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Biogeochemical Cycles: Learning From Natural and Semi-natural Ecosystems to Design Sustainable Agro-Systems

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With collaborations of

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Current intensive cropping systems are not sustainable on many aspects

- Continuous degradation of soil assets:
 - - 40% of initial soil organic matter (SOM) stock within 10 years
 - Loss of « soil fertility »
- Dependency of humankind to mineral fertilizer
 - Half of world population directly depends on mineral fertilizers
 - Peak of phosphorus extraction planned for 2050
 - C-cost of ammonia production: 1,5-4 kg CO₂/kg NH₃
- Damage ecosystem health, water resource and climate
 - Stream, lake and coastal eutrophication
 - Agriculture contributes to 17% of global GHG



Li et al 2019

Ornes 2022

NiD France Rapport 2020

FAO Report « Emissions due to agriculture 2000-2018 »

Lal 2003

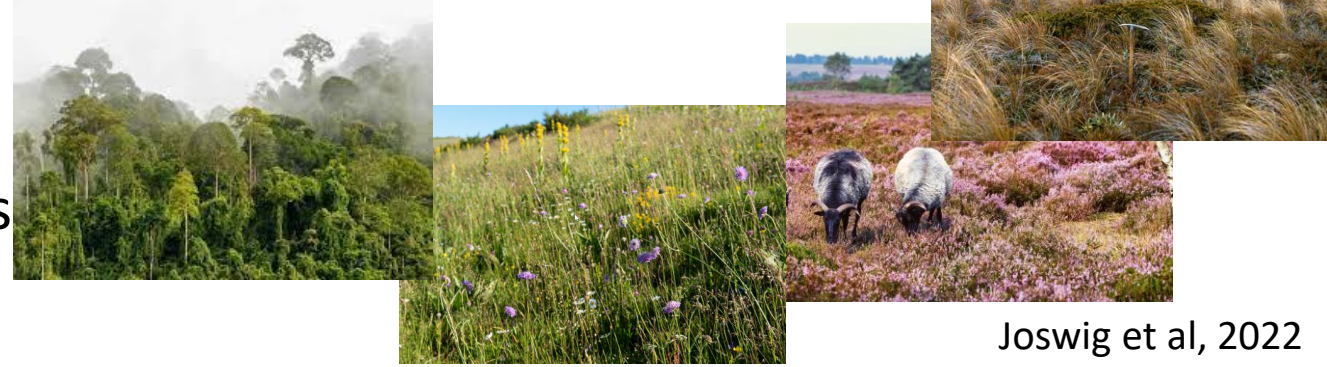
How to develop efficient agroecological strategies ?

- Semi-natural forests and grasslands used as models
 - As productive as high-input annual crops
 - Accumulate soil C, retain nutrients, low GHG emissions
- Which aspects should be copied ? How to translate in practices?
- Current focus on:
 - General ecosystem attributes such as high diversity, root biomass, fungal biomass...
 - Improvement of specific functions such as N retention by plant roots, symbiotic N₂ fixation, C input to soil.



Current difficulties/limits for agroecology development

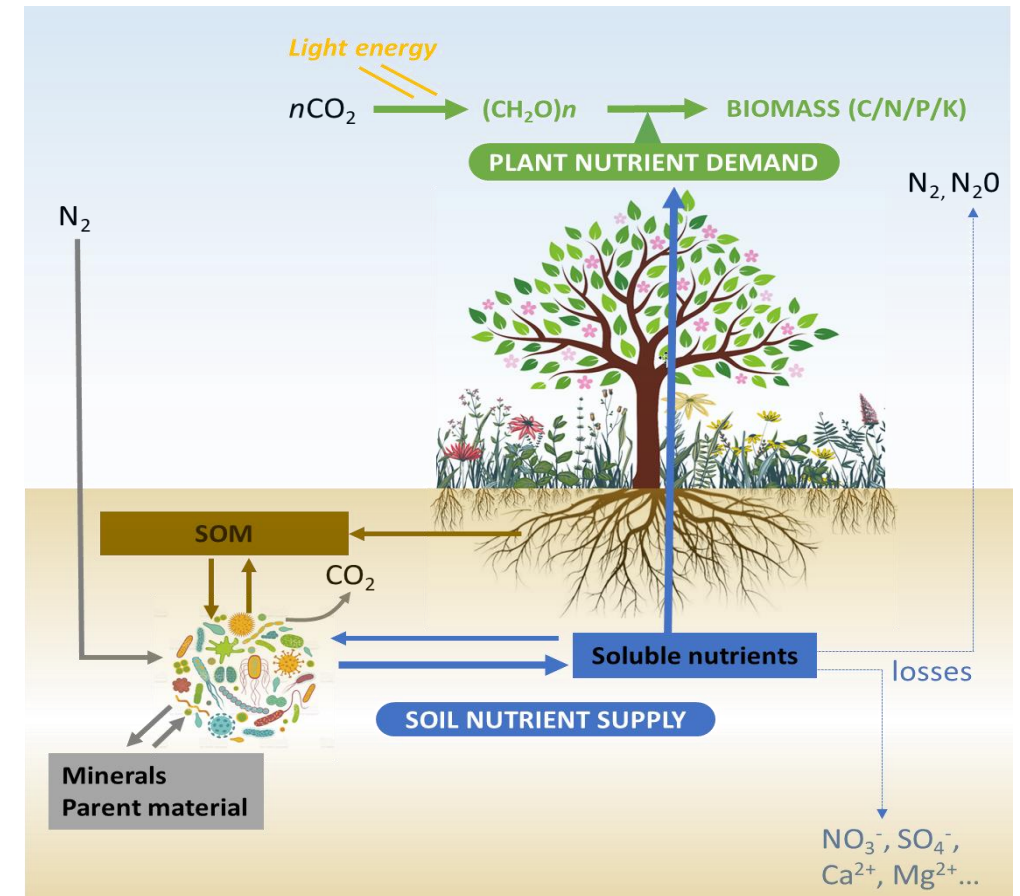
- Diversity and traits of organisms (plant, soil) are extremely variables between ecosystems



