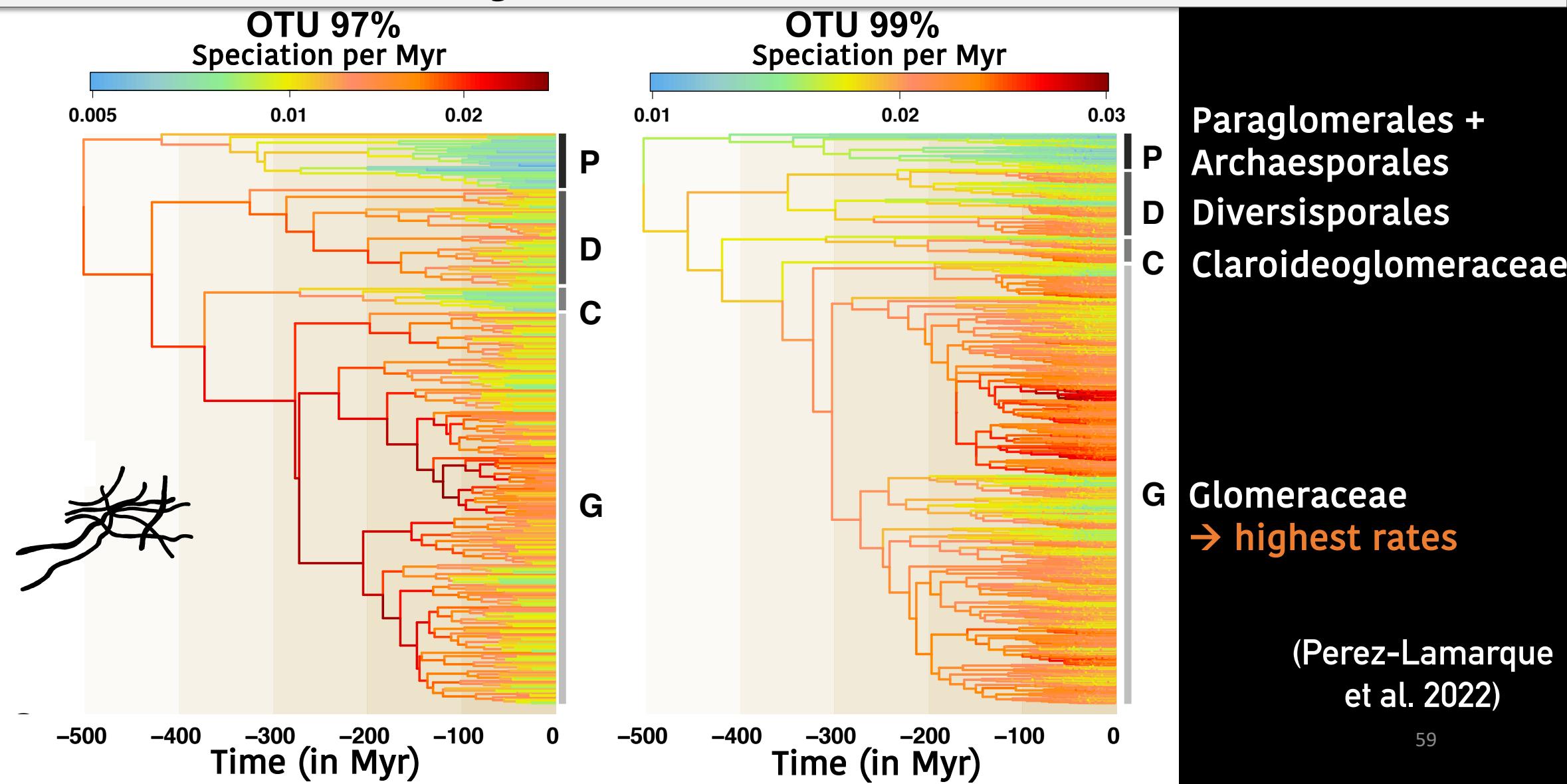


- Species delineation
- Phylogenetic reconstruction
- Estimation of the current global diversity of the group
- Use of species diversification models

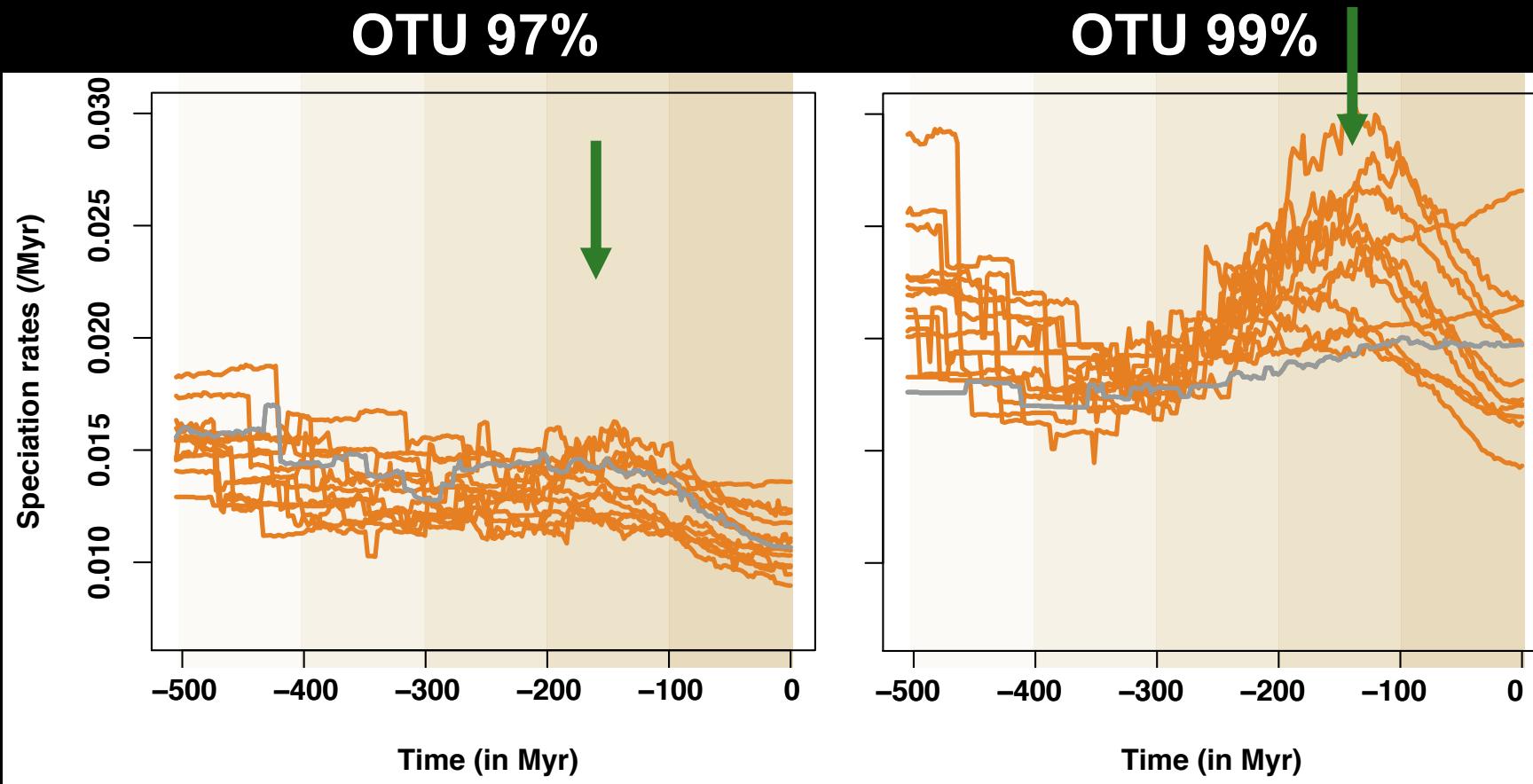
Problem of species delineation in microbial systems



