Environmental and Ecological Interactions of Forest Soil Fungi

Ana Mª Rincón

Instituto de Ciencias Agrarias, ICA-CSIC

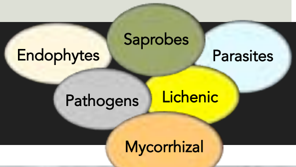
The fungal kingdom

Ascomycota diversity. **(A-B)** Apothecia,**(C-D, F-G)** Thallus with apothecia. **(E)** Bitunicate asci. **(H)** Perithecia. **(I)** Earth-tongue apothecia. **(J)** Cleistothecia **(K)** Operculate ascus of Peziza. **(L)** Ascostroma **(M)** Unitunicate asci. **(N)** Prototunicate ascus.

Basidiomycota diversity. **(A)** Puccinia iridis, (B) Pheogena, **(C) Coleosporium, (D) yeast, (E) Ustilago, (F) Exobasidium, (G) Monliella, (H) Wallemia, (I) Phallus, (J) Clavaria, (K) Amylostereum, (L) Clavariadelphis, (M) Pycnoporus, (N) Russula, (O) Boletus, (P) Lycoperdon.**

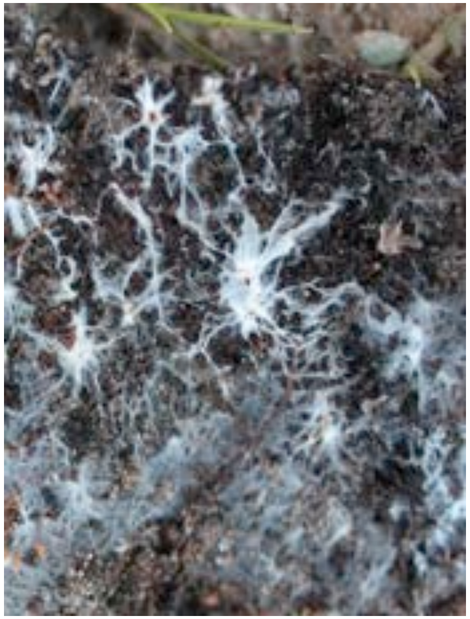
Spataphora et al. (2017) Microbiol Spectrum

Fungal ecology


Endophytes
Saprobes
Parasites
Pathogens
Lichenic
Mycorrhizal


White-rot


Brown-rot


Litter-decayers


Mycorrhizal

Fungi play key roles in forest ecosystems

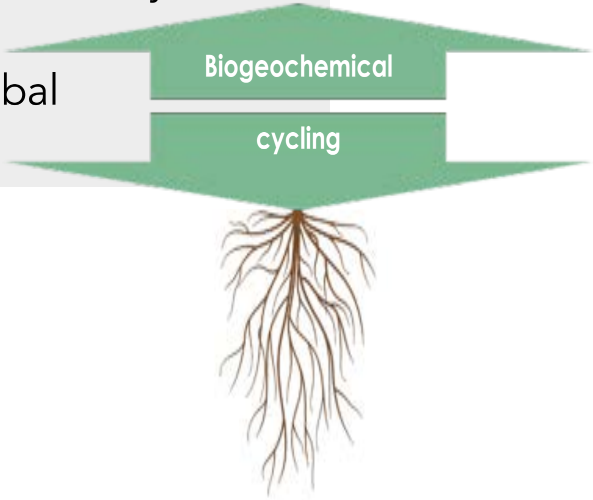
White-rot

Brown-rot

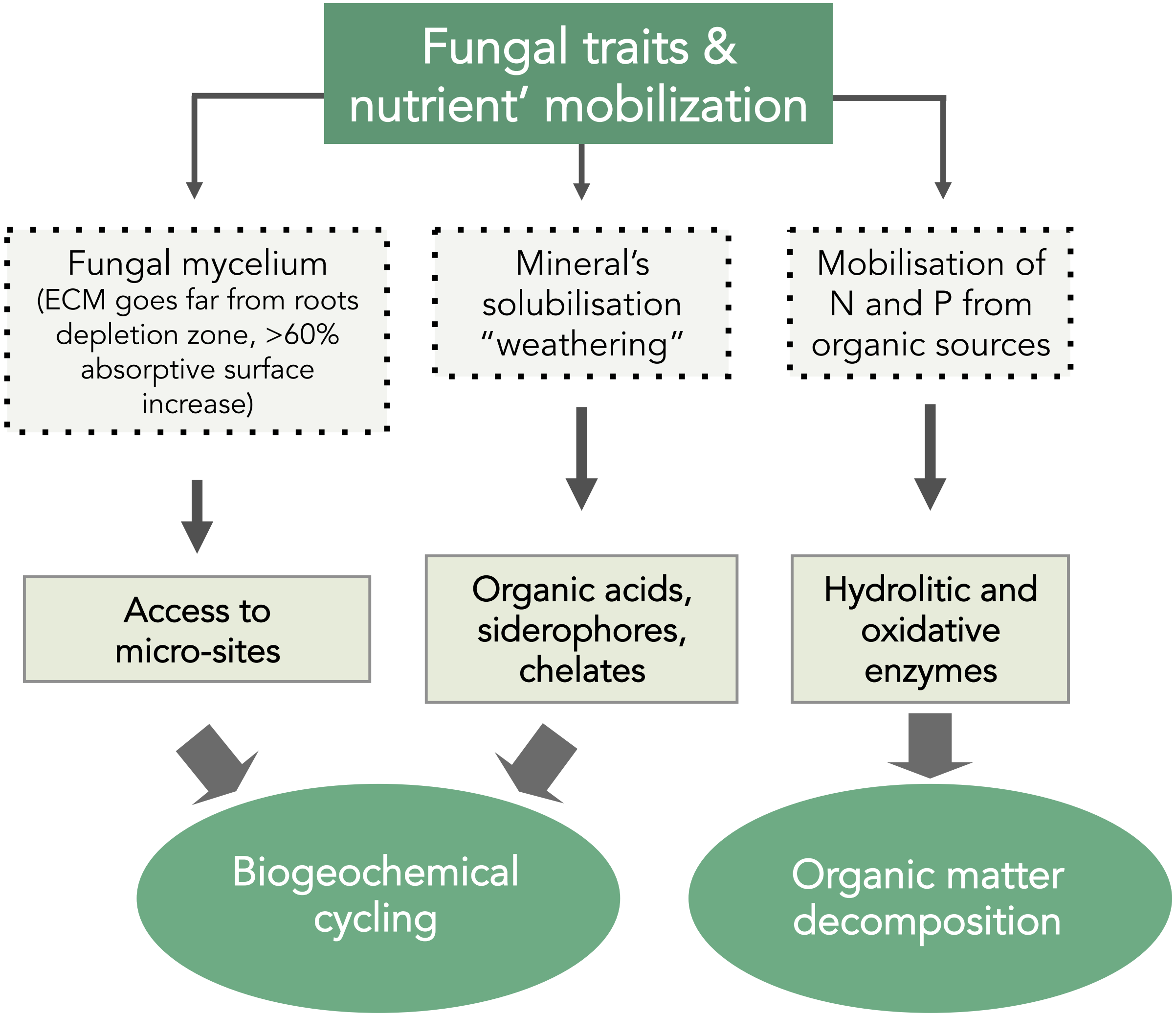
Litter-decayers

Mycorrhizal

- Soil stabilization ➔ ≈ 60-90 % soil microbial biomass in forests
- Trophic base of food webs ➔ relationships with other organisms
- Decomposition and mineralization ➔ extracellular enzymes
- Mutualistic associations ➔ MYC-nutrient acquisition strategies are key functional traits of plants with strong effects on biogeochemical cycles
- Effects from individual plants to ecosystem level, with global consequences ➔ productivity of forest ecosystems