- Ecosystem functioning depends on the coupling of many plant-soil processes
 - Improvement of one process does not necessarily improve the sustainability of the whole ecosystem (e.g. legumes)

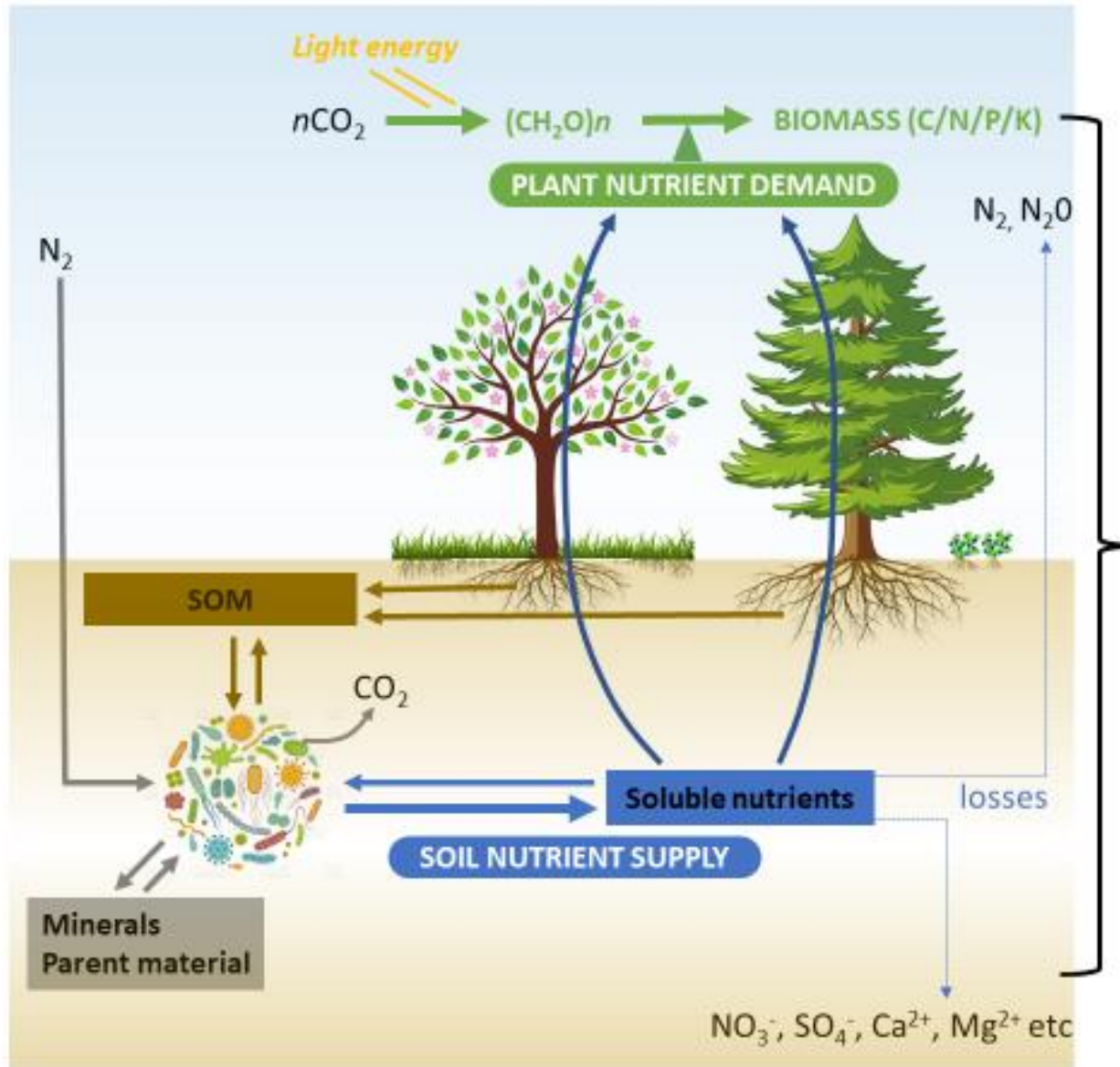
Need of a more systemic approach considering:

- the interactions of multiple co-occurring processes
- the adaptation of organisms/processes to pedoclimatic contexts



Introduction of the plant-soil synchrony concept

Ecosystem productivity & sustainability linked to the level of synchrony between plant N demand and soil supply