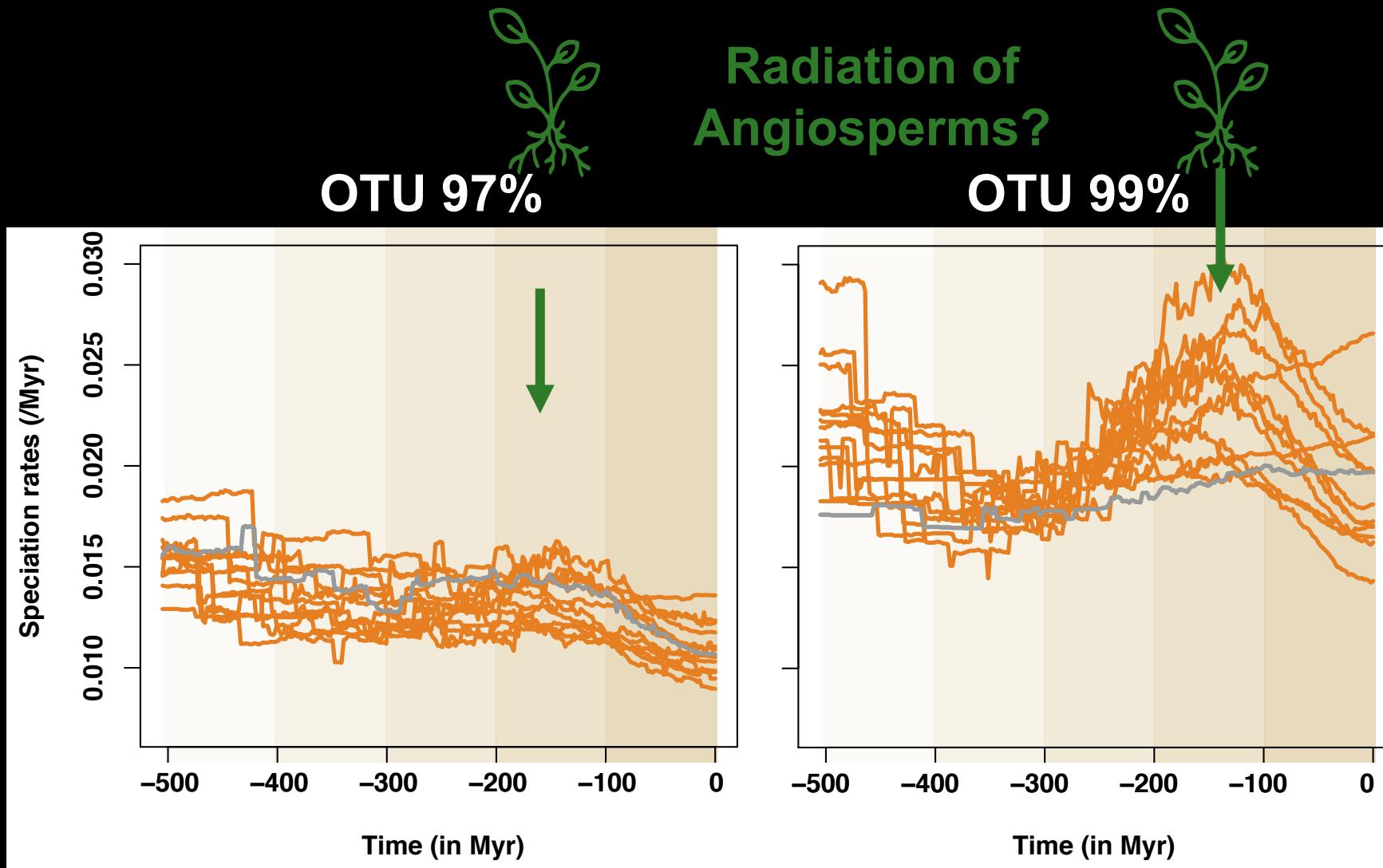
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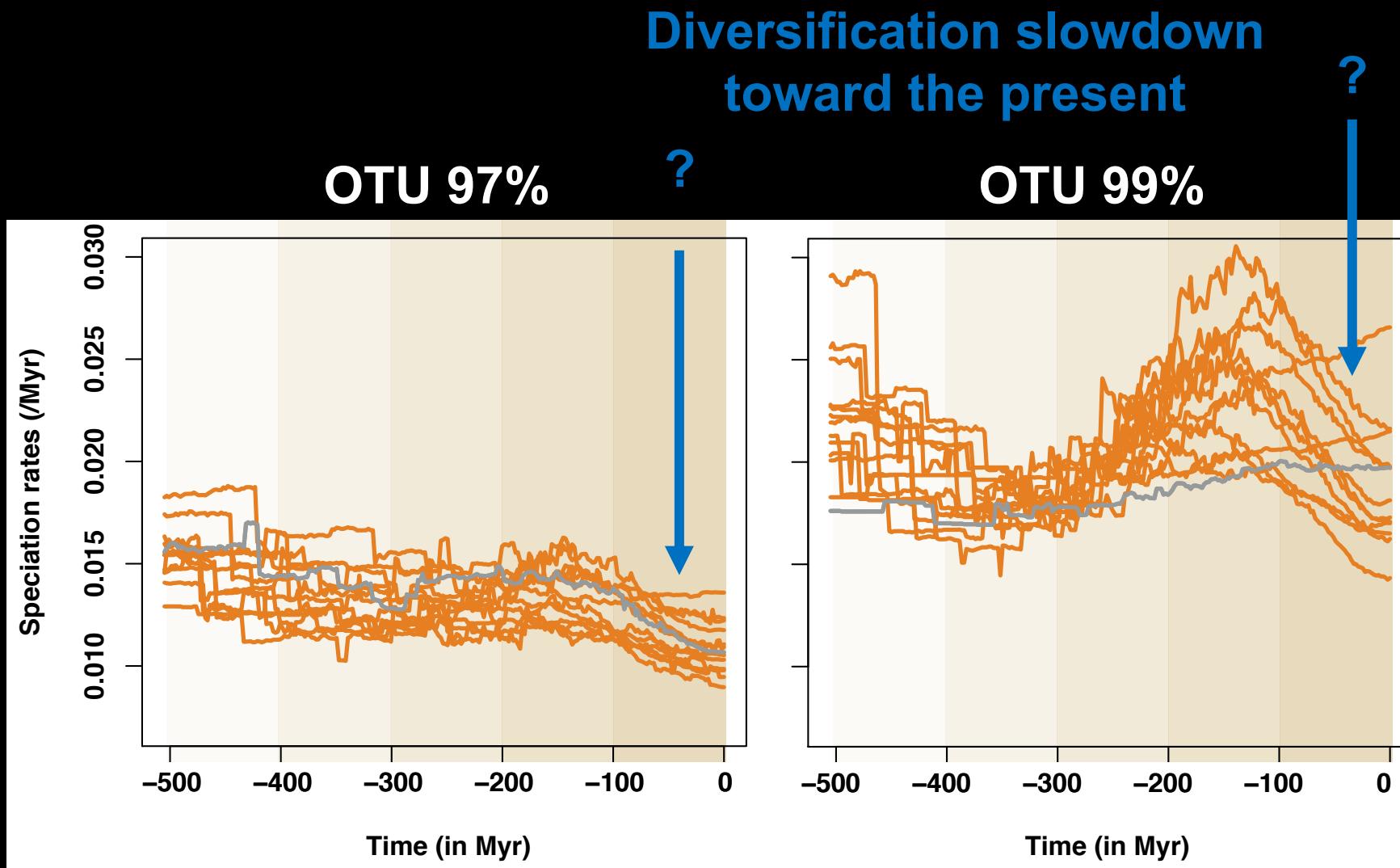
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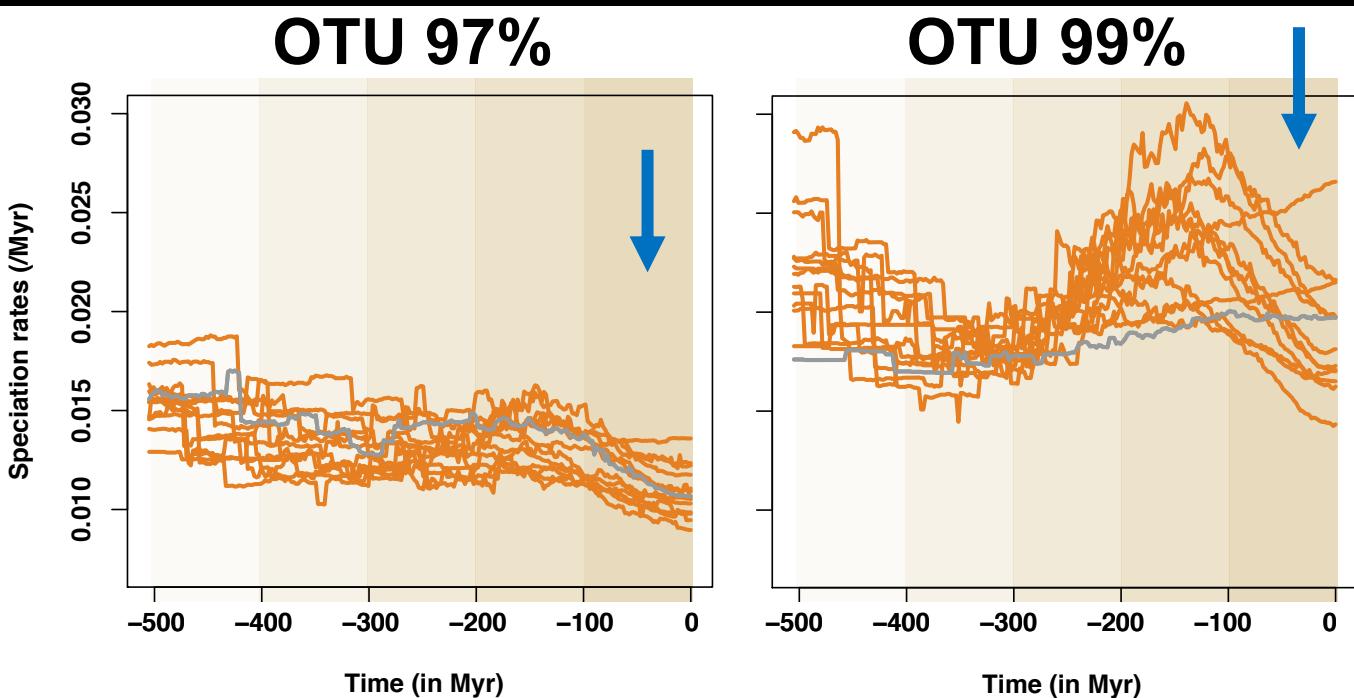
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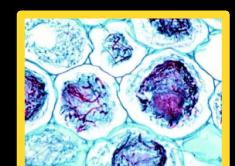
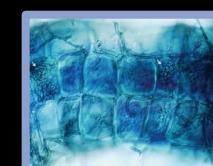
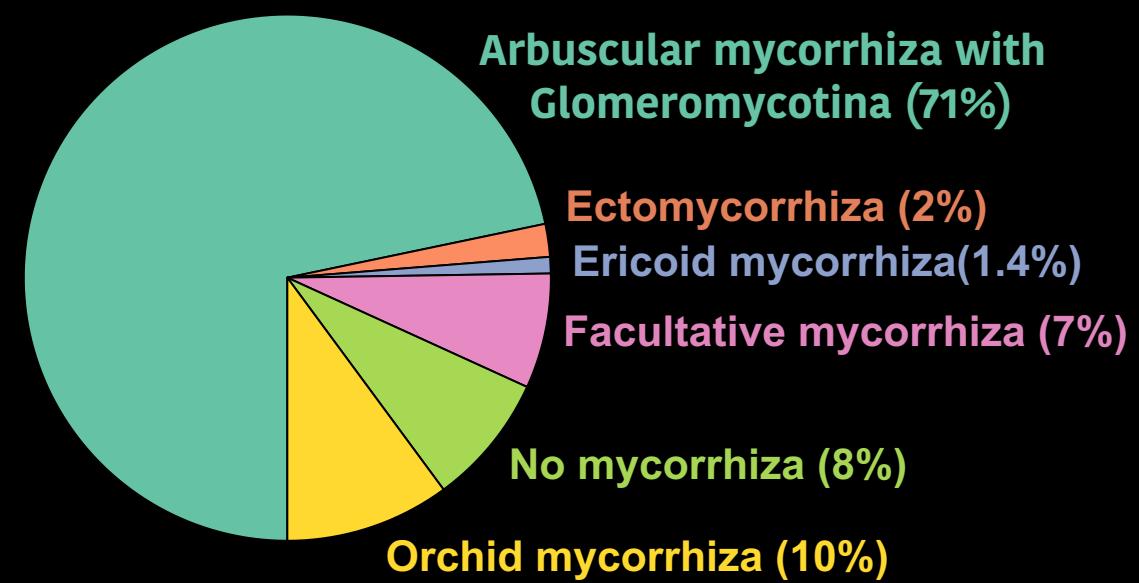
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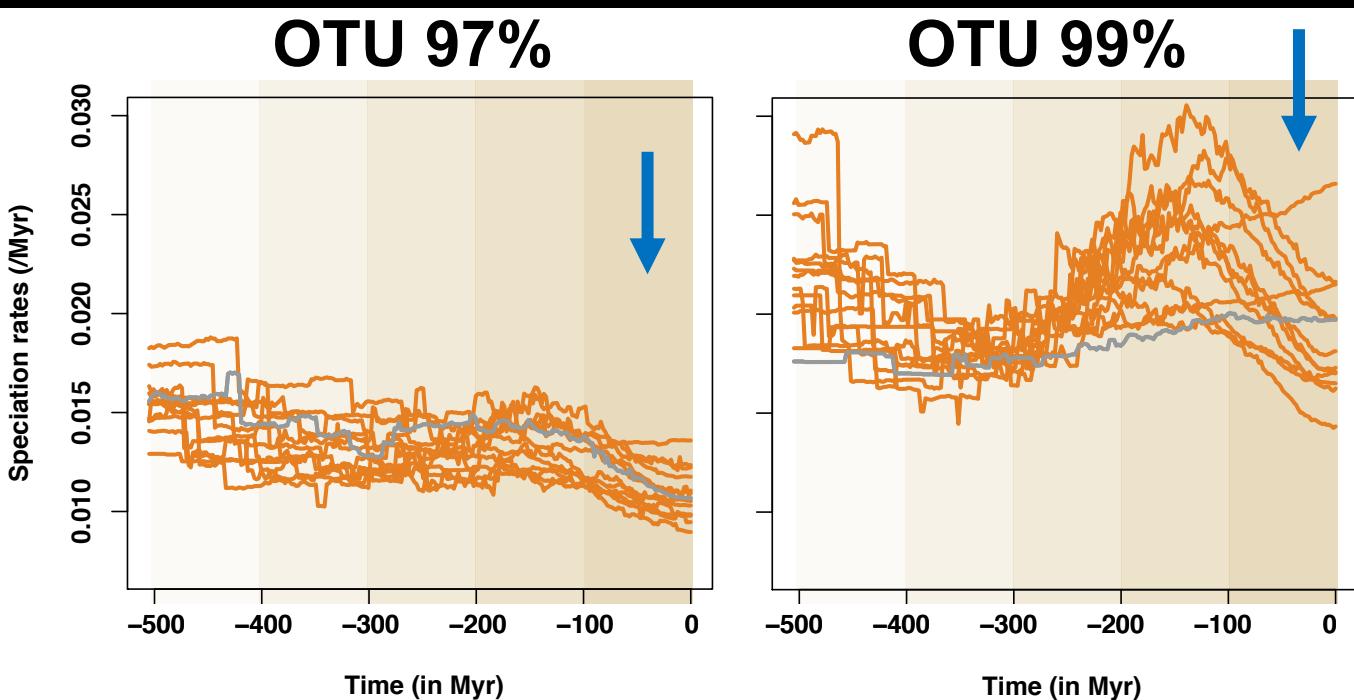
How to explain the diversification slowdown of Glomeromycotina?



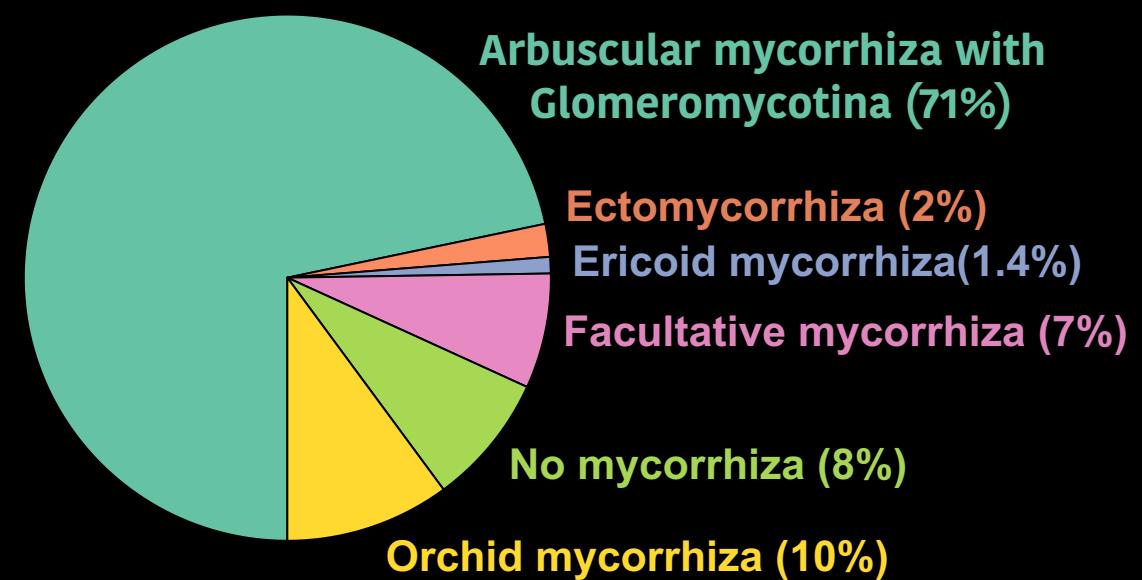
Slowdown linked to the loss of arbuscular mycorrhizal symbiosis by many plant lineages?



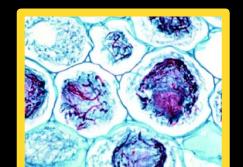
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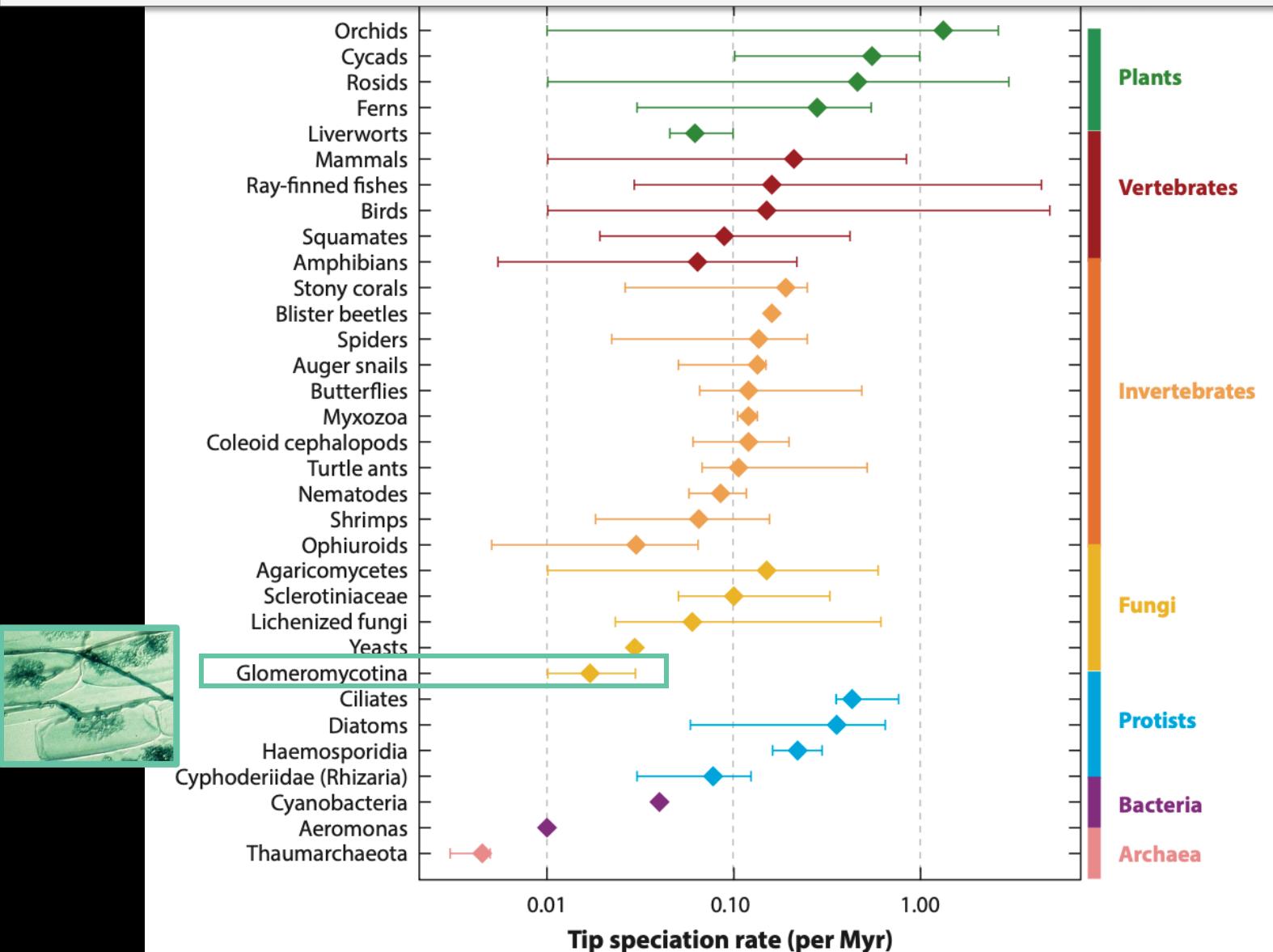
Slowdown linked to the loss of arbuscular mycorrhizal symbiosis by many plant lineages?