Fungal traits & soil carbon and nutrient cycling



Fungal traits & nutrient' mobilization

Fungal mycelium
(ECM goes far from roots depletion zone, >60% absorptive surface increase)

Mineral's solubilisation "weathering"

Mobilisation of N and P from organic sources

Access to micro-sites

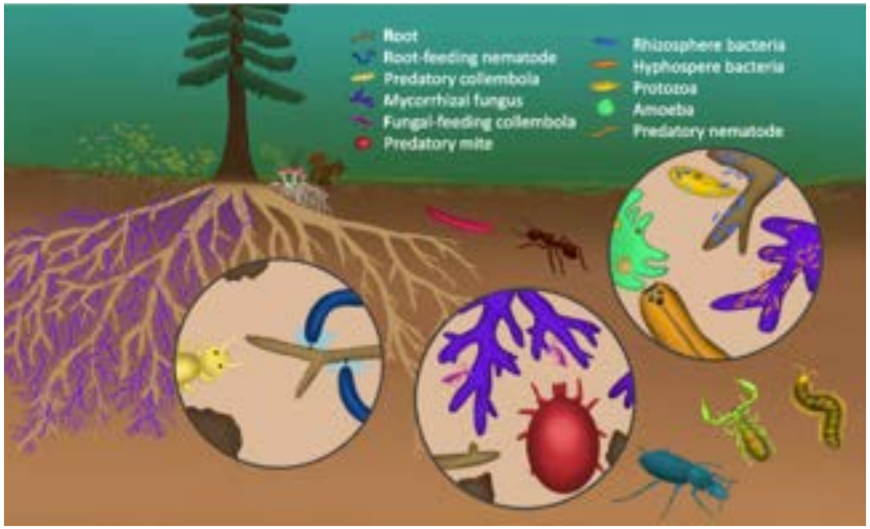
Organic acids, siderophores, chelates

Hydrolitic and oxidative enzymes

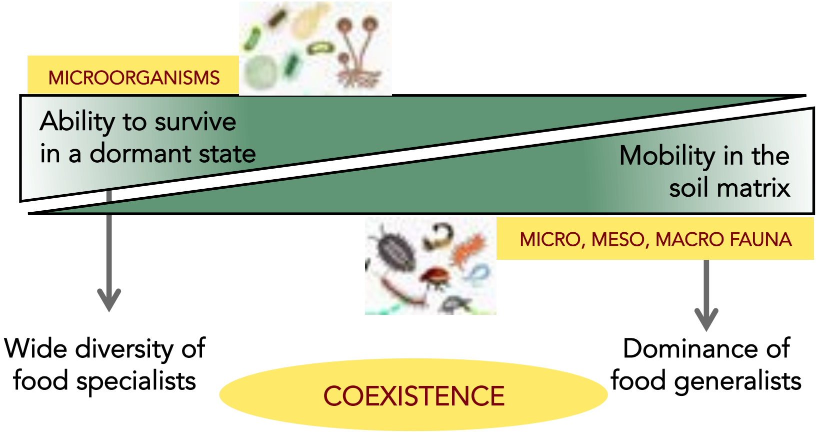
Biogeochemical cycling

Organic matter decomposition

The soil-fungal interface ➔ intra- and inter-kingdom interactions



From: Prescott & Grayston (2023) For Ecol Man 532



MICROORGANISMS

Ability to survive in a dormant state

Mobility in the soil matrix

MICRO, MESO, MACRO FAUNA

Wide diversity of food specialists

COEXISTENCE

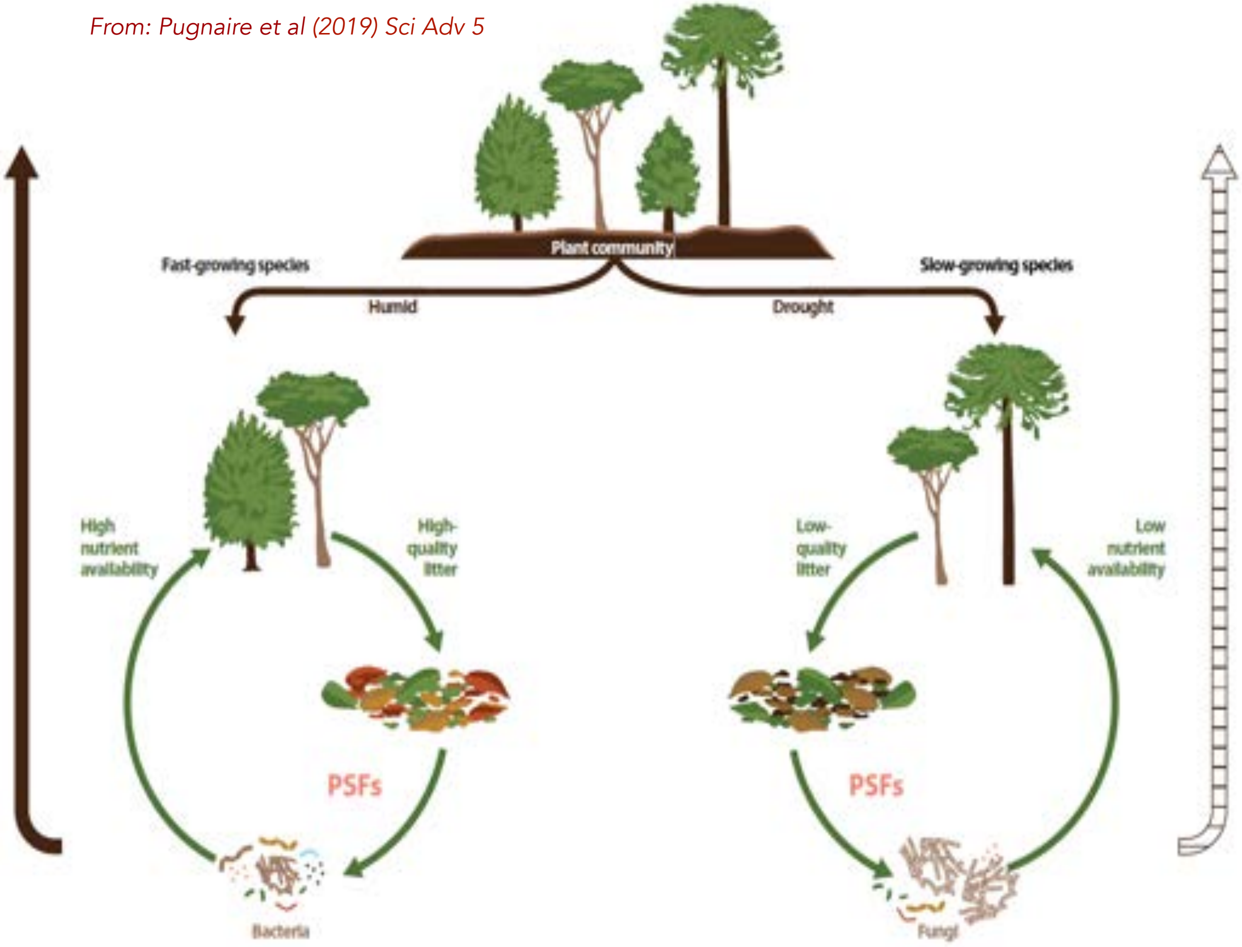
Dominance of food generalists

- Soil physical structure (pore size, connectivity, water and nutrient distribution) drives sensing and access to resources, via providing refuge and limiting mobility of organisms In the soil matrix
- Trophic interactions contribute to the formation of soil physical structure via relocating and mixing mineral and organic compounds
- Restrictions of interactions between consumers and preys allows to the coexistence in soil of hyper-diverse microbial communities (fungi, bacteria) and fauna
- Primary producers at the top of forest soil food-webs