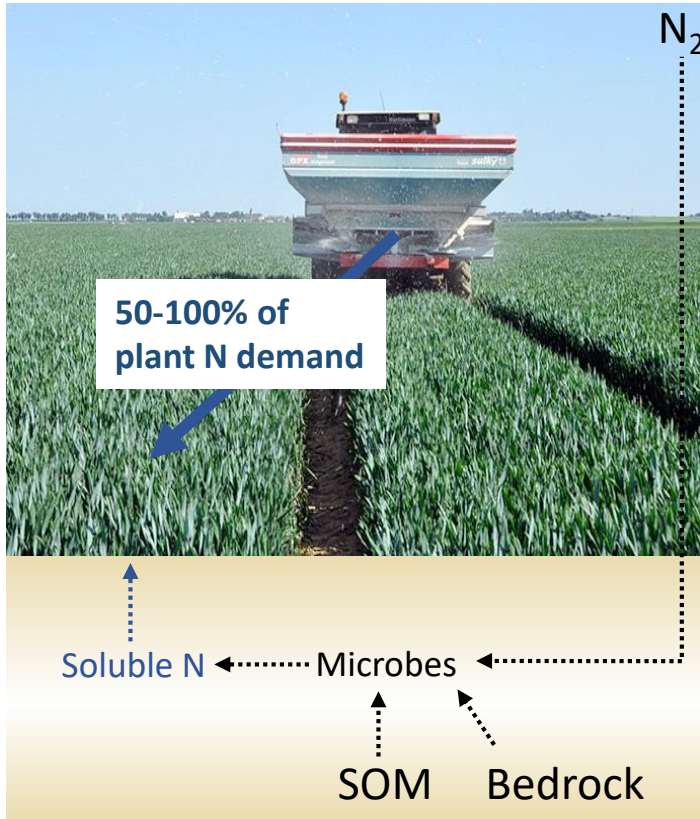


High level of synchrony promotes

- **↑** biomass production by **↓** N limitation
- **↓** excess of soluble N, N losses (<5%)
- **↑** building of SOM

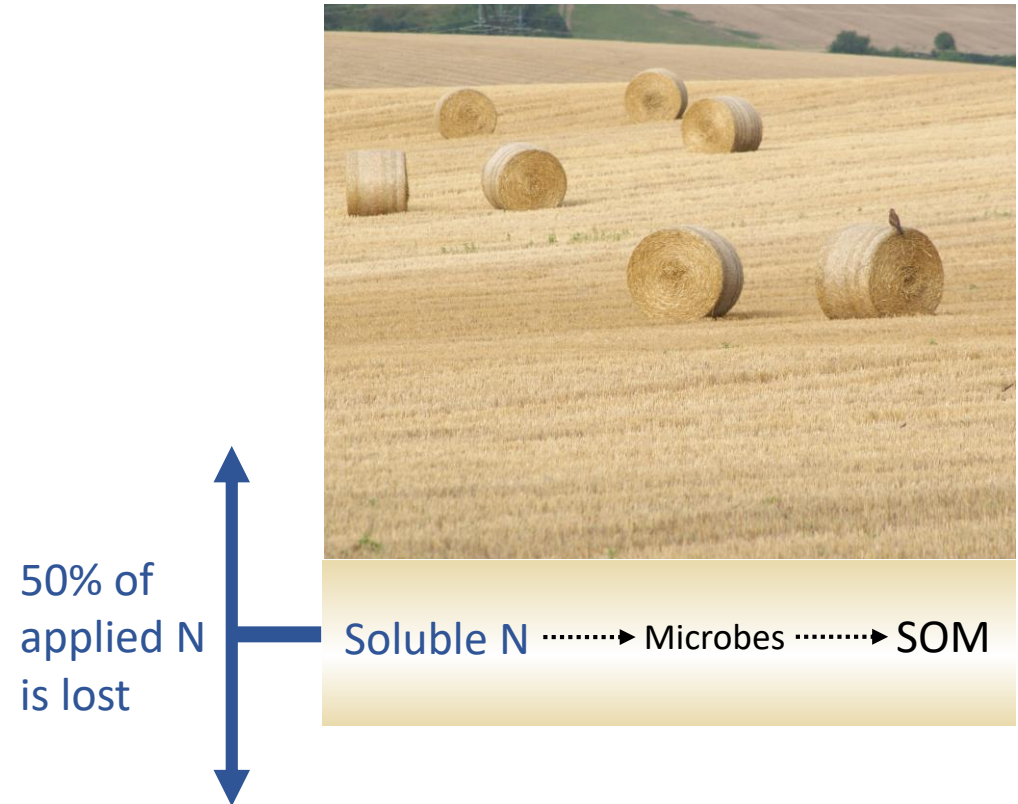
Intensive agrosystems characterized by a low demand/supply synchrony