+ Shrinkage of tropical regions

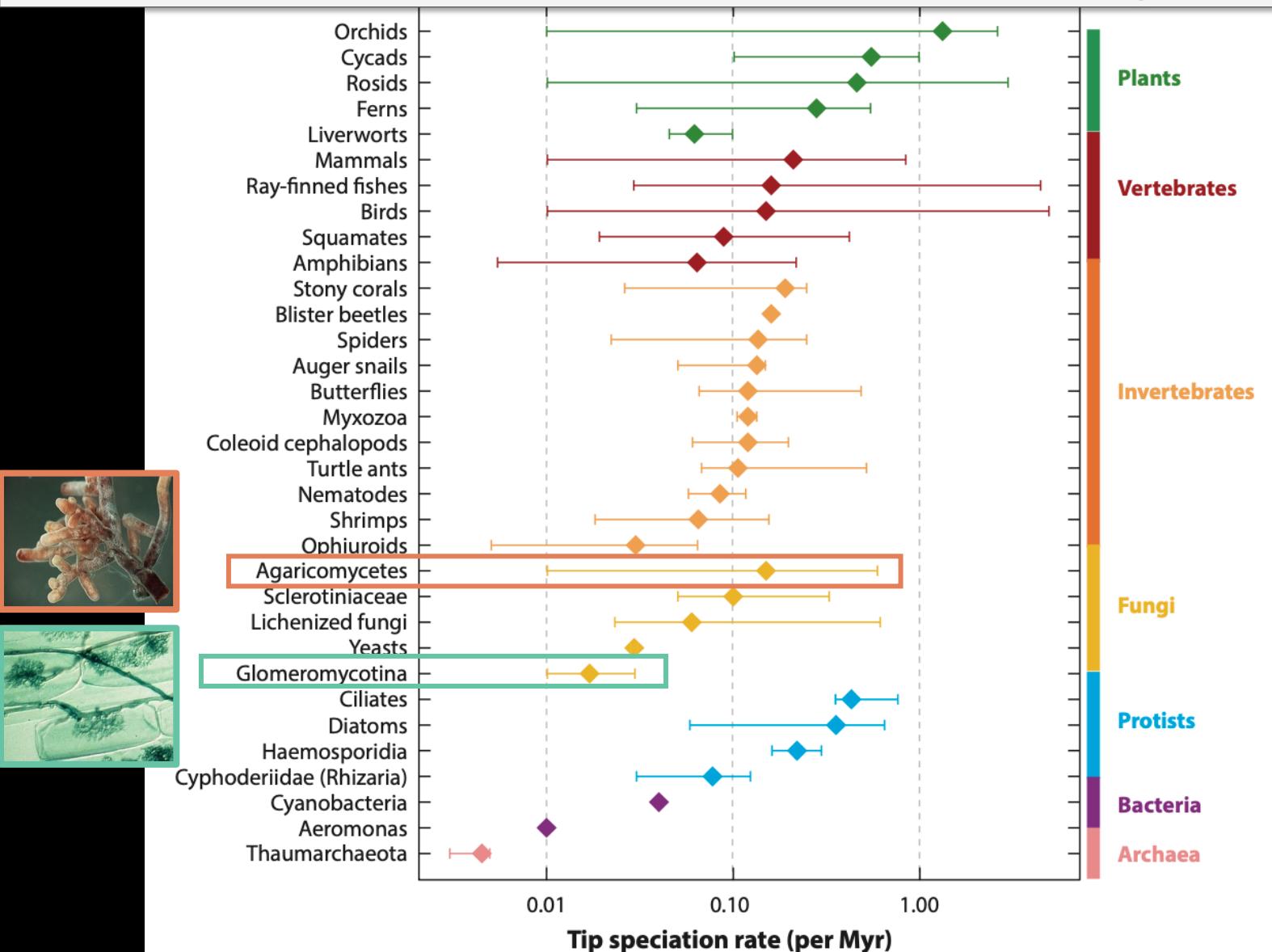


How to explain the diversification slowdown of Glomeromycotina?



→ Glomeromycotina have very low speciation rates

How to explain the diversification slowdown of Glomeromycotina?



→ Glomeromycotina have very low speciation rates (one order of magnitude lower than some ectomycorrhizal fungi)

What have been the consequences on the emergence of more specialized mycorrhizal symbioses on the Glomeromycotina ?

- Low diversification rates → unique biology and ecology?

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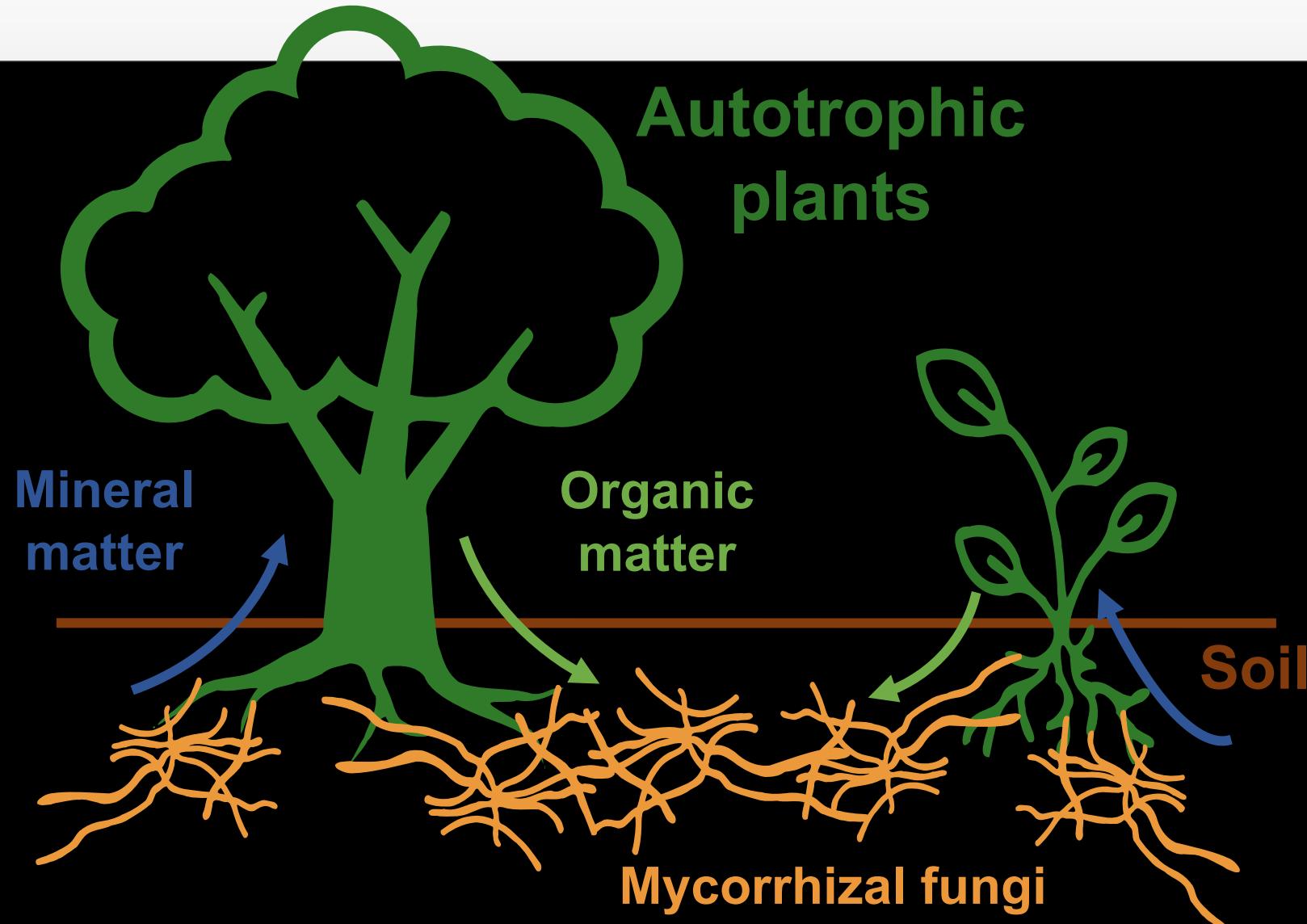
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Glomeromycotina as “*an evolutionary cul-de-sac, albeit an enormously successful one*”(Malloch, 1987)

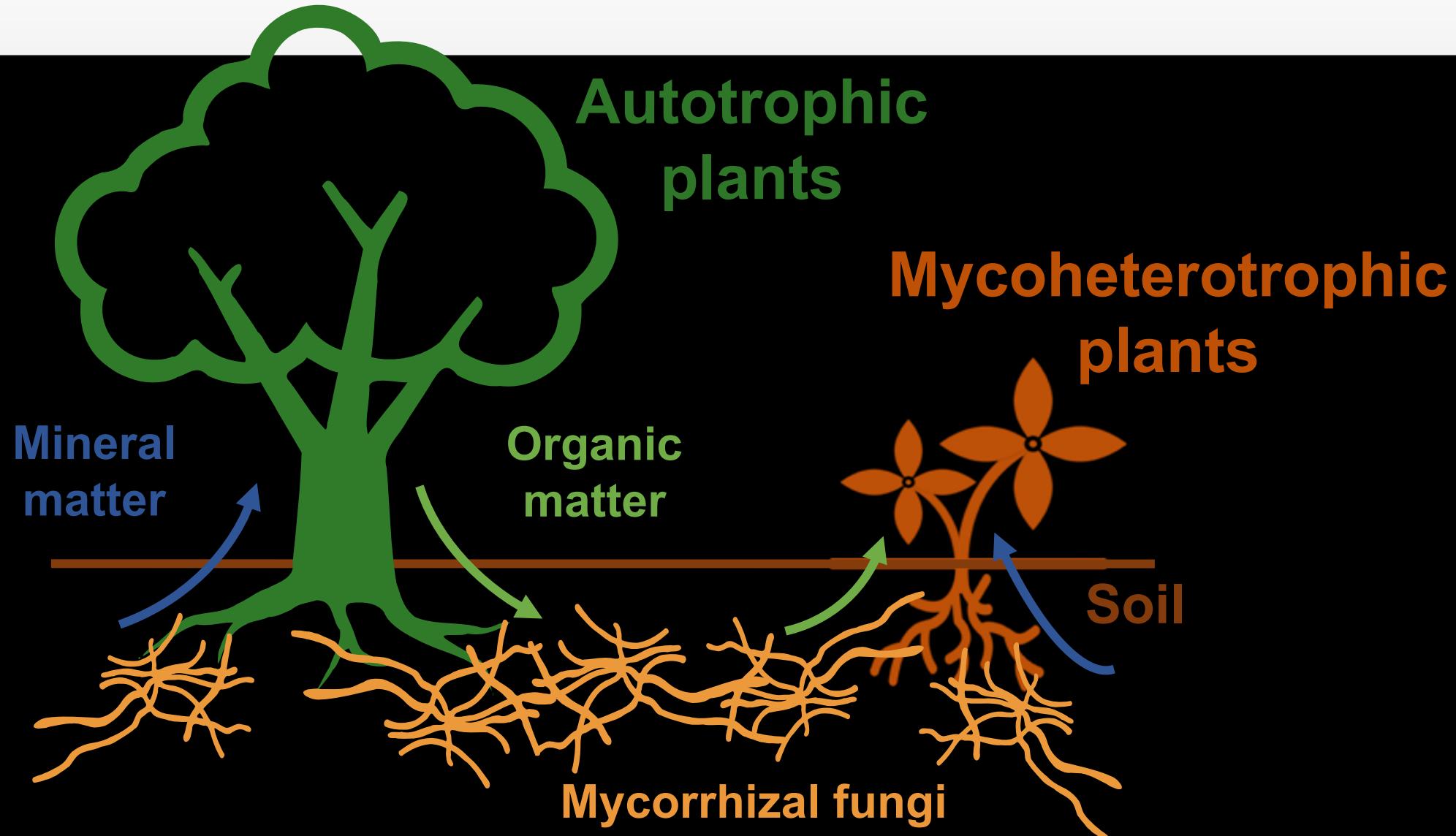
3) The evolution of mycoheterotrophy

The evolution of cheating strategies



(Sachs et al., 2004; Merckx, 2013)

The evolution of cheating strategies



(Sachs et al., 2004; Merckx, 2013)

The evolution of cheating strategies

Entirely mycoheterotrophic plants



Voyria caerulea
(Gentianaceae)



Afrothismia winkleri
(Burmanniaceae)

Initially mycoheterotrophic plants



Lycopodium clavatum
(Lycopodiaceae)

**Mycoheterotrophic
gametophyte**



**Autotrophic
sporophyte**



Lycopodium clavatum
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The evolution of cheating strategies

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gametophyte



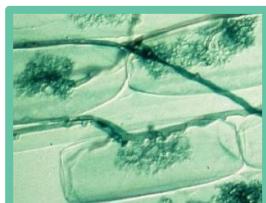
Autotrophic
sporophyte



Lycopodium clavatum
(Lycopodiaceae)

MaarjAM database

→ 41 species (5 families)



(Merckx, 2013; Öpik et al. 2010)

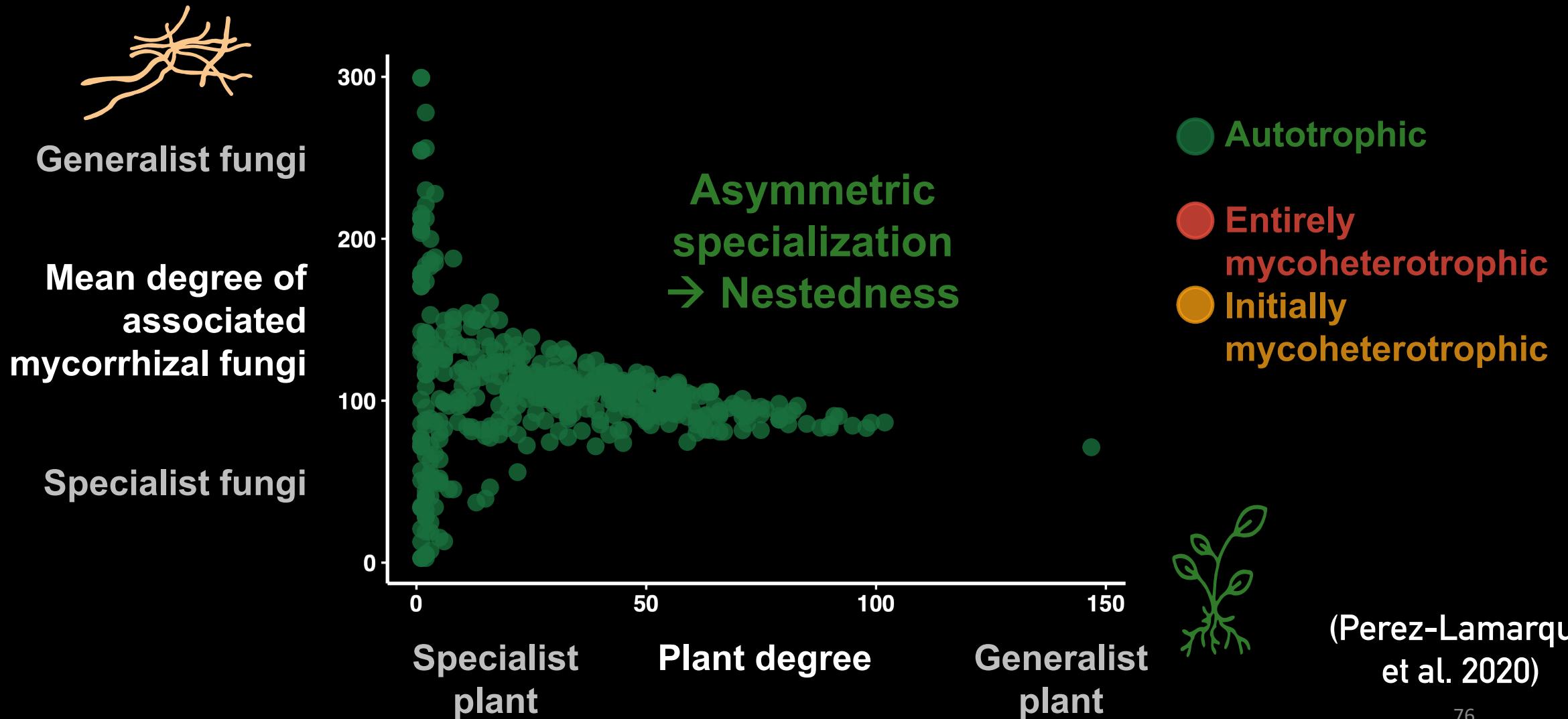
→ 15 species (3 families)