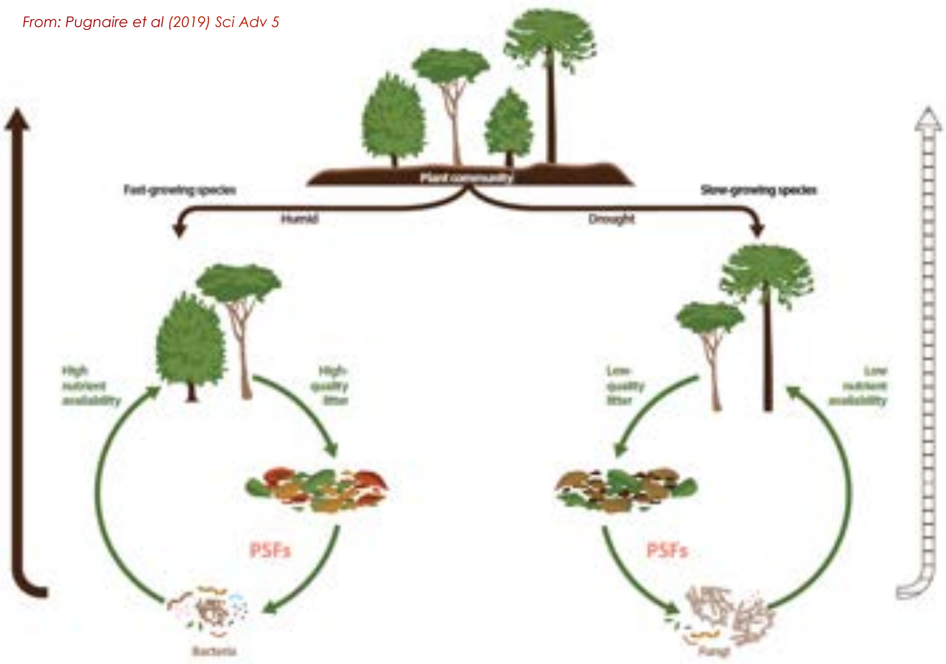
Plant-soil feedbacks in forest ecosystems

- The quality of plant inputs in soil ➔ a main driver of plant-soil-microbial feedbacks

From: Pugnaire et al (2019) Sci Adv 5



Mycorrhizal associated nutrient economy (MANE)



From: Pugnaire et al (2019) Sci Adv 5

AMF dominated — **MANE** — **ECM dominated**

Philips et al. (2013) New Phytol 199

AMF dominated

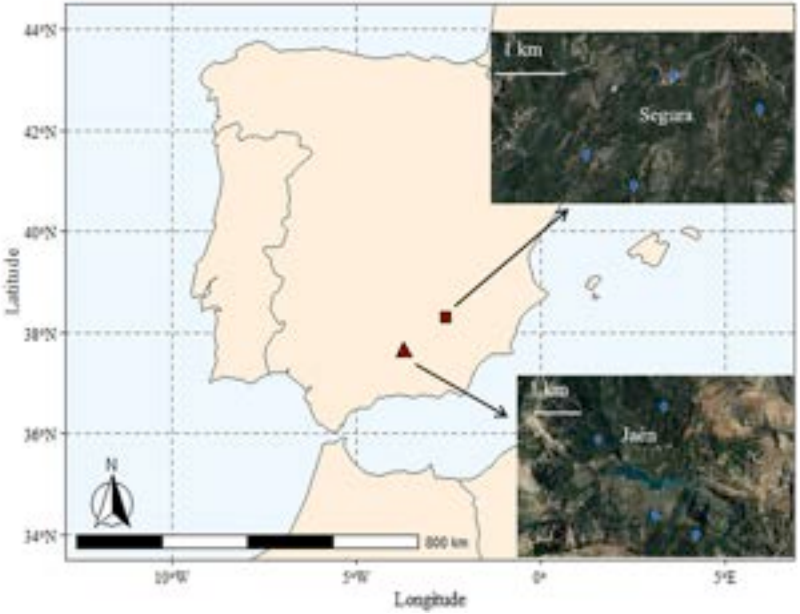
- P- limiting habitats
- Faster nutrient cycling
- Greater saprotrophs and bacteria activities
- Higher N leaching and nitrification processes
- Biological weathering attributable to bacteria
- Priming effects on bacteria

ECM dominated

- N- limiting habitats
- Slower nutrient cycling
- Greater SAP and ECM/ErM fungal activity
- More efficient in fungal mineral weathering (organic acids, quelators)
- Higher priming effects

- ECM dominated habitats can bypass the nutrient mineralization loop for nutrient uptake

Plant Traits and Phylogeny Predict Soil Carbon and Nutrient Cycling in Mediterranean Pine-Quercus Mixed Forests



Sierras de Cazorla, Segura y Las Villas Natural Park (*Segura*)

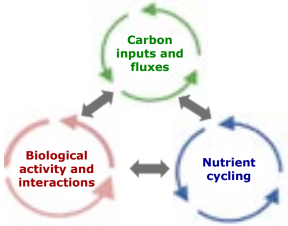
Monte-La Sierra Park (*Jaén*)

Plant community (32 spp) ➔ AM-type (75%), ECM (25 %)

Plant community phylogenetic diversity

Plant morpho-functional trait database

Enzymatic activities of rhizospheric soils



Prieto-Rubio et al (2023) Ecosystems 26

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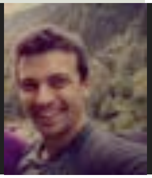
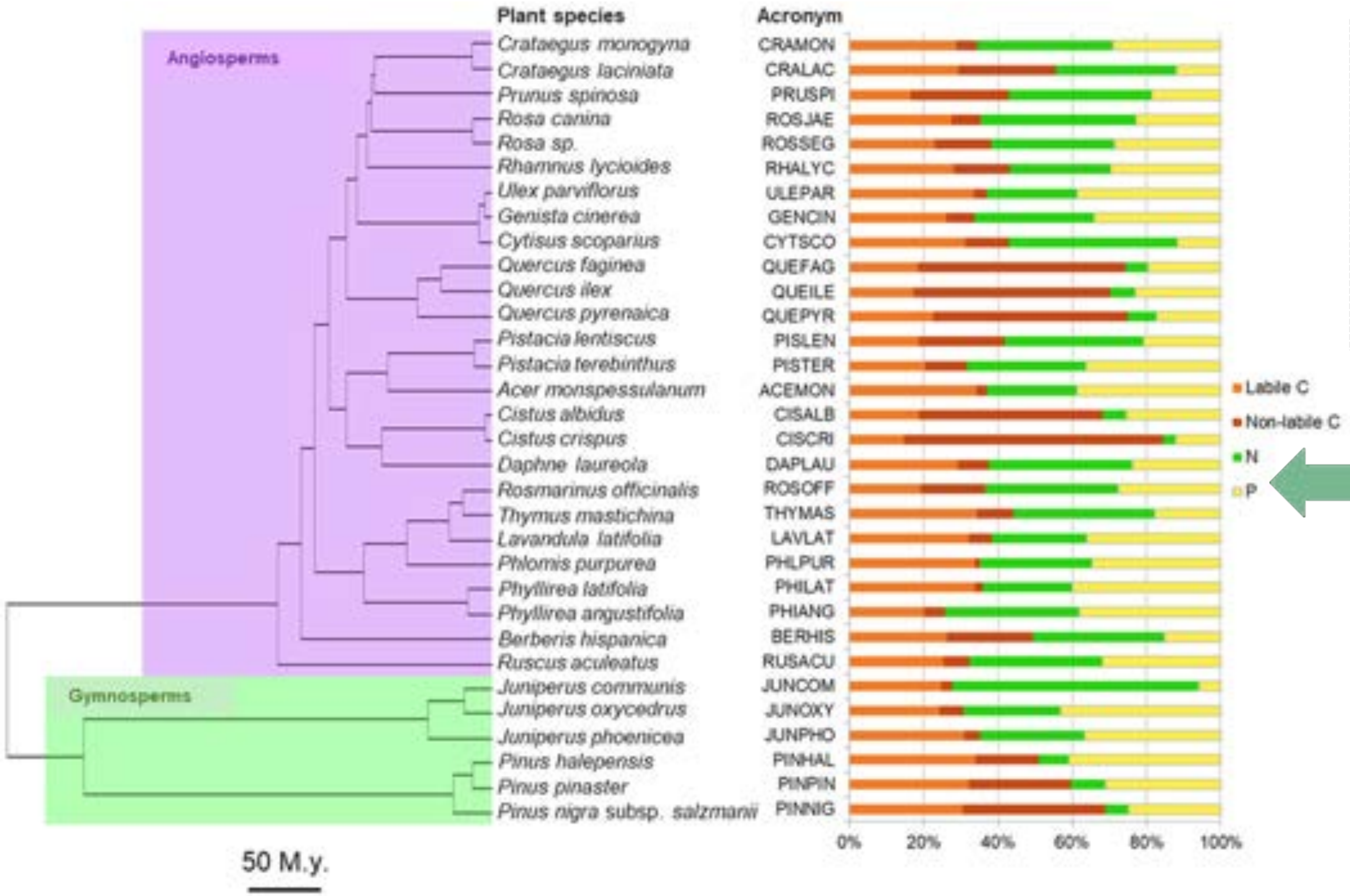