High plant demand



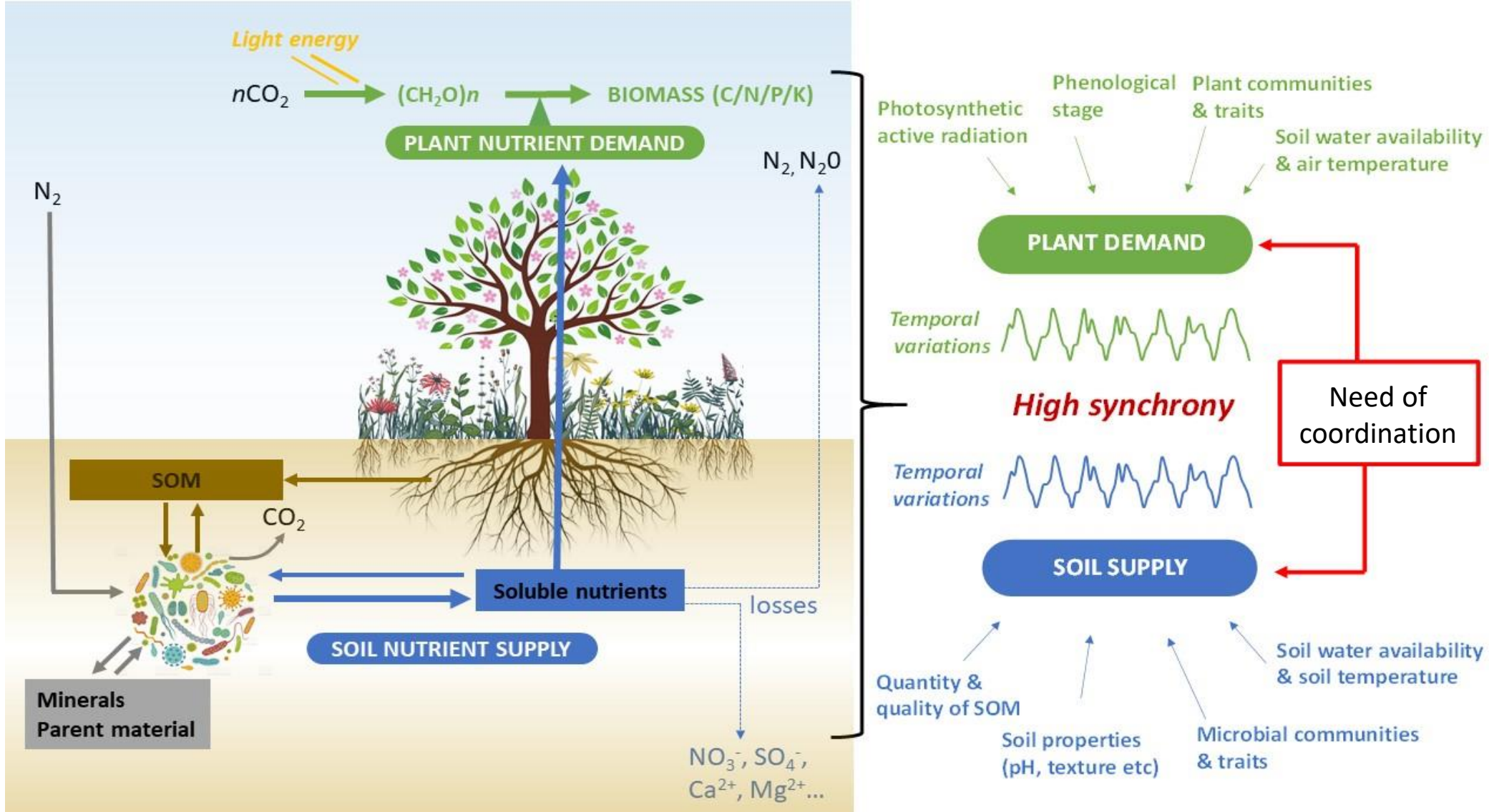
➤ Dependence to fertilizers

Low plant demand



➤ High loss of nutrient and SOM

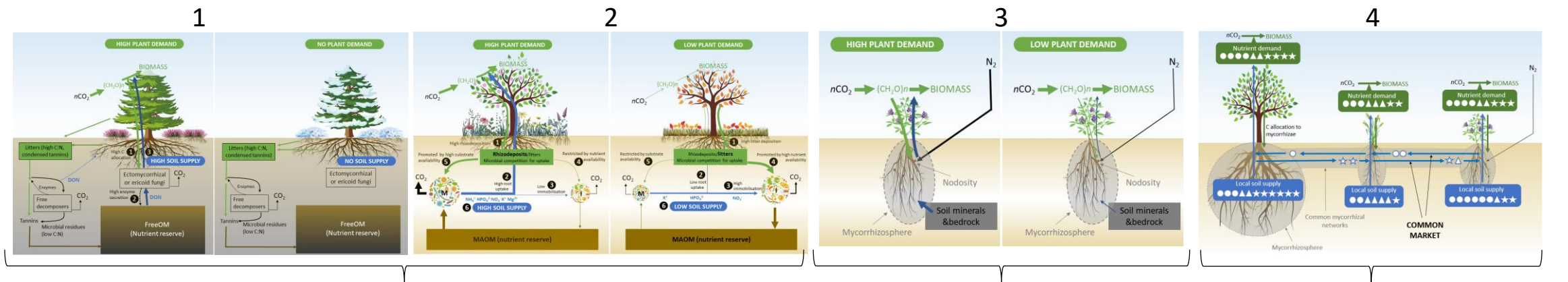
How can a high level of synchrony can be reached in natural ecosystems?



➤ Synchrony requires the coordination of many plant-soil processes

Review of latest advances in ecology, biogeochemistry & agronomy

Identification of 4 systems of synchrony (coordination of processes)