Specialization of mycoheterotrophic species

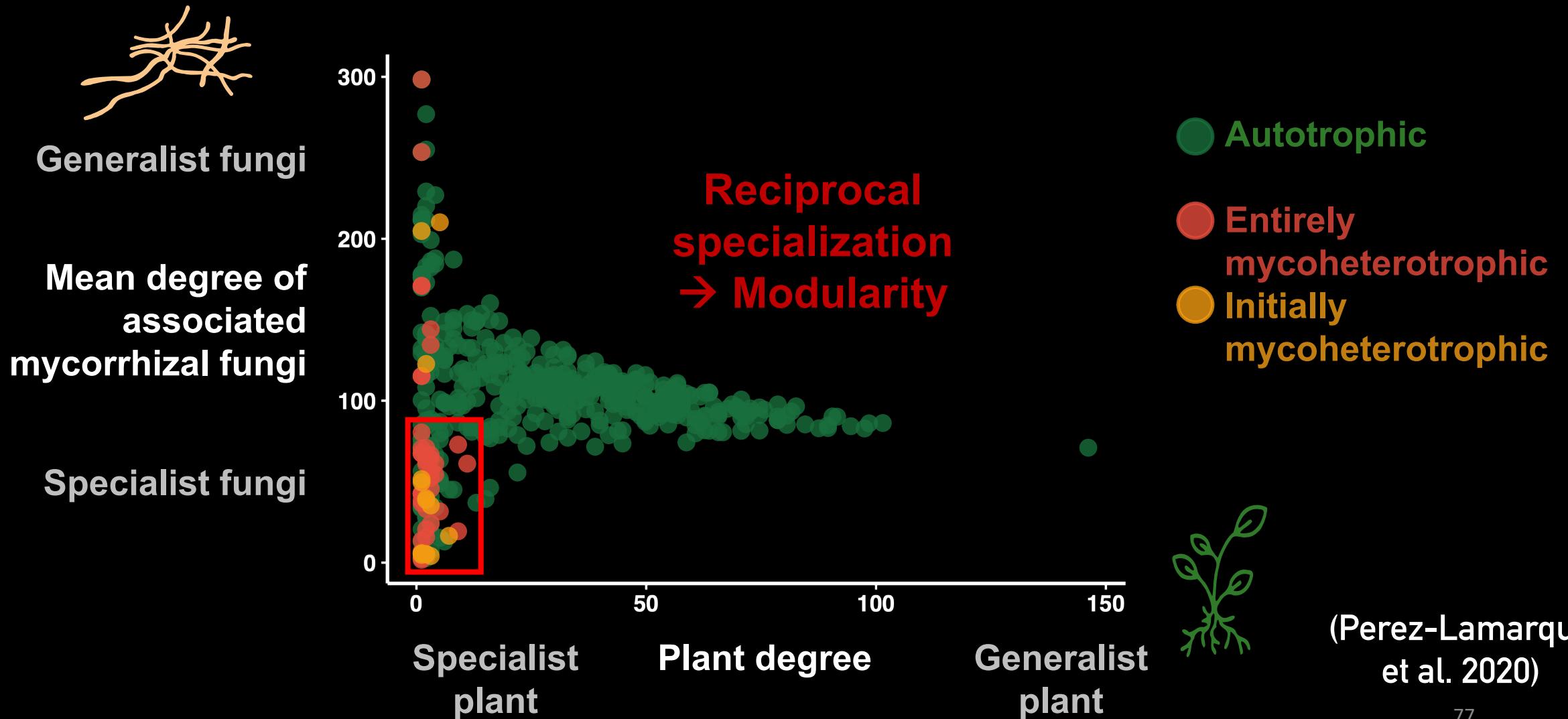


(Perez-Lamarque et al. 2020)

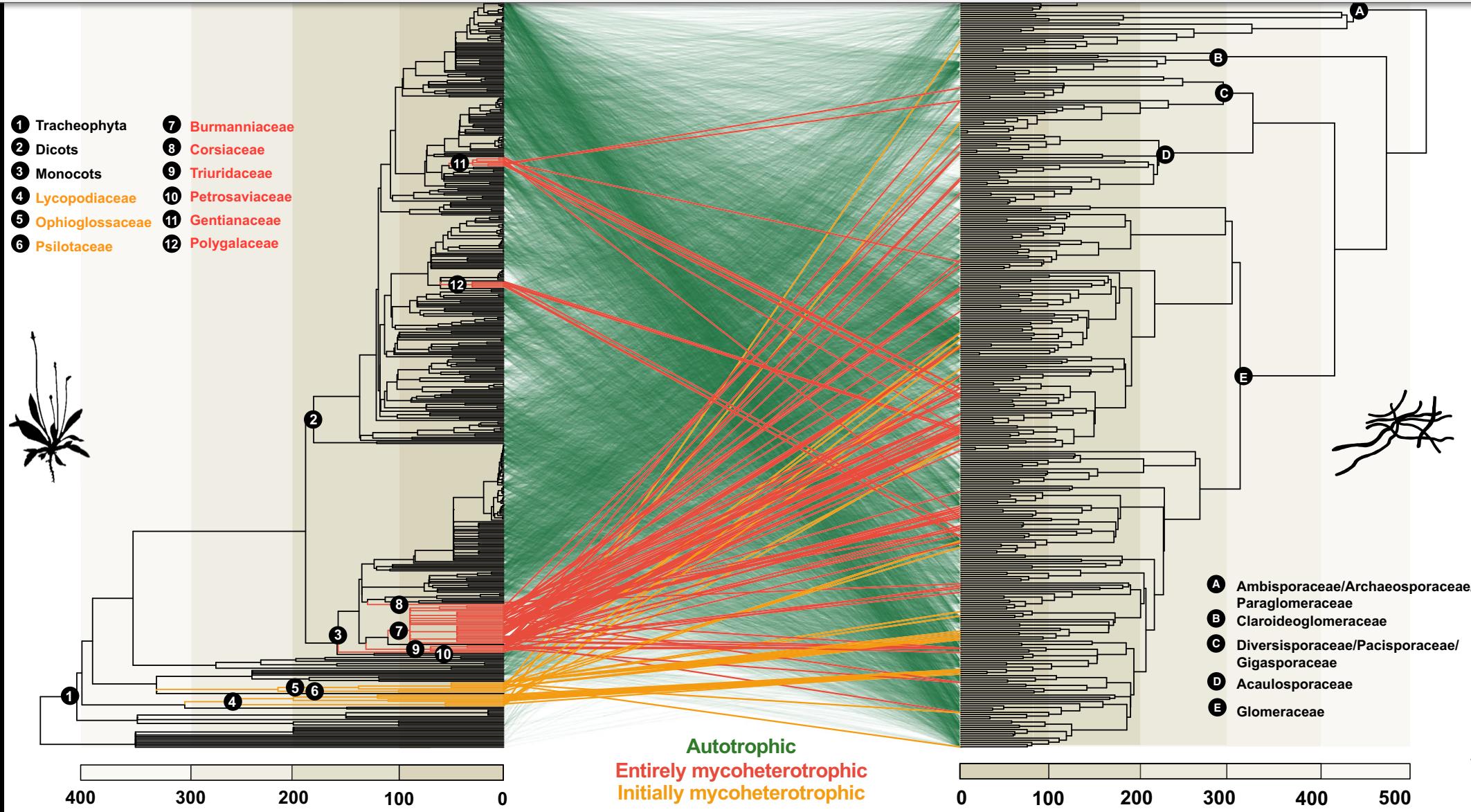
Specialization of mycoheterotrophic species



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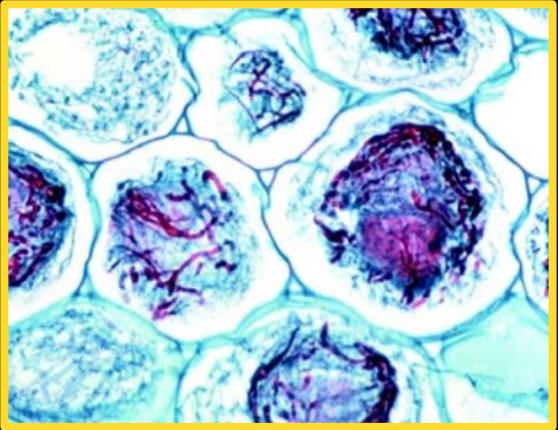


Rare, convergent and constrained emergences of mycoheterotrophy



The evolution of mycoheterotrophy: an evolutionary dead end?

Neottieae



**Autotrophic
(AT)**



**Mixotrophic
(MX)**



**Mycoheterotrophic
(MH)**



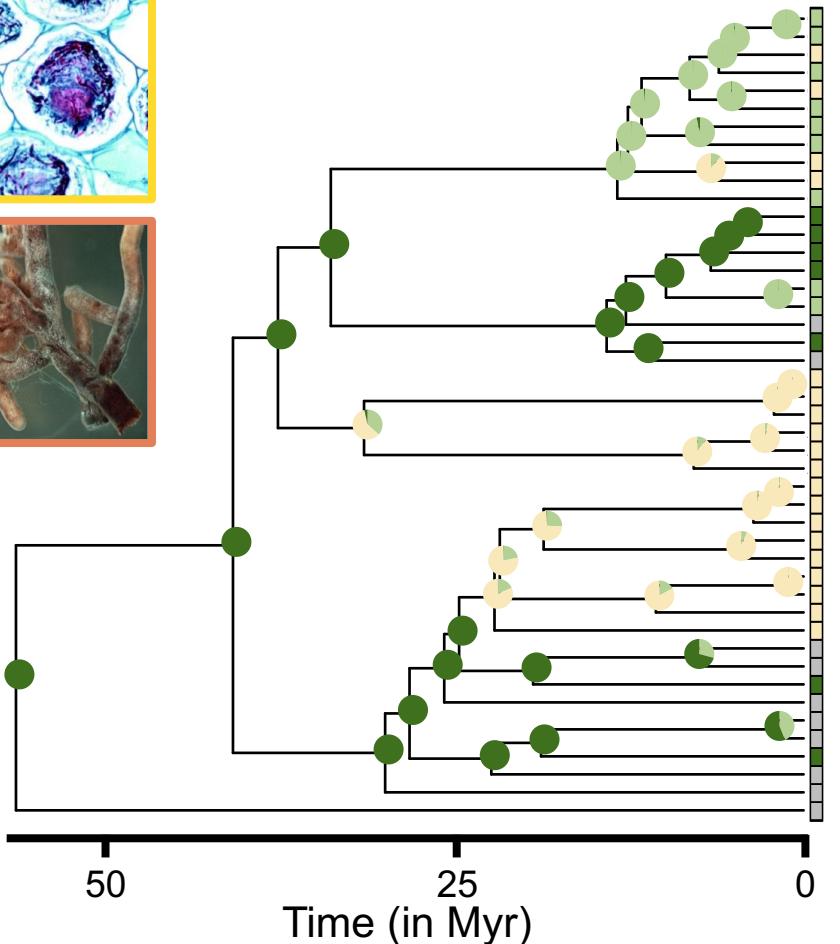
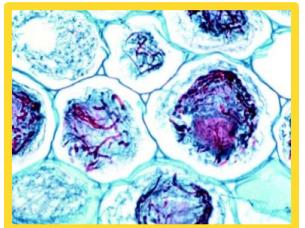
*Neottia
nidus-avis*



*Cephalanthera
longifolia*

The evolution of mycoheterotrophy: an evolutionary dead end?

Neottieae



Autotrophic
(AT)



Mixotrophic
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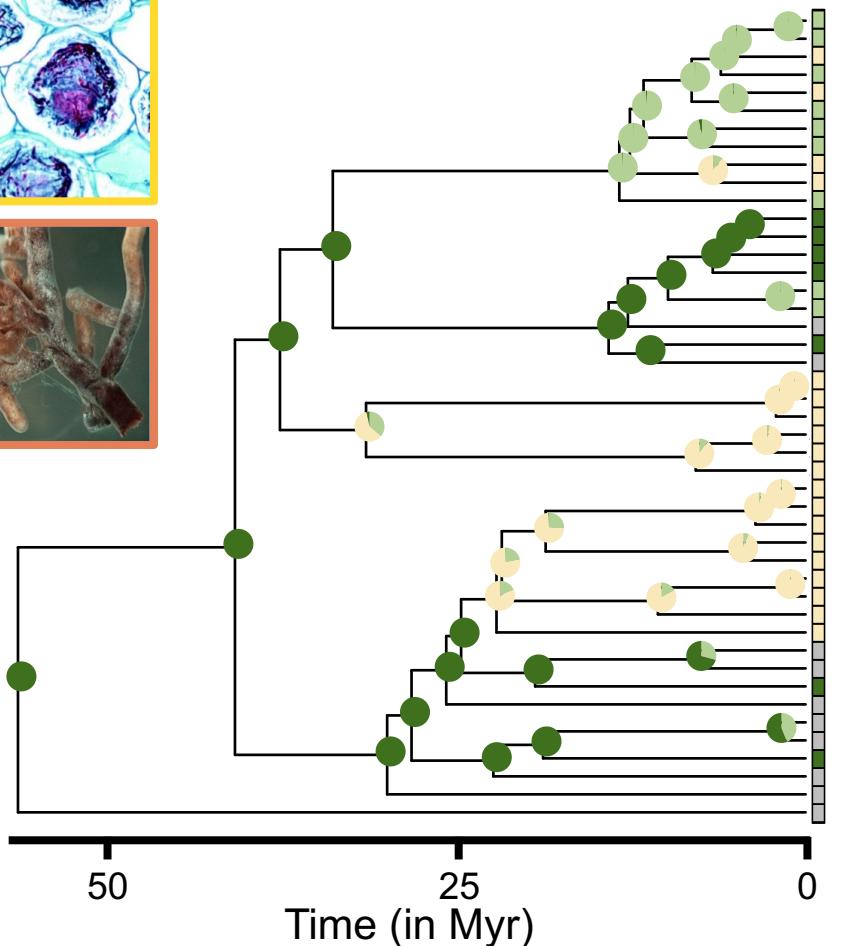
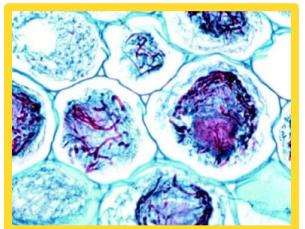
*Cephalanthera
longifolia*

*Neottia
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The evolution of mycoheterotrophy: an evolutionary dead end?