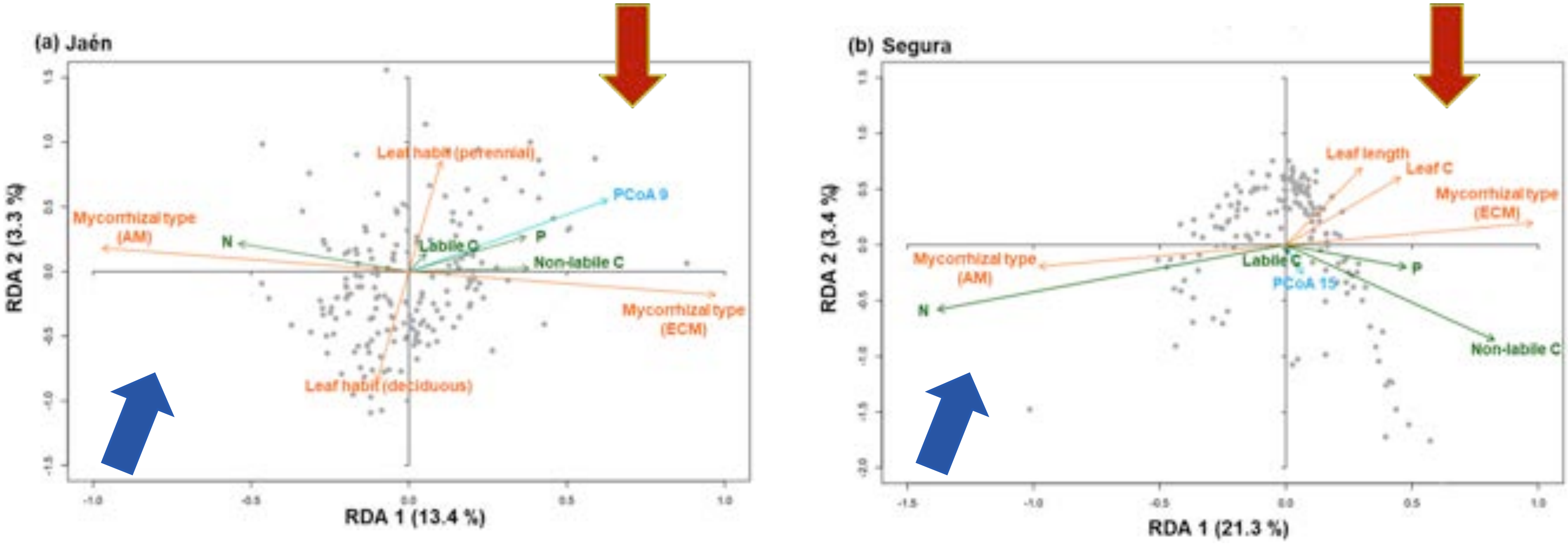


Significant phylogenetic signal of the plant community on soil functioning

(i.e., enzymatic activities related with C and nutrient cycling)

Prieto-Rubio et al (2023) Ecosystems 26

Plant Traits and Phylogeny Predict Soil Carbon and Nutrient Cycling in Mediterranean Mixed Forests



AM-type
& N cycling

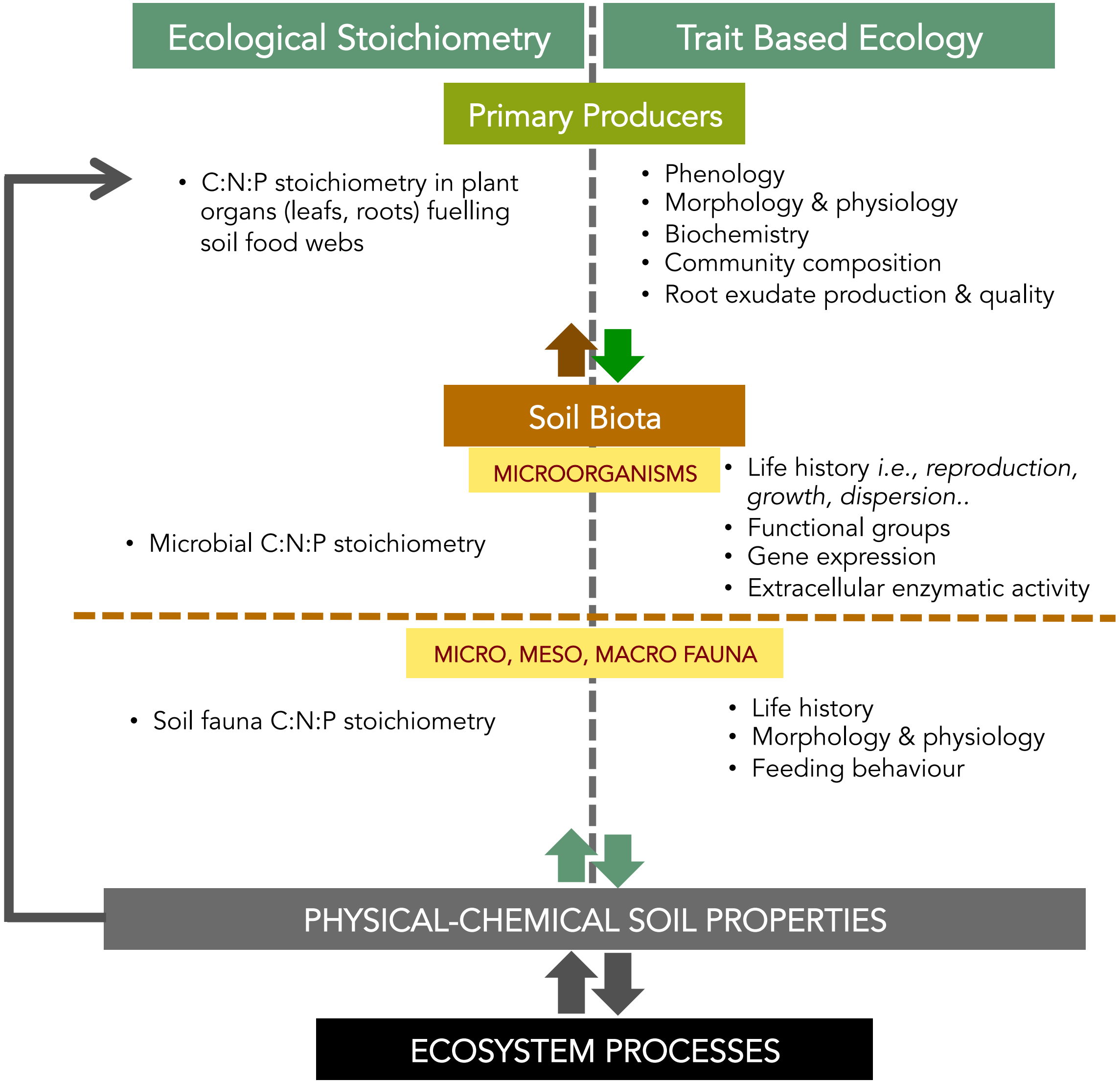
ECM-type
Leaf length, leaf C, leaf habit
& Non-labile C