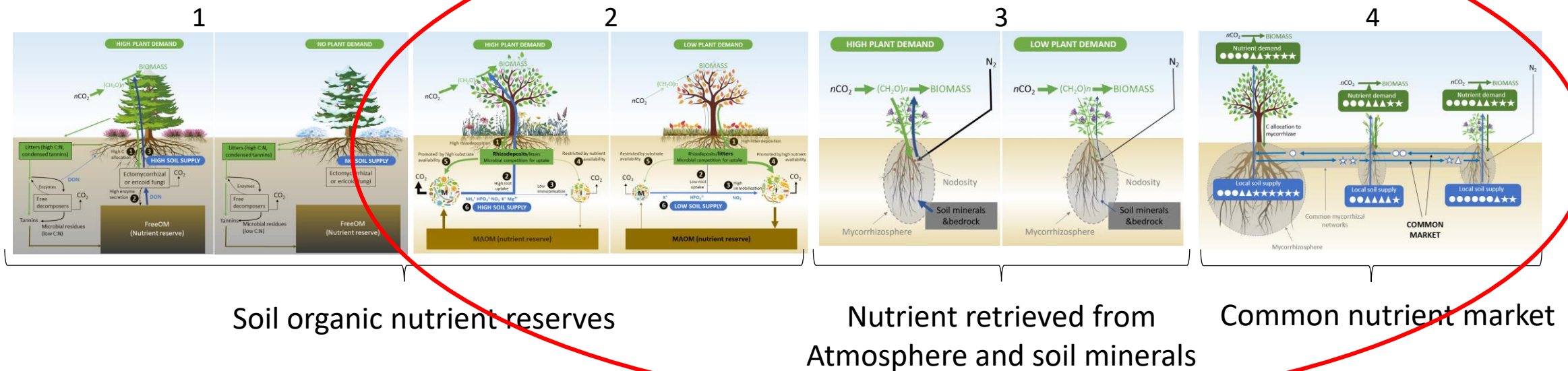
Soil organic nutrient reserves

Nutrient retrieved from atmosphere and soil minerals

Common nutrient market

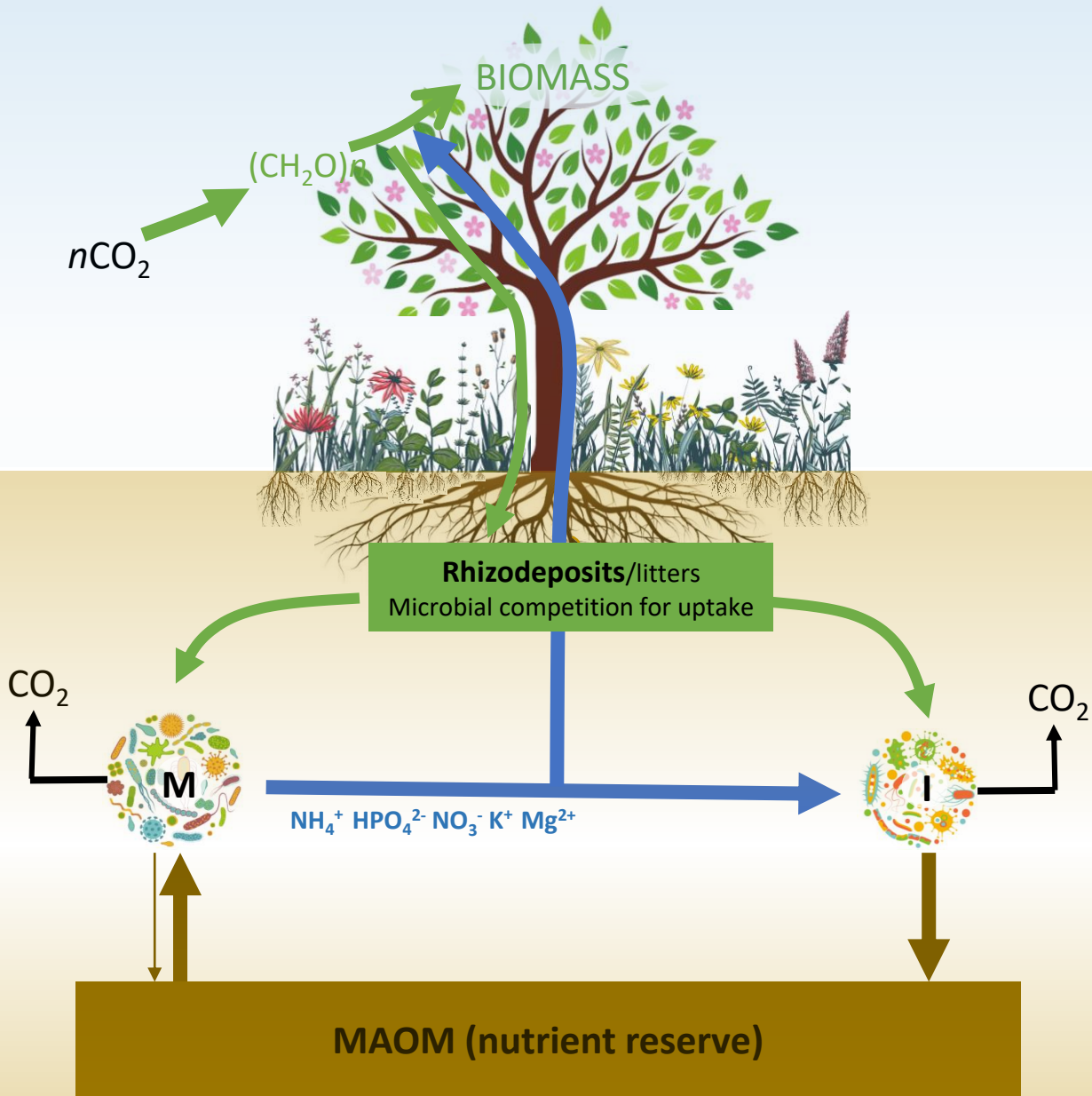
Review of latest advances in ecology, biogeochemistry & agronomy

Identification of 4 systems of synchrony (coordination of processes)