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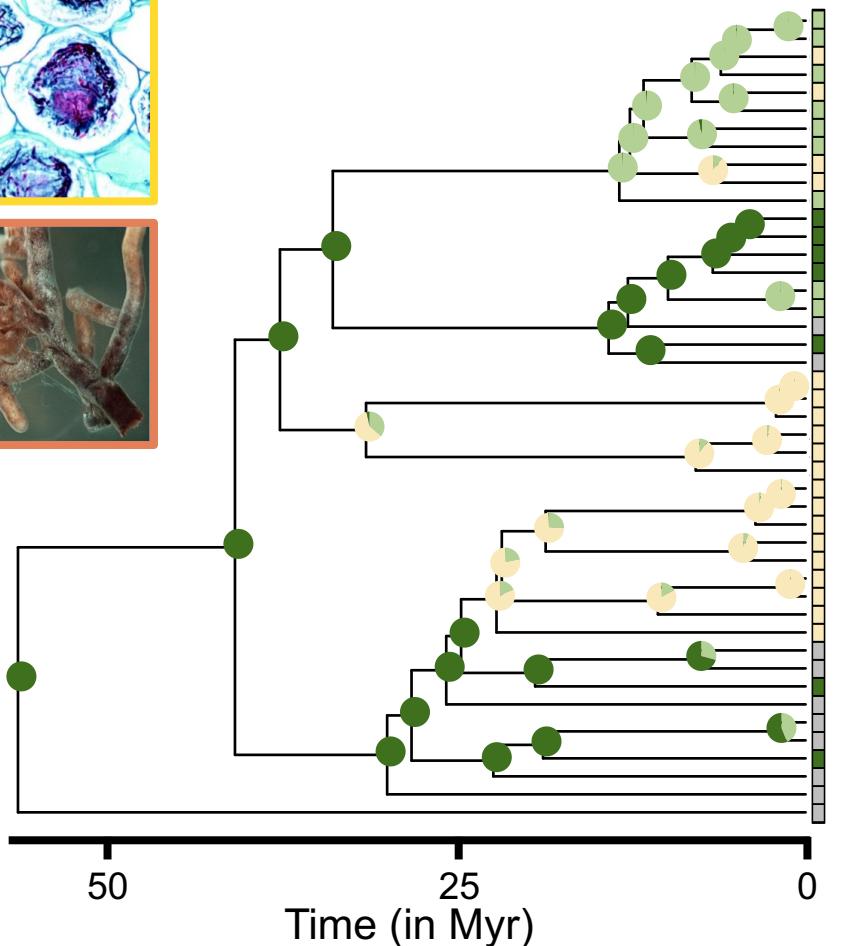
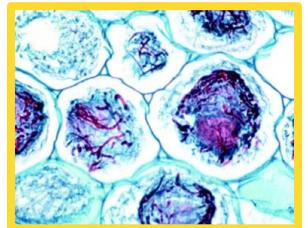
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The evolution of mycoheterotrophy: an evolutionary dead end?

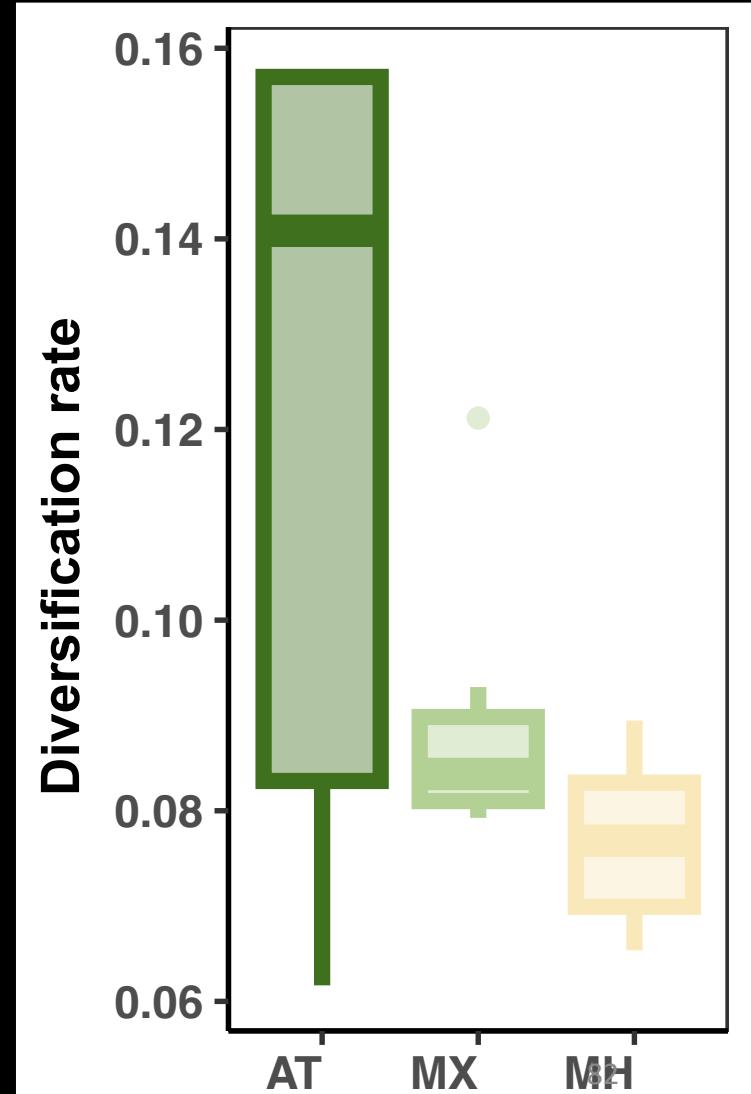
Neottieae



Autotrophic
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(MH)



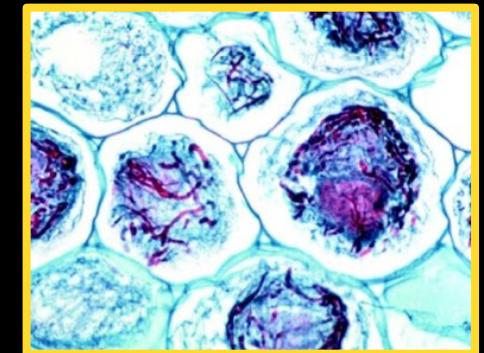
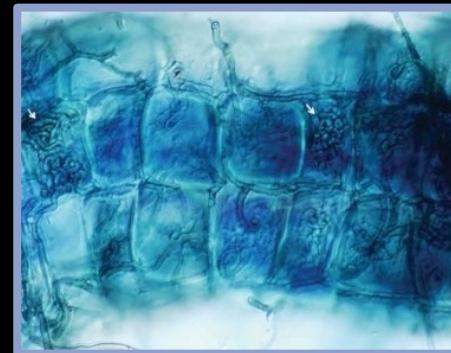
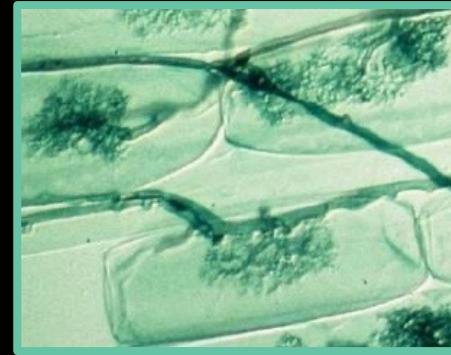
The evolution of mycoheterotrophy: an evolutionary dead end?

- Strong specialization
- Constrained emergences
- An evolutionary dead end?



Dynamics of mycorrhizal networks

How do mycorrhizal networks assemble and evolve?



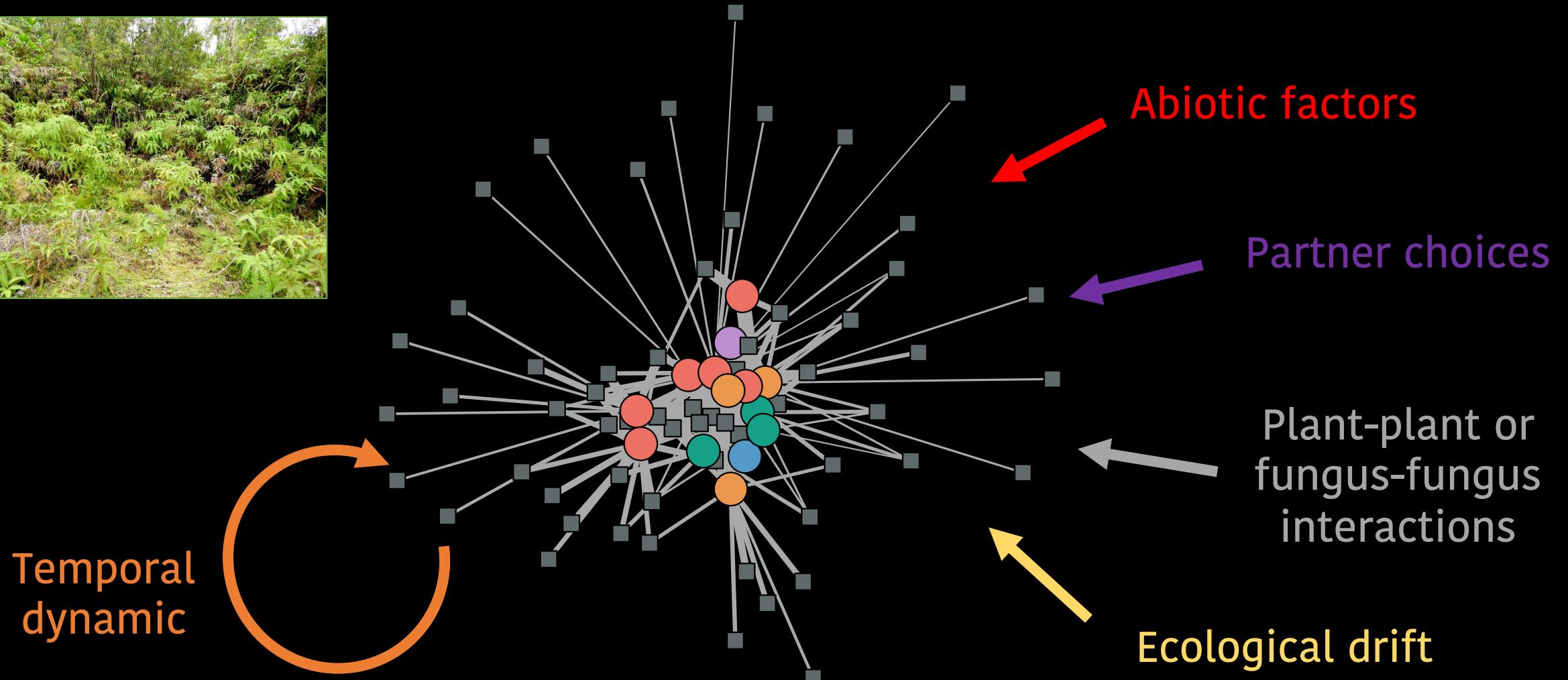
Perspective 1: Better understand the factors shaping the ecological dynamic



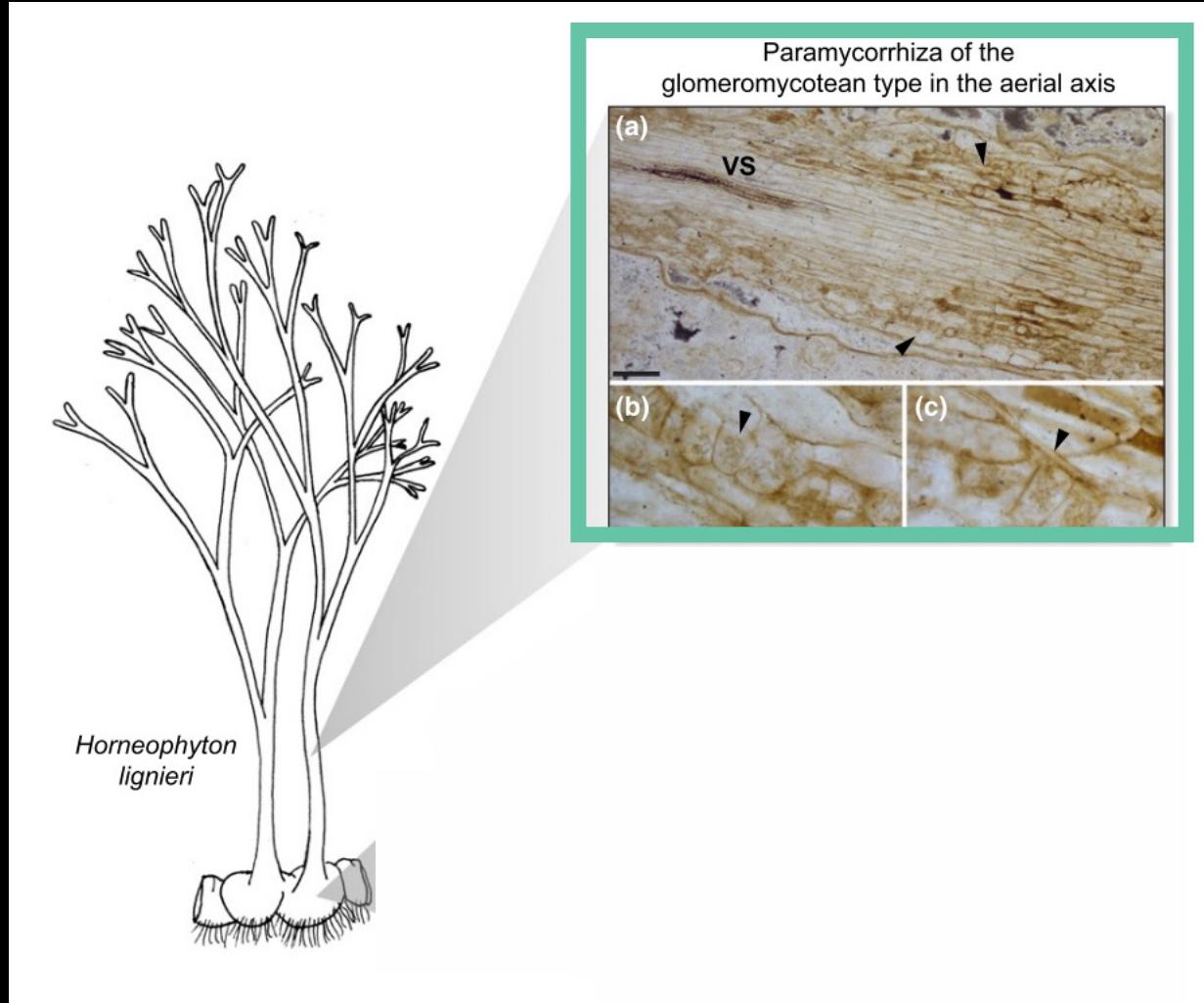
Temporal
dynamic



Perspective 1: Better understand the factors shaping the ecological dynamic

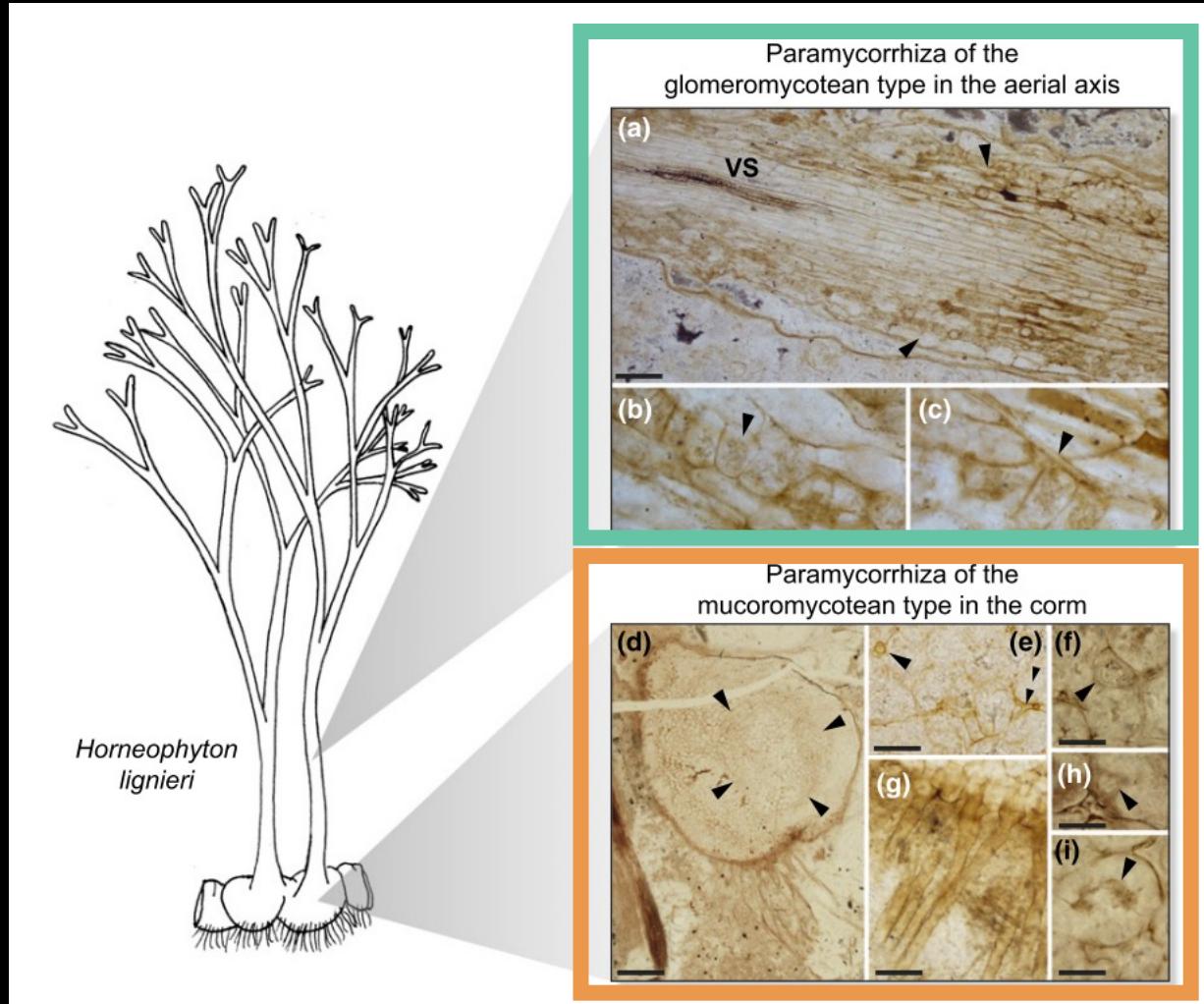


Perspective 2: Unravel the evolutionary history of plant-Mucoromycotina symbiosis