Plant community structure, morpho-functional leaf traits and MYC-type are main drivers of soil C and nutrient cycling in Mediterranean mixed forests

Mycorrhizal associated nutrient economy (MANE)

Prieto-Rubio et al (2023) Ecosystems 26

Environmental and ecological interactions in forest ecosystems



Ecological Stoichiometry

Trait Based Ecology

Primary Producers

- C:N:P stoichiometry in plant organs (leafs, roots) fuelling soil food webs

- Phenology
- Morphology & physiology
- Biochemistry
- Community composition
- Root exudate production & quality

Soil Biota

MICROORGANISMS

- Microbial C:N:P stoichiometry

- Life history *i.e., reproduction, growth, dispersion..*
- Functional groups
- Gene expression
- Extracellular enzymatic activity

MICRO, MESO, MACRO FAUNA

- Soil fauna C:N:P stoichiometry

- Life history
- Morphology & physiology
- Feeding behaviour

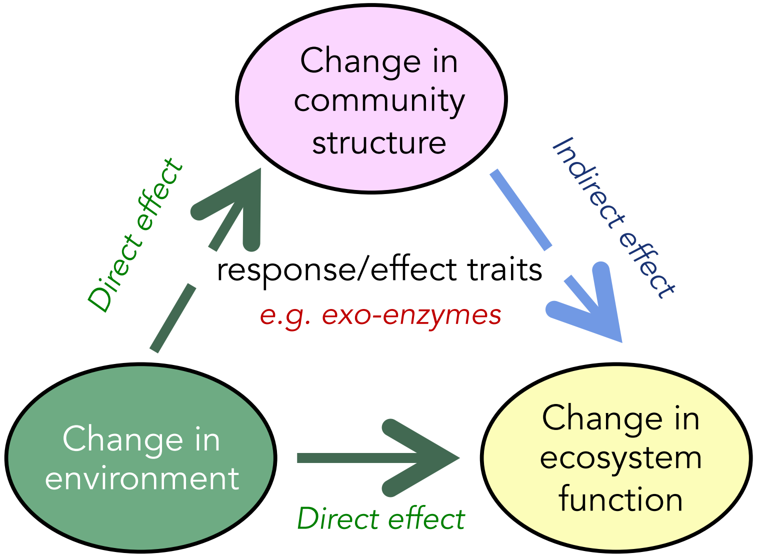
PHYSICAL-CHEMICAL SOIL PROPERTIES

ECOSYSTEM PROCESSES

From: Maaroufi et al (2020) Front Glob Chang

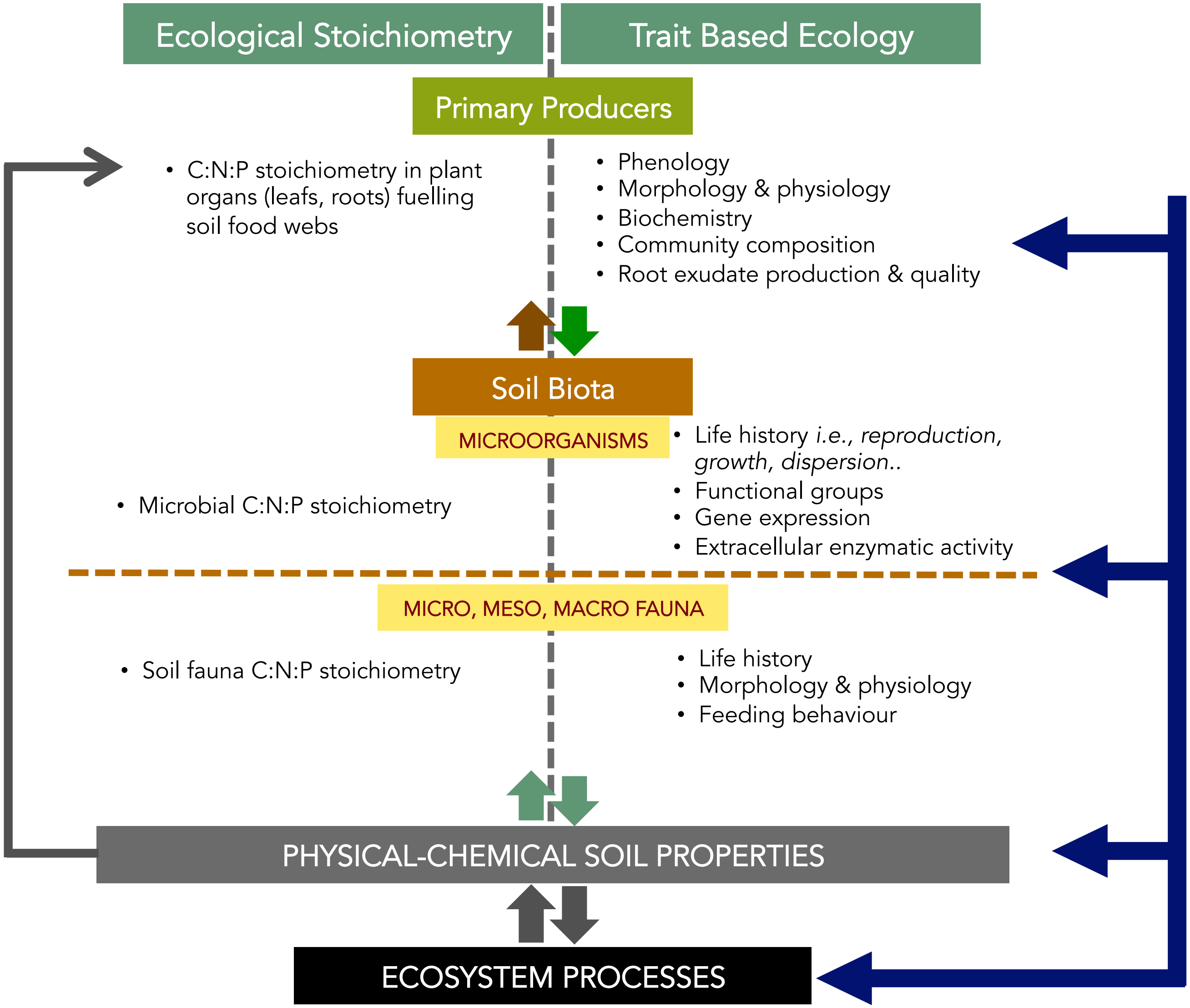
Soil fungal communities ➔ linkages between biodiversity and functioning

- Community ecology goal ➔ predict environmental change effects on ecosystem function
- Hyper-diverse soil fungal communities (taxonomically / phylogenetically / functionally)
- Links between biodiversity and functioning may help to predict ecosystem's response to environmental variations
- Resilience and recovery of forest ecosystems



Koide et al. (2014) New Phytologist , 201

Environmental and ecological interactions in forest ecosystems



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PHYSICAL-CHEMICAL SOIL PROPERTIES