Synchrony based on organic nutrient reserve

1. MAOM-based synchrony (Sync-MAOM)

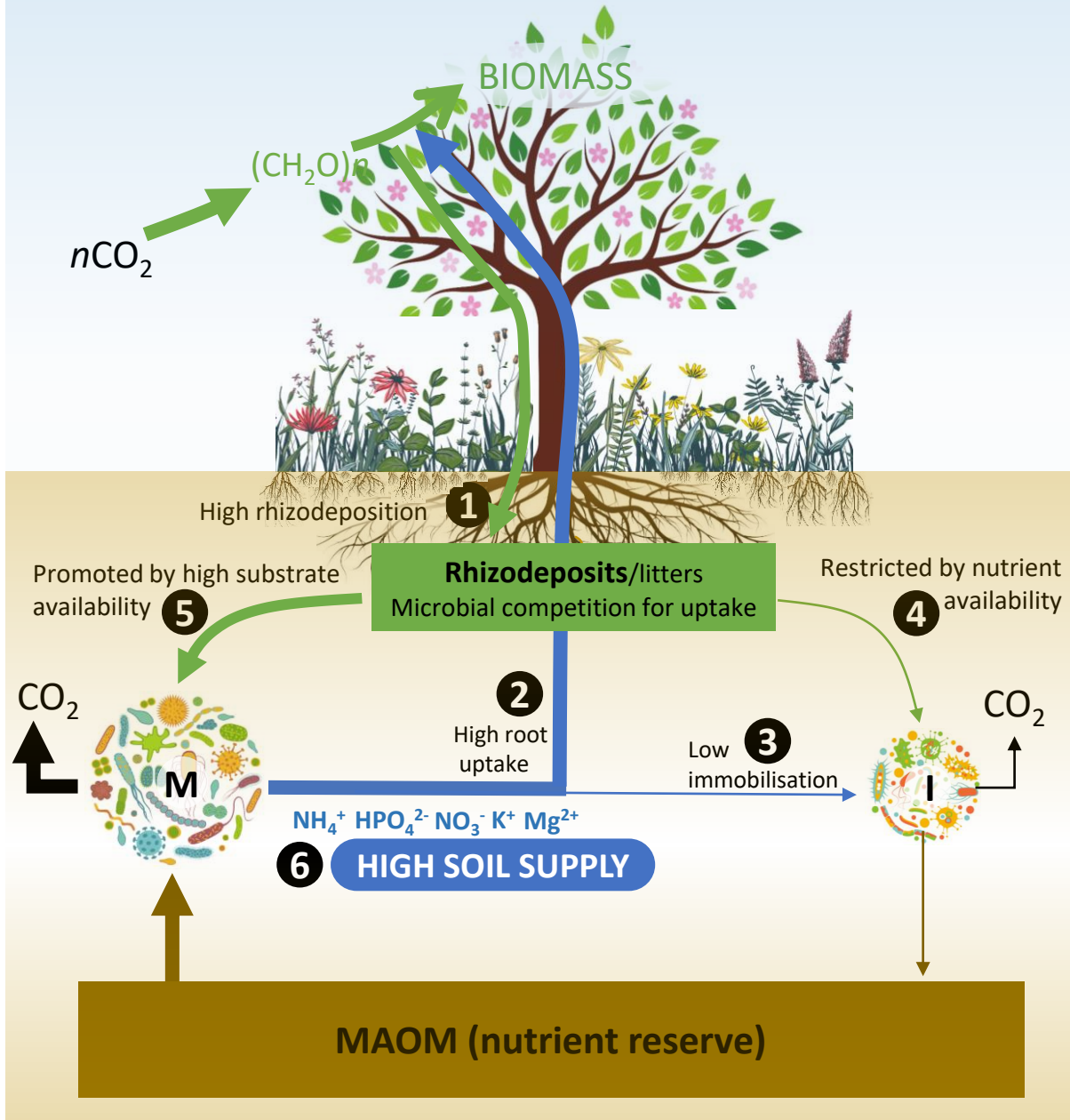


Resource-acquisitive plant species
 Fast growth and tissue turnover
 High rhizodeposition
 Fast decomposing litter (low lignin, low C/N)