Glomeromycotina

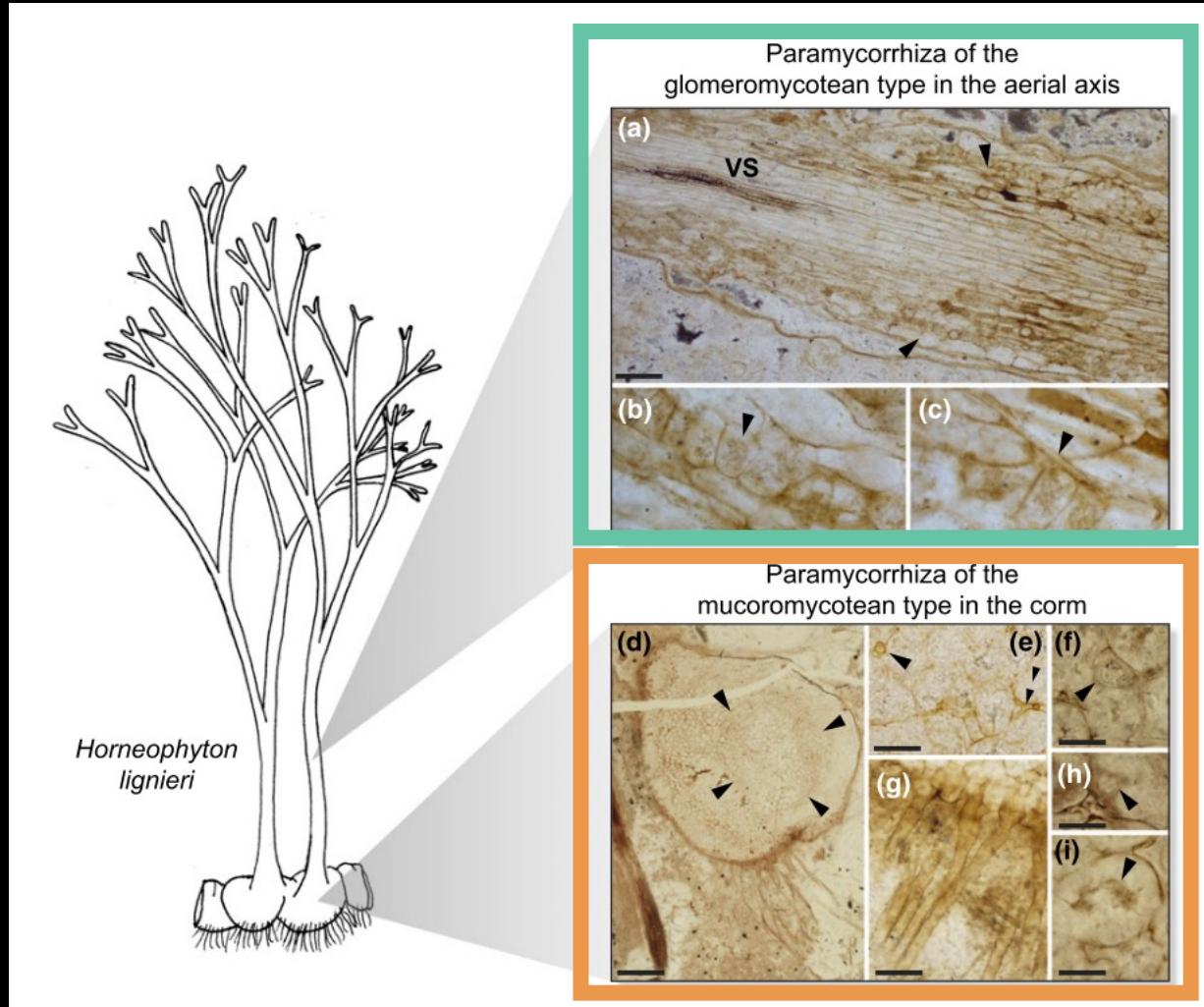
Perspective 2: Unravel the evolutionary history of plant-Mucromycotina symbiosis



Glomeromycotina

Mucoromycotina

Perspective 2: Unravel the evolutionary history of plant-Mucromycotina symbiosis

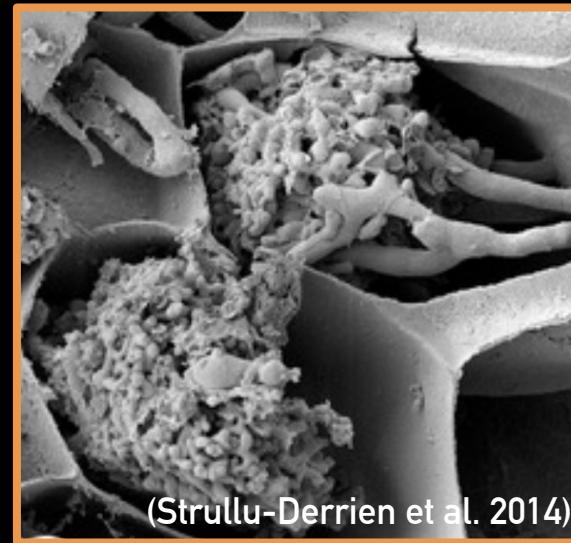
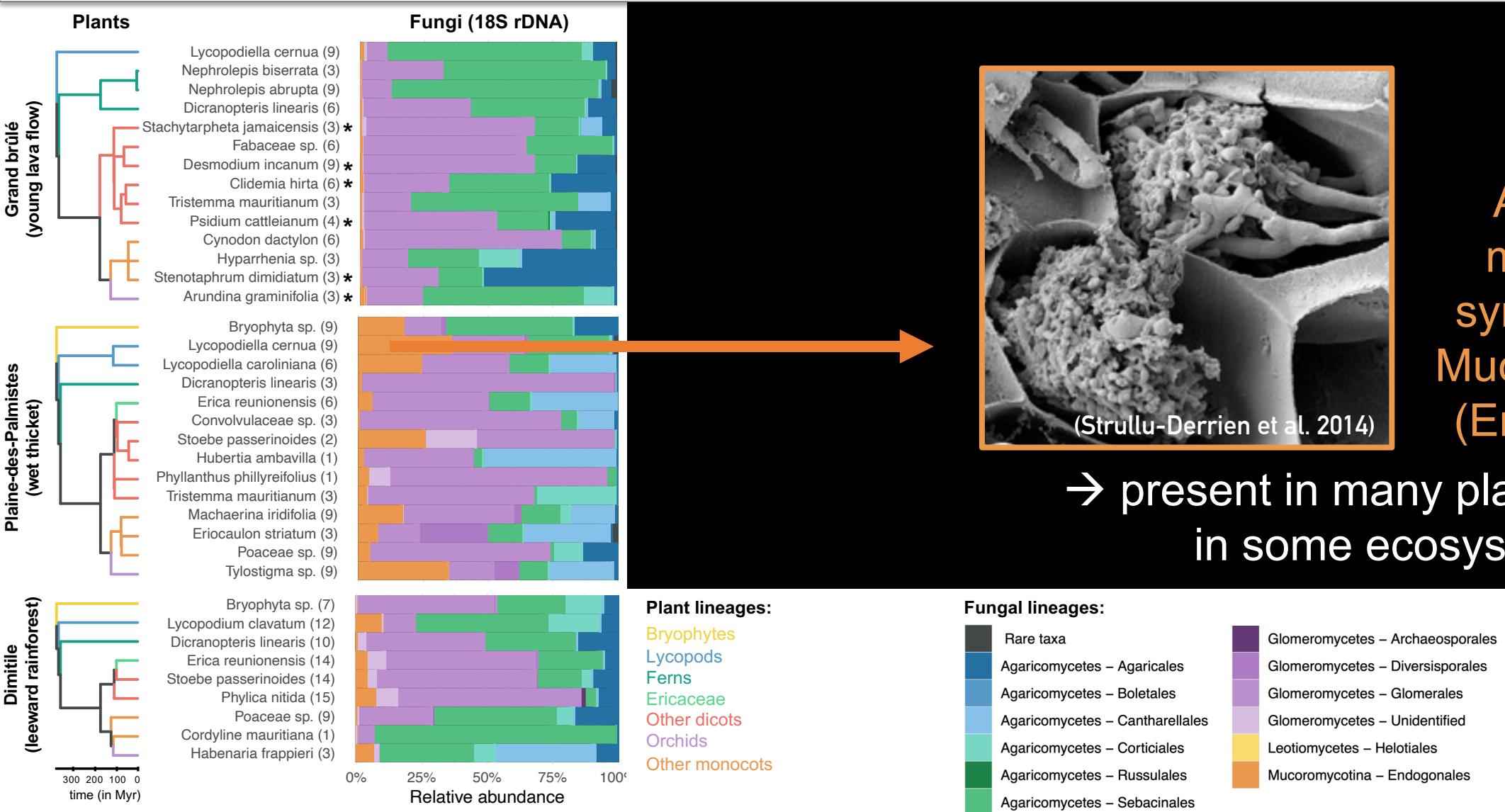


Glomeromycotina

Mucoromycotina

Undetected before:
→ similar
morphologies
→ primer biases

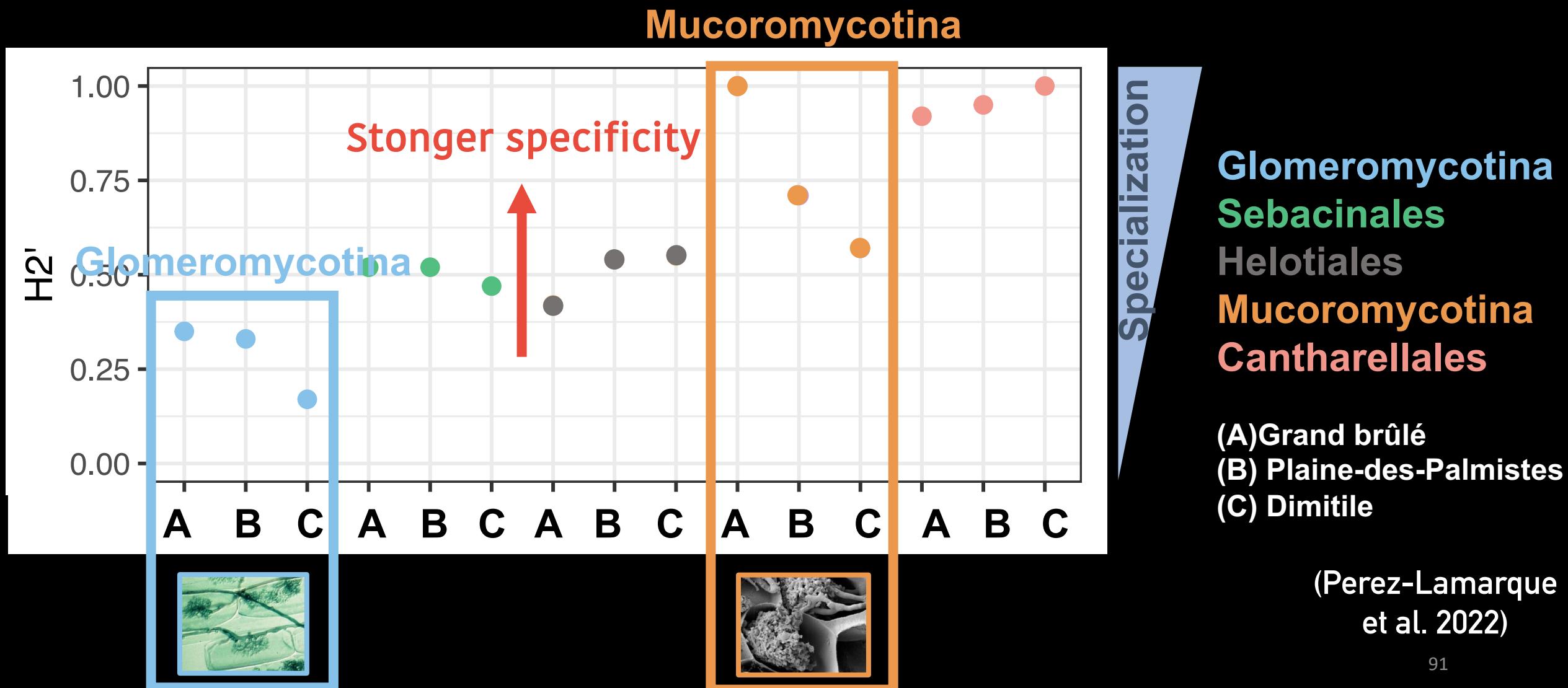
Perspective 2: Unravel the evolutionary history of plant-Mucoromycotina symbiosis