ECOSYSTEM PROCESSES

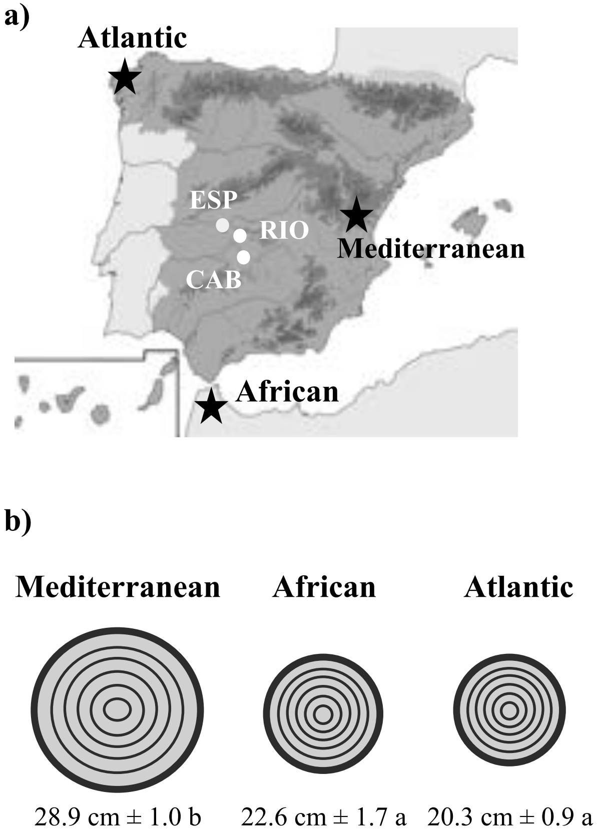
Forest soil fungi: environmental and ecological interactions

Influence of the plant genotype / phenotype and the plant community on the structure and functioning of soil microbial communities

Relationships between edaphic-climatic conditions and soil fungal communities or individual taxa

Structure and functional responses of fungal communities to disturbance

Plant intraspecific variation modulates nutrient cycling through its below-ground microbiome



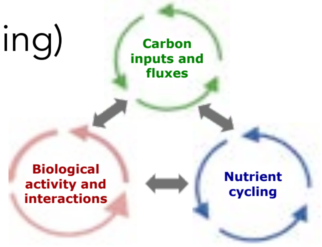
Pinus pinaster Ait. genotypes differing in productivity (DBH, diameter at 1.30 m)

Common garden design 45-yr old trees

n = 108 trees

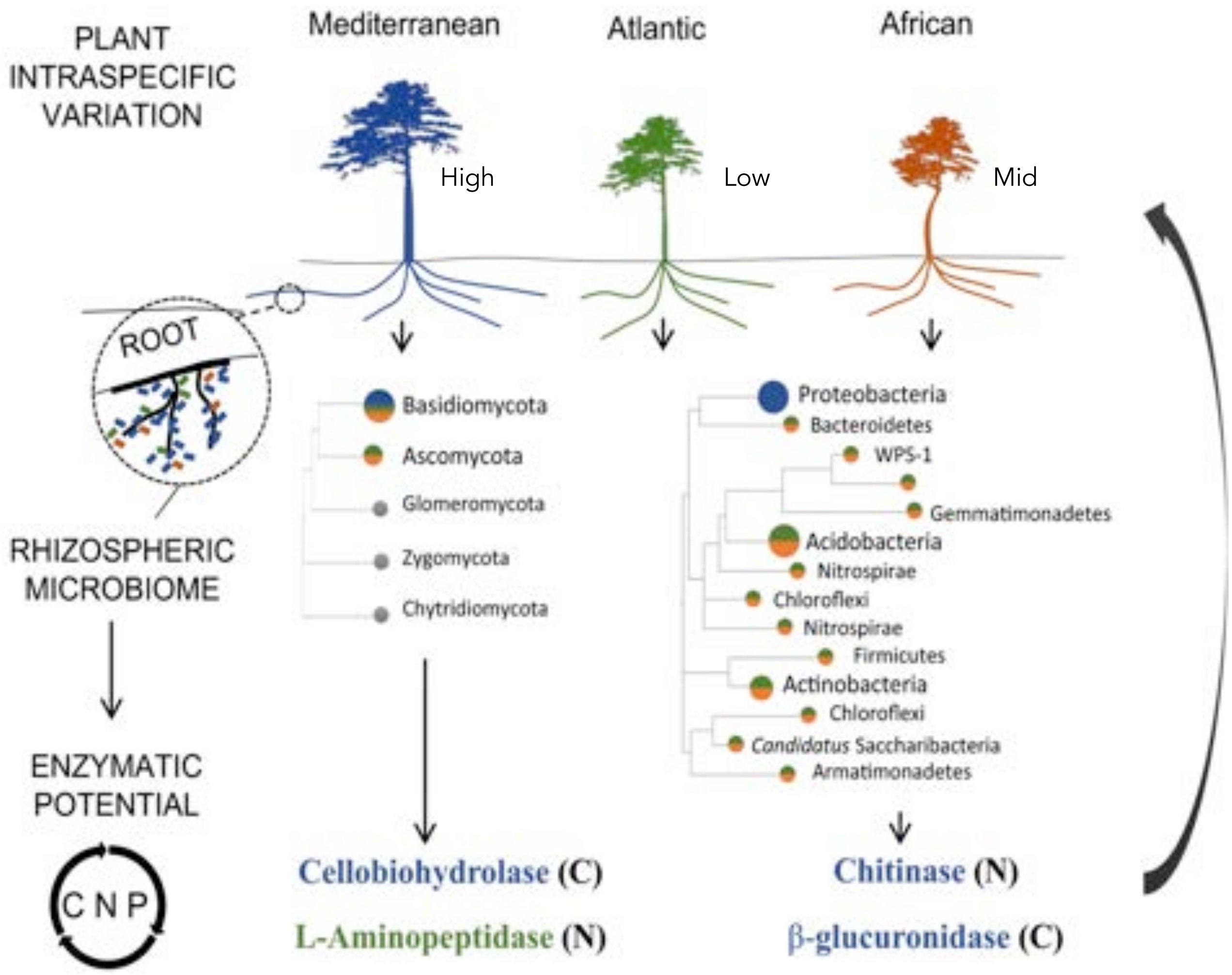
Microbial communities (bulk soil and root-tip) (NGS)

Enzymatic activities (C & nutrient cycling)



Pérez-Izquierdo et al (2017) Env Microbiol, 19:1639
Pérez-Izquierdo et al (2019) J Ecol, 107:1594

Plant intraspecific variation modulates nutrient cycling through its below-ground rhizospheric microbiome



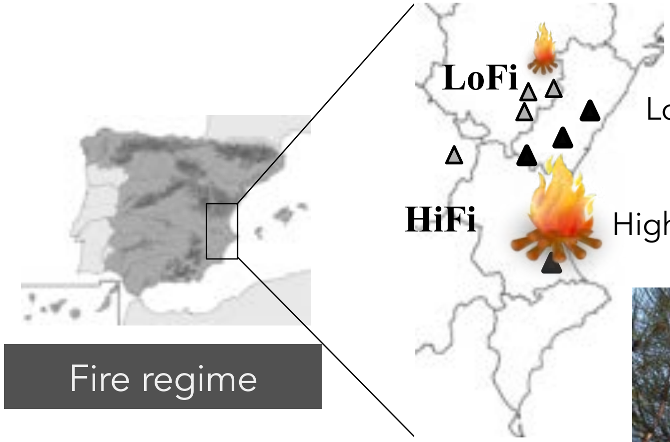
🟩 Atlantic – low productivity
🟦 Mediterranean – high
🟧 African – mid