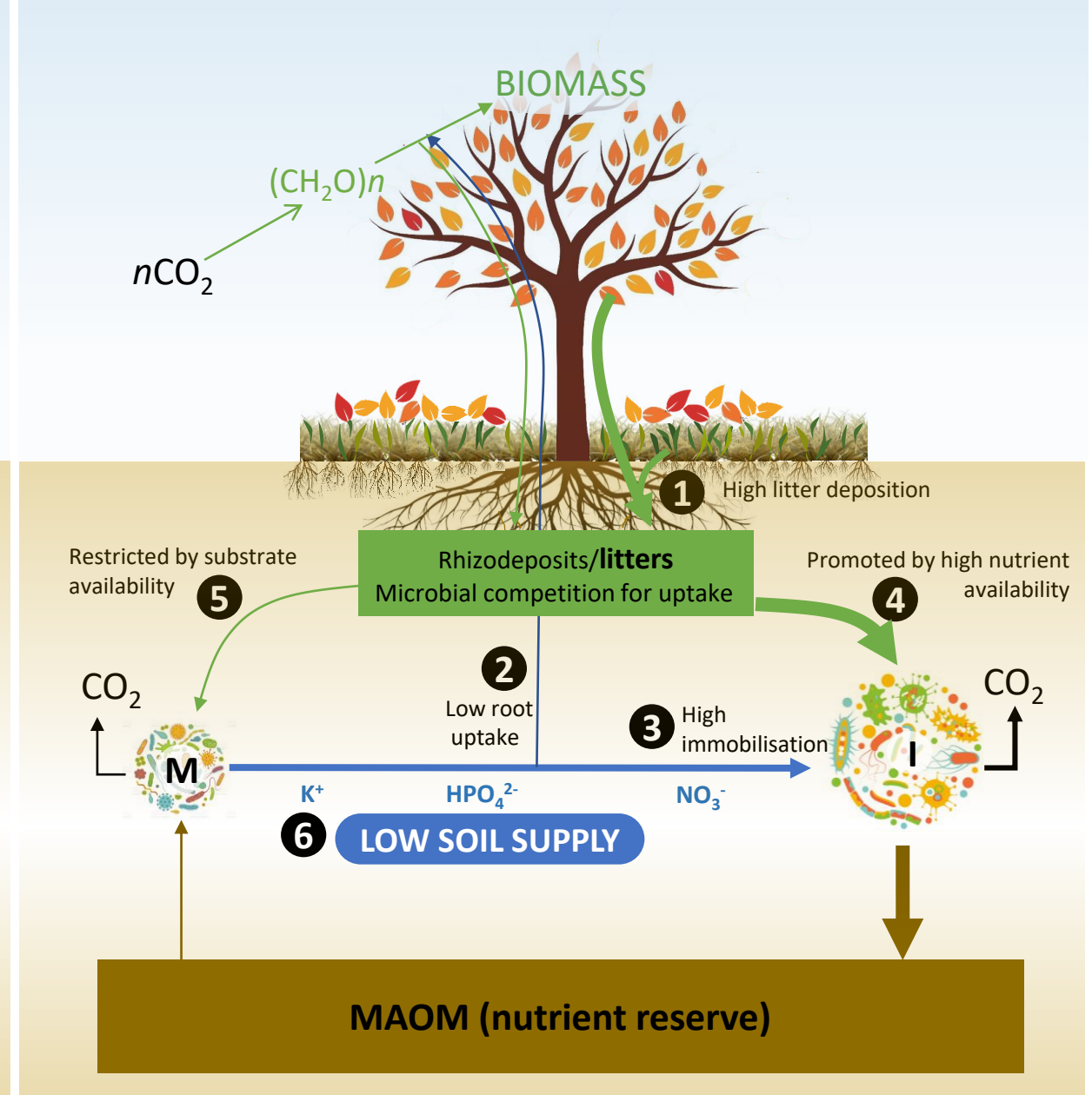
Two functional groups of microbes (M & I)
Supply chain of mineral nutrients for plants