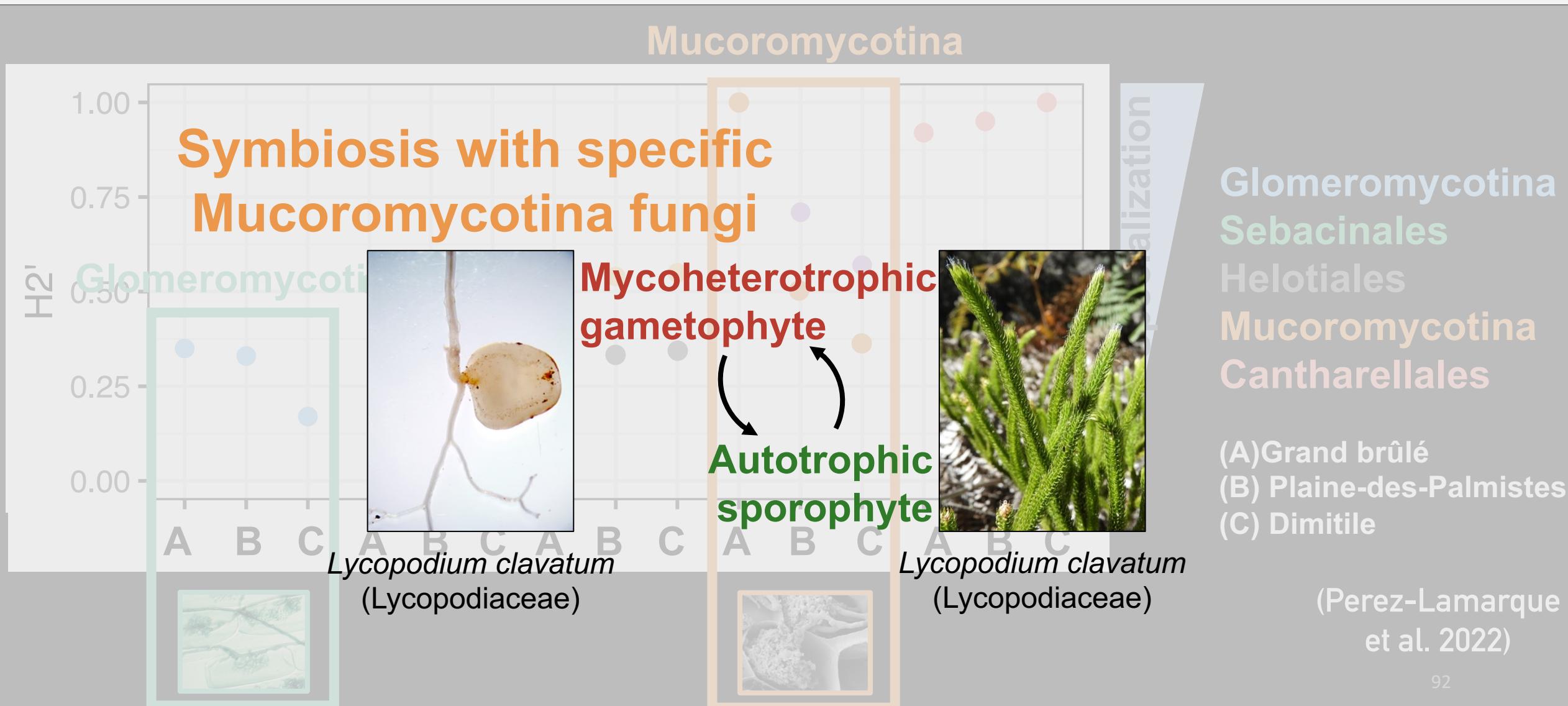
Arbuscular
mycorrhizal
symbiosis with
Mucoromycotina
(Endogonales)

→ present in many plant lineages
in some ecosystems

Perspective 2: Unravel the evolutionary history of plant-Mucromycotina symbiosis



Perspective 2: Unravel the evolutionary history of plant-Mucromycotina symbiosis



Perspective 2: Unravel the evolutionary history of plant-Mucromycotina symbiosis

Mucromycotina

How to explain the stronger specificity of the plant-Mucromycotina symbiosis?

Saprotrophic fungi?

Multiple independent evolutions?

Associated with N-limited ecosystems?



Glomeromycotina

Sebacinales

Helotiales

Mucromycotina

Cantharellales

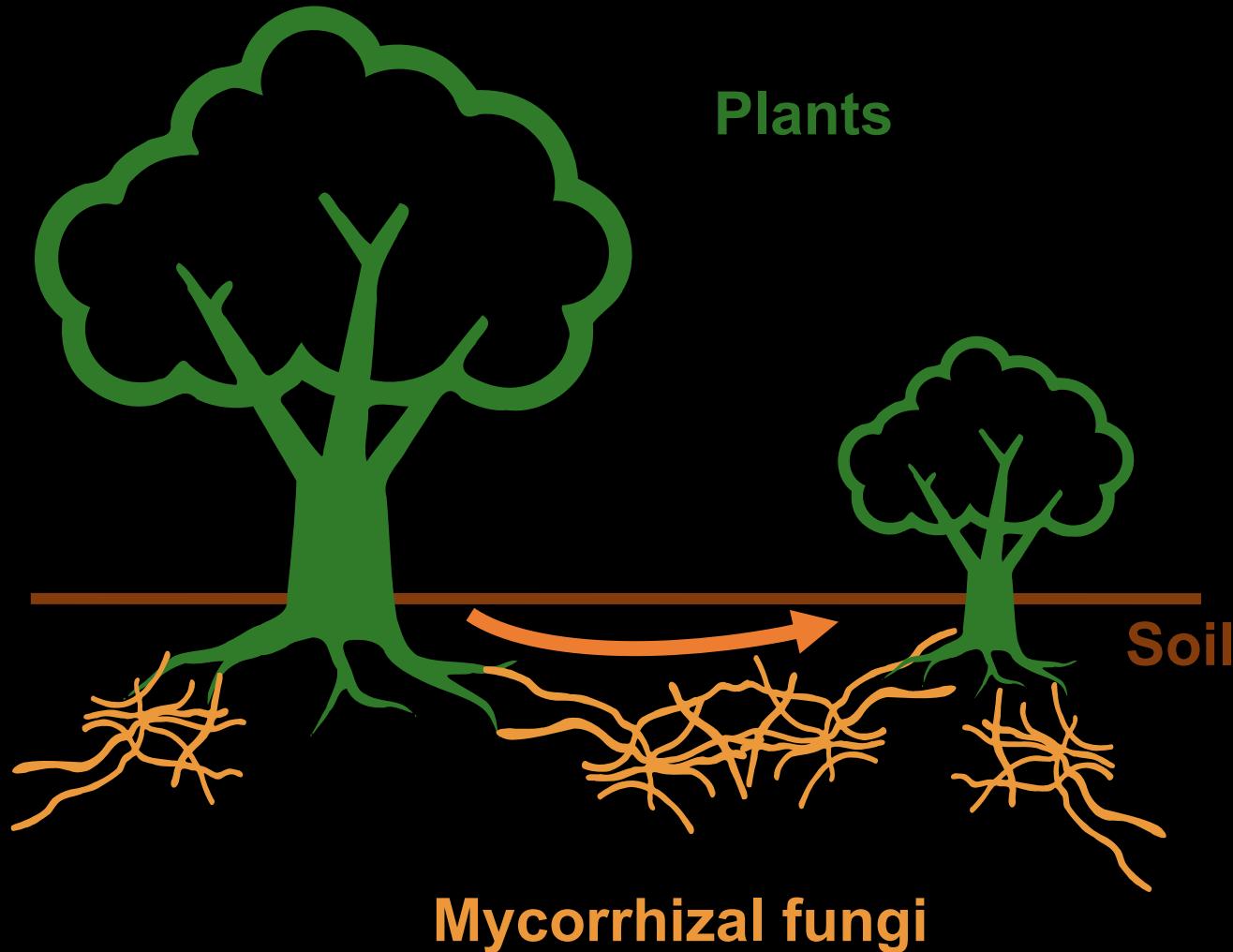
(A) Grand brûlé

(B) Plaine-des-Palmistes

(C) Dimitile

(Perez-Lamarque et al. 2022)

Perspective 3: Test the functioning of common mycorrhizal networks



How frequent are exchanges of matter and information through mycorrhizal networks?

The “Mother Tree hypothesis”: resources are transferred through mycorrhizal networks to increase seedling performance?
(Simard et al.)

Perspective 3: Test the functioning of common mycorrhizal networks

nature ecology & evolution

Perspective

<https://doi.org/10.1038/s41559-023-01986-1>

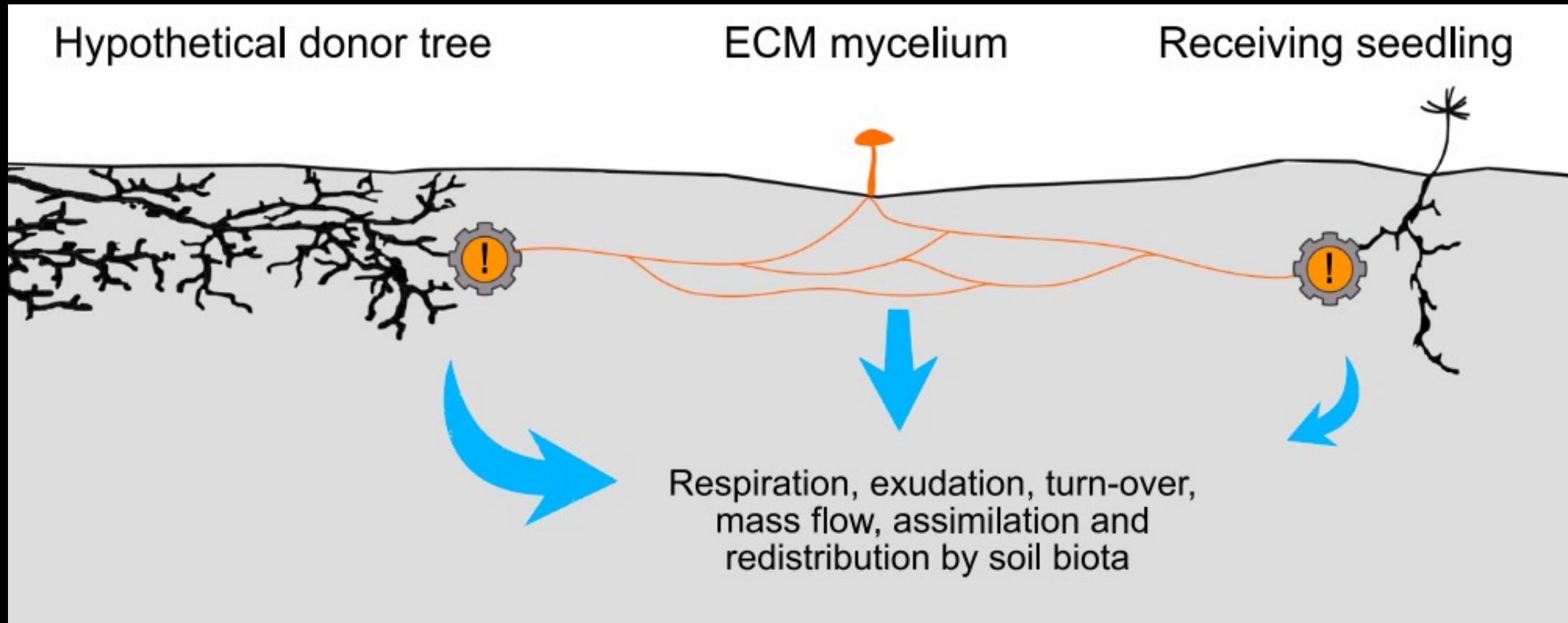
Positive citation bias and overinterpreted results lead to misinformation on common mycorrhizal networks in forests