Prevalence of Basidiomycetes and Proteobacteria at the rhizosphere of the most productive tree genotype

Plant intra-specific variation has a key ecological relevance in modulating the microbial controls of C and nutrient cycling

Pérez-Izquierdo et al (2019) JEcol, 107:1594

Ectomycorrhizal fungal diversity decreases in Mediterranean pine forests adapted to recurrent fires



Fire regime

Low fire recurrence (LoFi) ➔ non serotinous

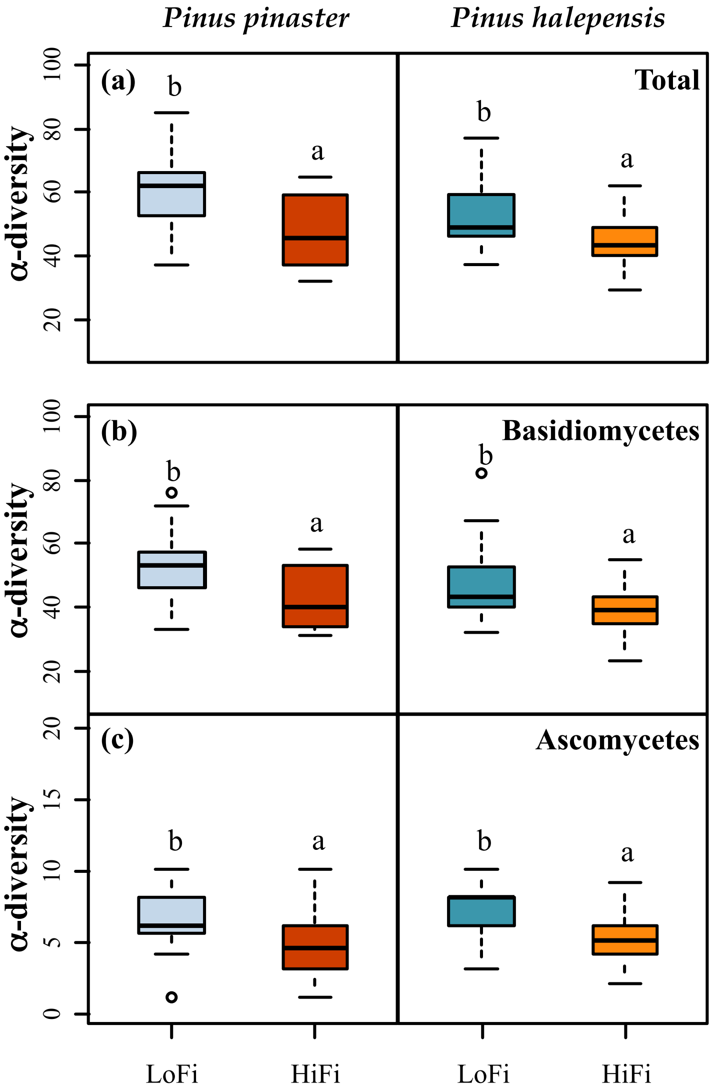
High fire recurrence (HiFi) ➔ serotinous (cones closed till fire happens)

- Root-tip & bulk soil fungal communities (NGS)
- Enzymatic activities

Fig 1. (A) Closed cones of serotinous *Pinus halepensis* Mill. trees. (B) Wildfire in a *Pinus pinaster* Ait. forest in Eastern Spain.

Pérez-Izquierdo et al (2020) Mol Ecol

Ectomycorrhizal fungal diversity decreases in Mediterranean pine forests adapted to recurrent fires

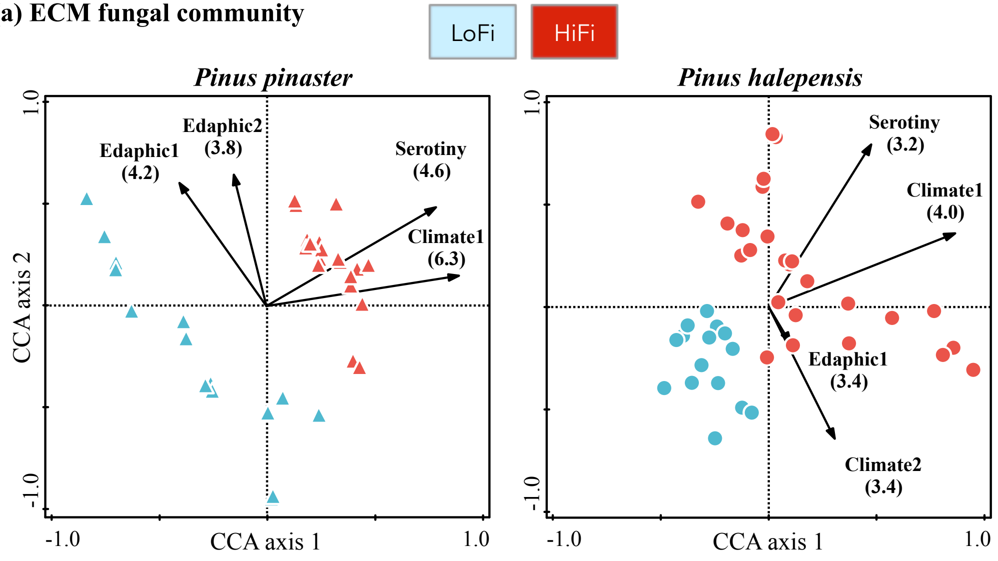


Root-tip ECM diversity declined in pine populations subjected to high fire recurrence, pointing to the community simplification (with prevalence of fire-prone fungi), due to the high selective pressure of fire (i.e., edaphic transformations, drier environment..)

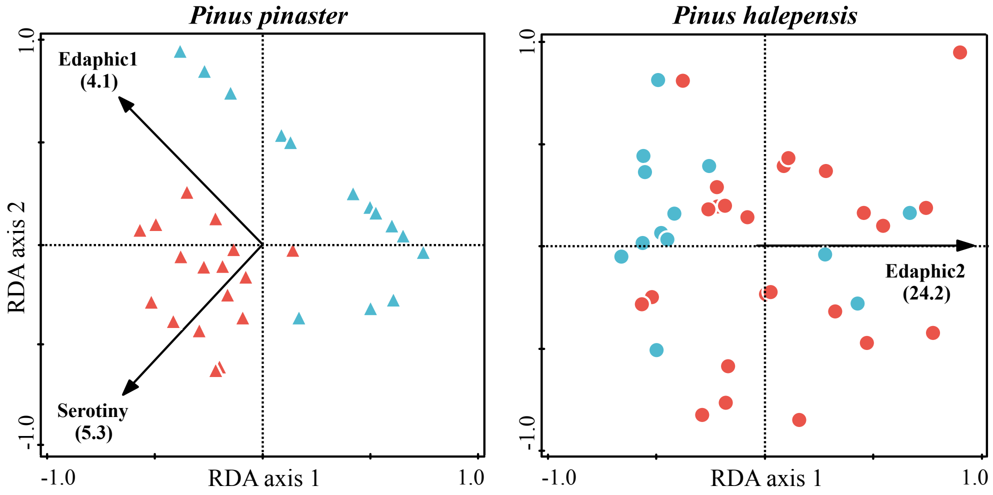
Pérez-Izquierdo et al (2020) Mol Ecol

Main drivers of root-tip ectomycorrhizal community structure and function in Mediterranean pine forests adapted to recurrent fires

(a) ECM fungal community



(b) Enzymatic activity



Climate and edaphic factors were major drivers of ECM fungal community structure and functioning in the later case

Serotiny (i.e. tree fire-adaption trait, did significantly explain the structure and, for *P. pinaster* also the functioning, of the root-tip ECM fungal community

Knowing the structure and function of ECM fungal communities of fire-prone pine species may have important implications for the dynamics and resilience of these Mediterranean ecosystems

Pérez-Izquierdo et al (2020) Mol Ecol

Forest soil fungi: environmental and ecological interactions

Evaluation of microbial biodiversity-based strategies for soil restoration and remediation assessment

Response to stress (fire, soil degradation)

MIDIVERSOIL

Ecology & applications in truficulture

TUBERLINKS

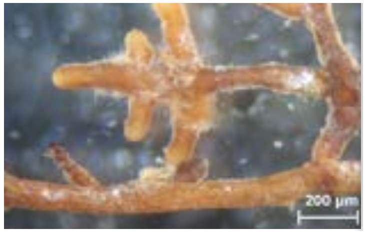
Deciphering biodiversity and soil-plant feedbacks in the truffle environment for fitting best management practices to optimise the productions of truffle systems

TUBERSYSTEMS and TUBERLINKS Projects

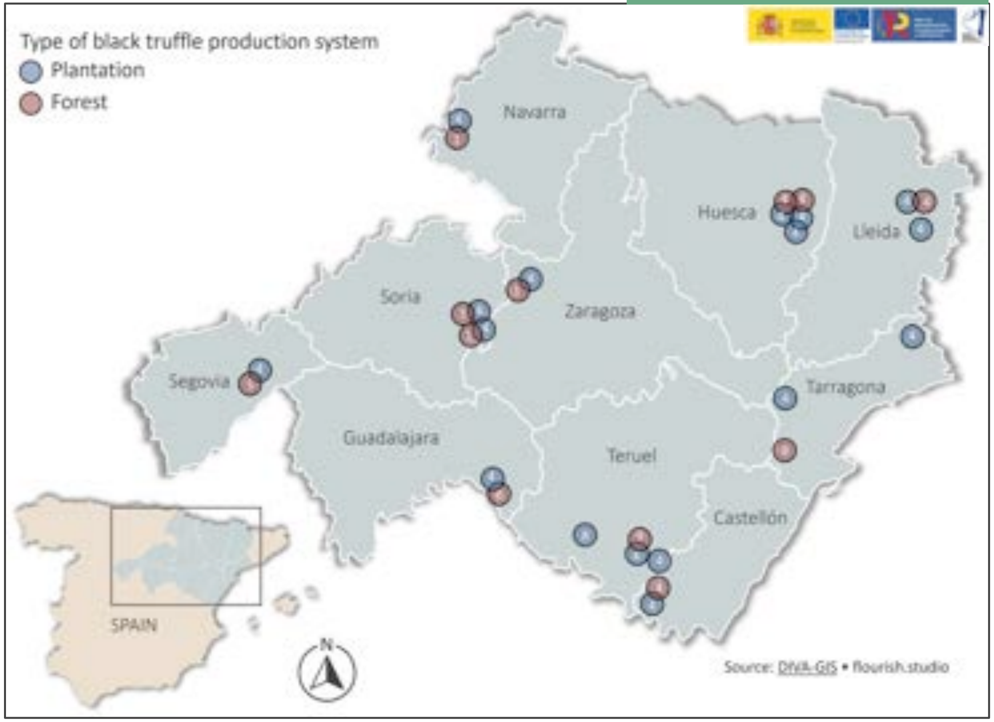
Tuber melanosporum VITTAD.

Proyecto TUBERSYSTEMS

Sistemas multiproductivos sostenibles en Truficultura y servicios ecosistémicos asociados



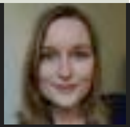
https://www.tubersystems.com



Source: DIVA-GIS • flourish.studio

- Ascomycete ECM fungus + *Q. ilex*
- Highly appreciated edible fungi
- Mediterranean distribution (Spain is a main producer)
- Types of production: wild and plantations (125 trees)

Modelling environmental drivers of *Tuber melanosporum* mycelium in productive holm oak plantations and forests



Compared with wild-producing systems, we expected:

i) higher Tmel mycelium in plantations and less dependency of climate due to the managed-controlled environmental conditions

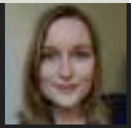
ii) Truffle mycelium biomass will respond to different environmental abiotic variables in forests *vs* plantations

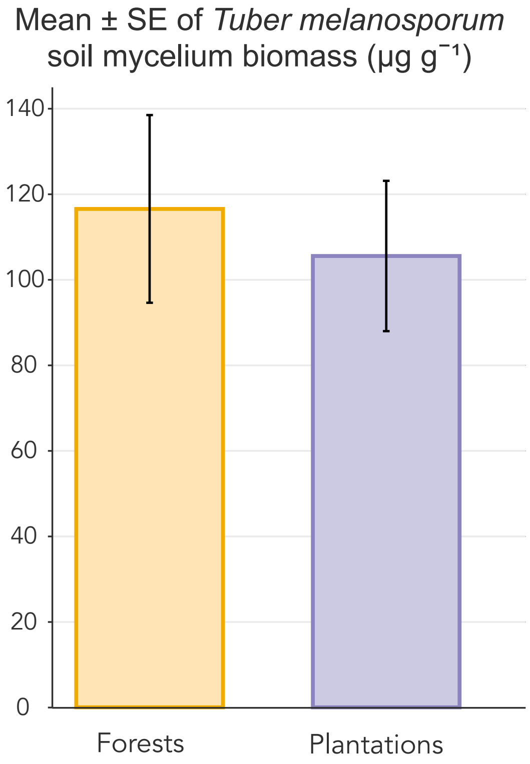
Generalized Additive Modelling (GAM) (≈ 30 abiotic variables)

Stepwise selection of best-fitted GAMs based on AIC

Barou et al (2024) In preparation

Modelling environmental drivers of *Tuber melanosporum* mycelium in productive holm oak plantations and forests





- No significant differences due to the type of truffle productive system (wild *vs* plantations)
- Variation in truffle mycelium biomass explained up to the 70 % in plantations and to the 50 % in forests, by the edaphic-climatic variables tested

Barou et al (2024) In preparation

Some Challenges in Soil Forest Fungal Research

- Functional potential ➔ comparison of genomes of distantly related taxa. Transcriptomics and proteomics approaches are needed to link genes to biological processes (SOM decay, nutrient mobilization, symbiosis establishment) *Lebreton et al. 2021. Annu. Rev. Ecol. Evol. Syst.*

- Links diversity-function ➔ understand the functional consequences of inter- and intra-specific fungal variability, and the patterns and drivers of fungal (hyper-diverse) communities assembling *Mony et al 2021. Front Ecol Evol*

- Fungal traits ➔ e.g. the extent of hyphae belowground (alive & necromas) is a challenging but important step for understanding fungal impacts on soil C fluxes (e.g. MYC nets may represent ~50 % of the total soil microbial biomass) *Wurzburger & Clemmensen 2017. J Ecol*

Some Challenges in Soil Forest Fungal Research

- Models ➔ e.g. MYC are a key entry point of C into soil food webs (estimates of 3.58 Gt C or 13.12 Gt CO2e), but we lack a robust quantitative and mechanistic understanding of the contribution of MYC associations to the global C cycle *Hawkins et al. 2023. Current Biol*

- From basic to applied research ➔ Need of knowledge transference of science-based solutions for forest and agro-forest management and productions optimization (e.g. forest conservation, climate change mitigation, truficulture)

Forest soil fungi: environmental and ecological interactions

Thank you for your attention!!

Collaborators

- Concepción Azcón, Álvaro García, José L. Garrido (EEZ-CSIC)
- Marc Buée (INRA-France)
- Marta Goberna (INIA-CSIC)
- Miguel Verdú, Jorge Prieto (CIDE-CSIC)
- Julio Alcántara (UJA)
- Leticia Pérez-Izquierdo (Bc3)
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