Received: 18 August 2022

Justine Karst¹✉, Melanie D. Jones² & Jason D. Hoeksema³

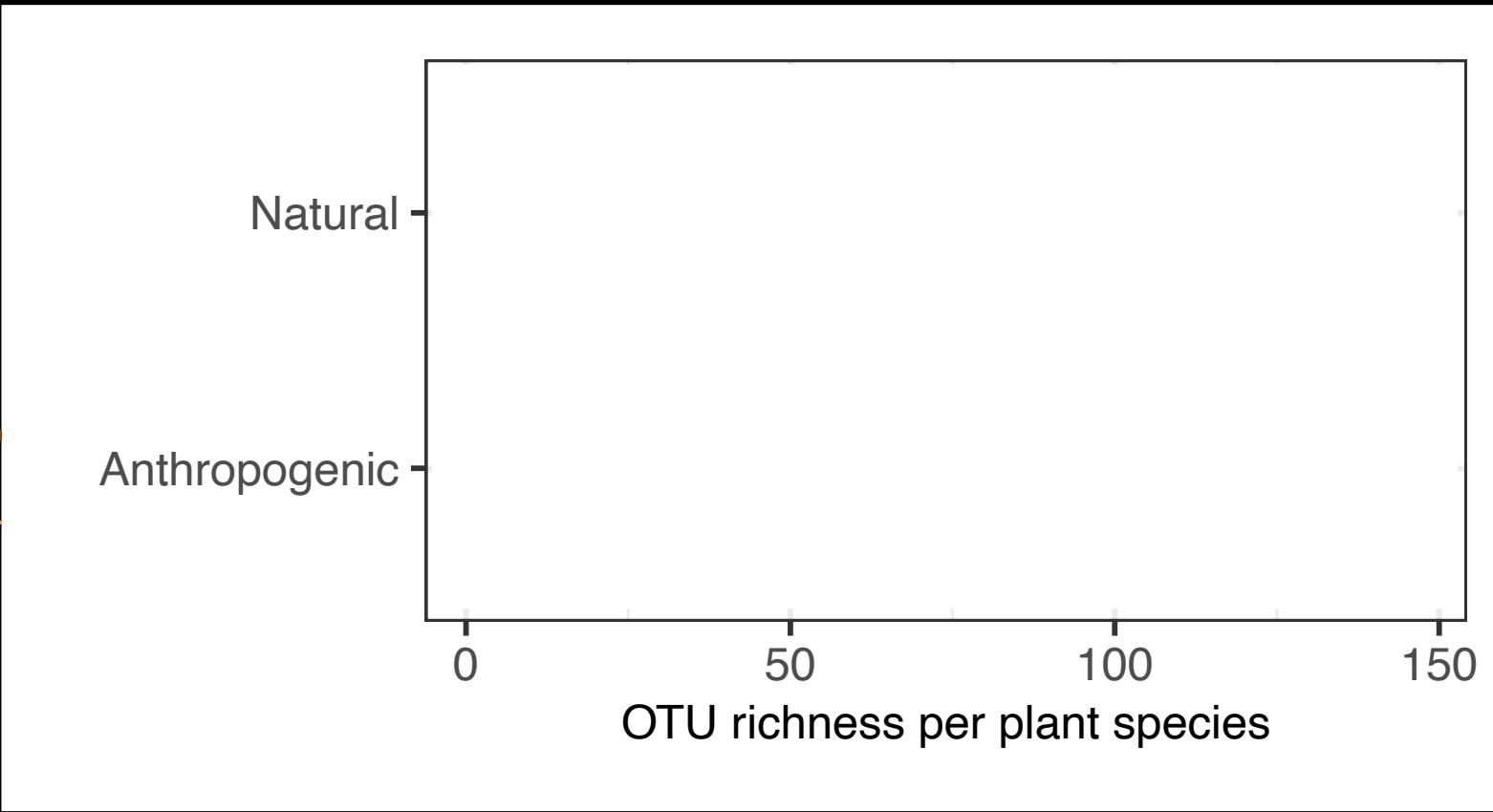
Accepted: 6 January 2023

Perspective 3: Test the functioning of common mycorrhizal networks



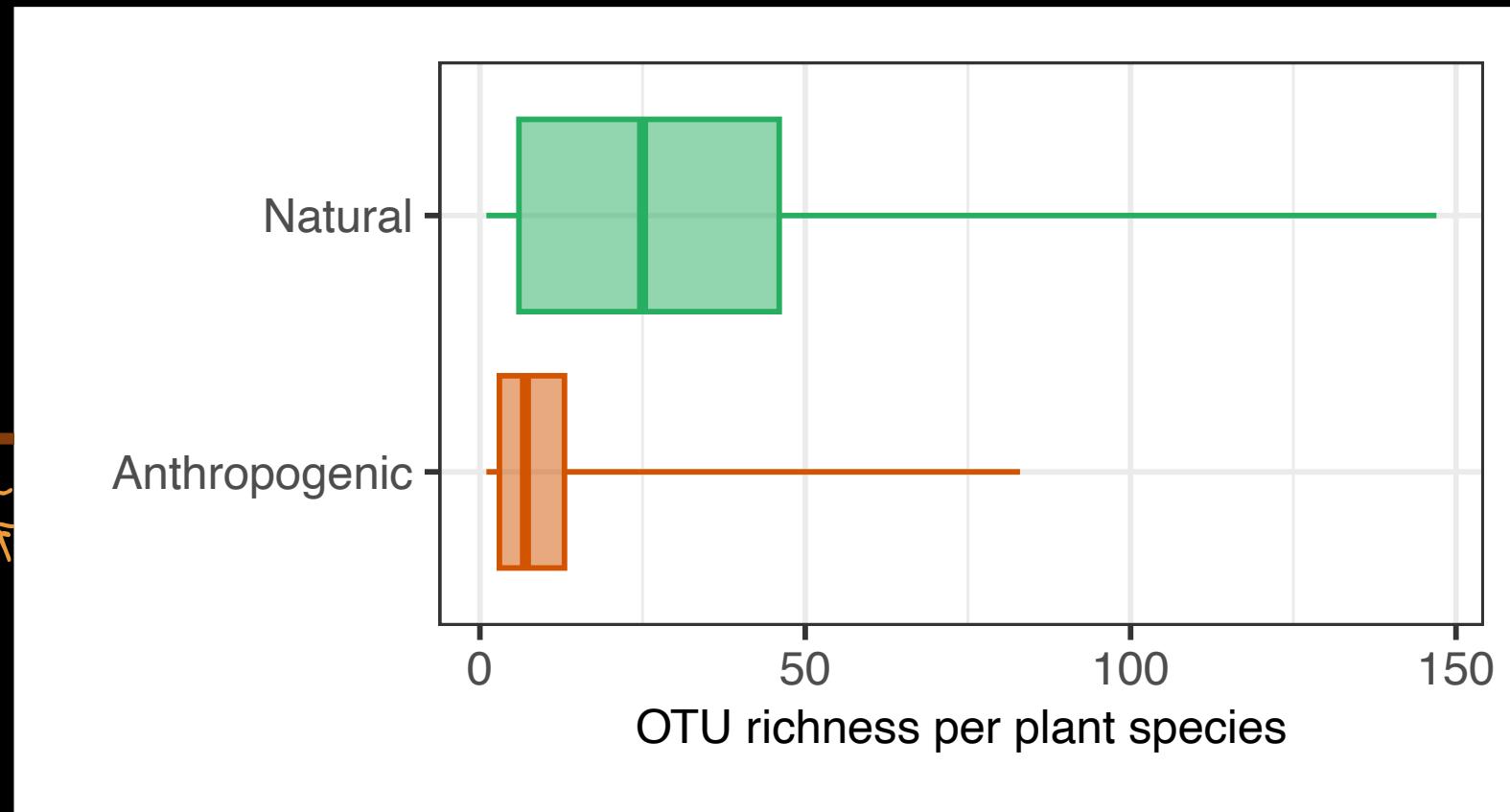
(Henriksson et al. 2023)

Perspective 4: Investigate human-driven loss of mycorrhizal communities



Data from the
MaarjAM database
on plant-
Glomeromycotina
interactions (Öpik et
al. 2010)

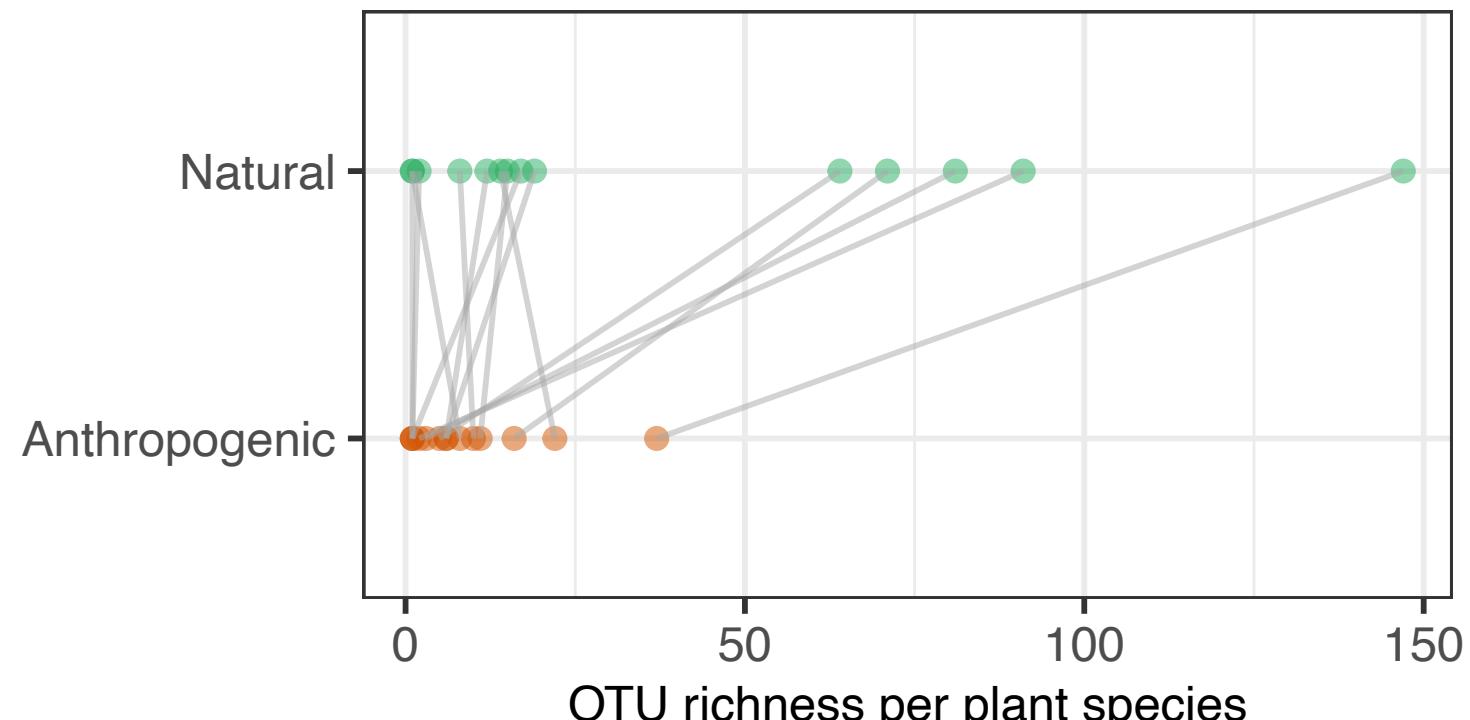
Perspective 4: Investigate human-driven loss of mycorrhizal communities



→ Diversity loss

Data from the
MaarjAM database
on plant-
Glomeromycotina
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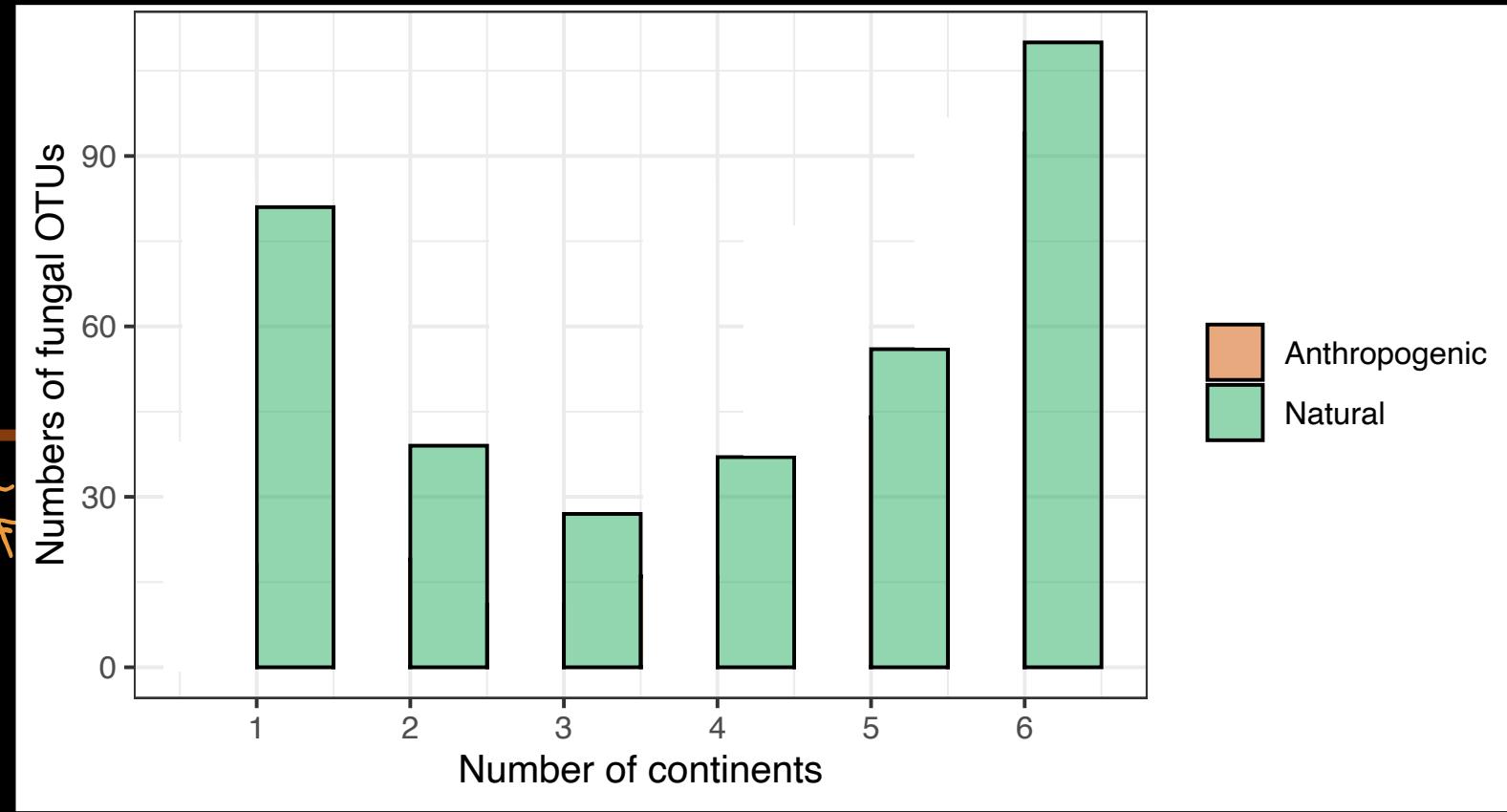
Perspective 4: Investigate human-driven loss of mycorrhizal communities



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→ Diversity loss

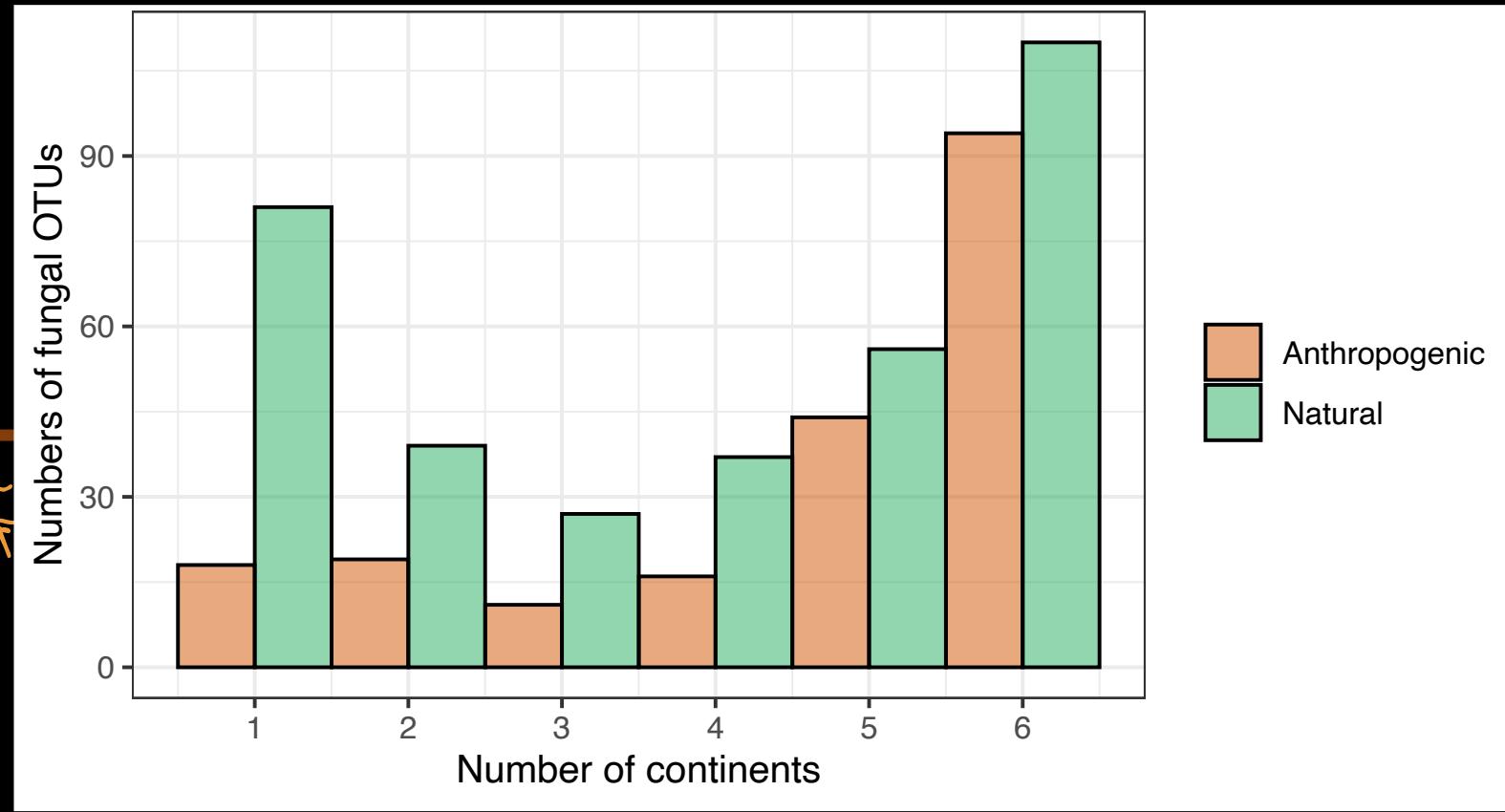
Perspective 4: Investigate human-driven loss of mycorrhizal communities



Data from the
MaarjAM database
on plant-
Glomeromycotina
interactions (Öpik et
al. 2010)

→ Diversity loss + spatial homogenization

Perspective 4: Investigate human-driven loss of mycorrhizal communities



Data from the
MaarjAM database
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Glomeromycotina
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al. 2010)

→ Diversity loss + spatial homogenization

Acknowledgments

Hélène MORLON
Marc-André SELOSSE
Florent MARTOS
Maarja ÖPIK
Fantine BODIN
Patricia JARGEAT



Dynamics of mycorrhizal networks

[https://github.com/BPerezLamarque/Scripts/tree/master/
Metabarcoding/tutorial_M1_TULIP/](https://github.com/BPerezLamarque/Scripts/tree/master/Metabarcoding/tutorial_M1_TULIP/)