Main nutrient reserve : organic matters
 bound to soil minerals

HIGH PLANT DEMAND



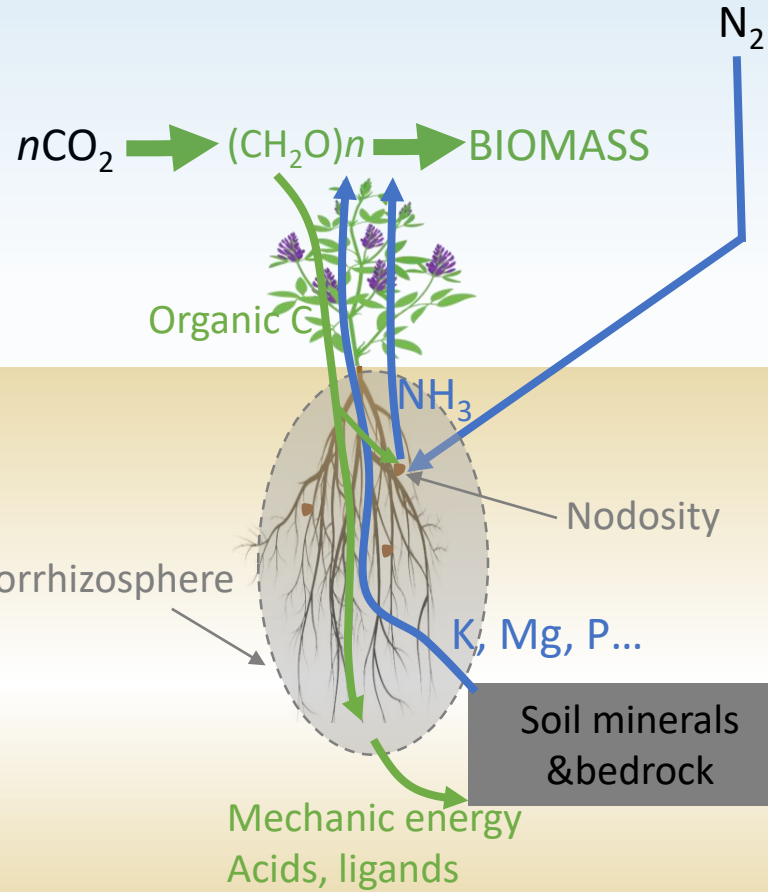
LOW PLANT DEMAND



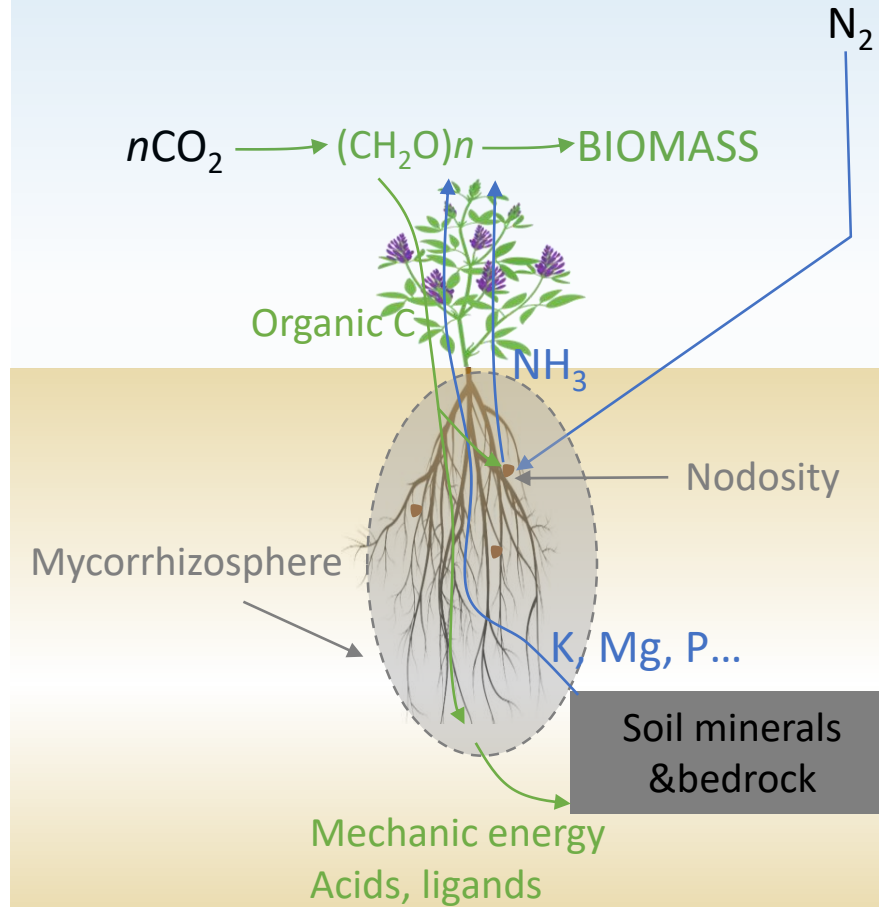
Synchrony based on nutrient
retrieved from atmosphere and
soil minerals

(Sync-Inorganic)

HIGH PLANT DEMAND

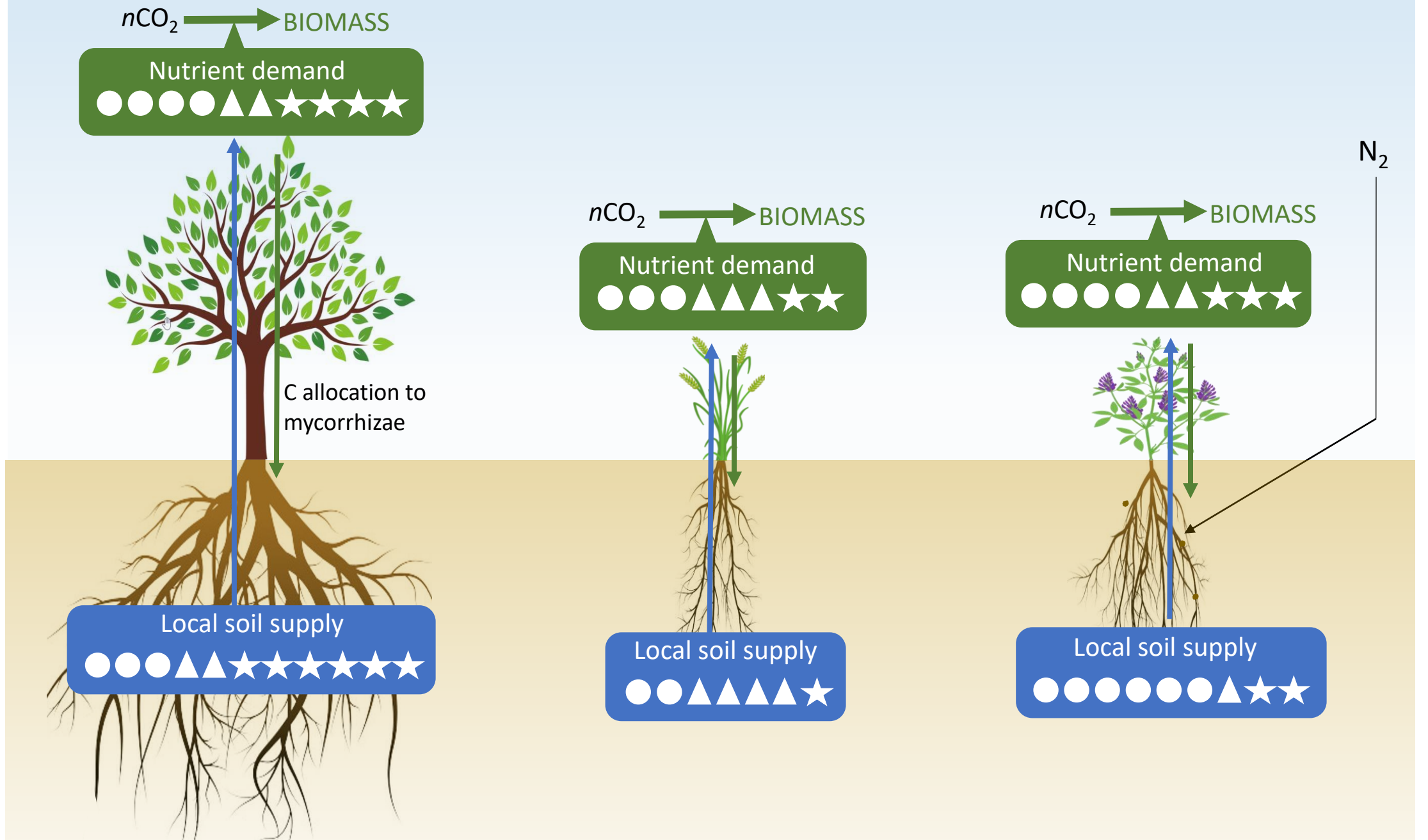


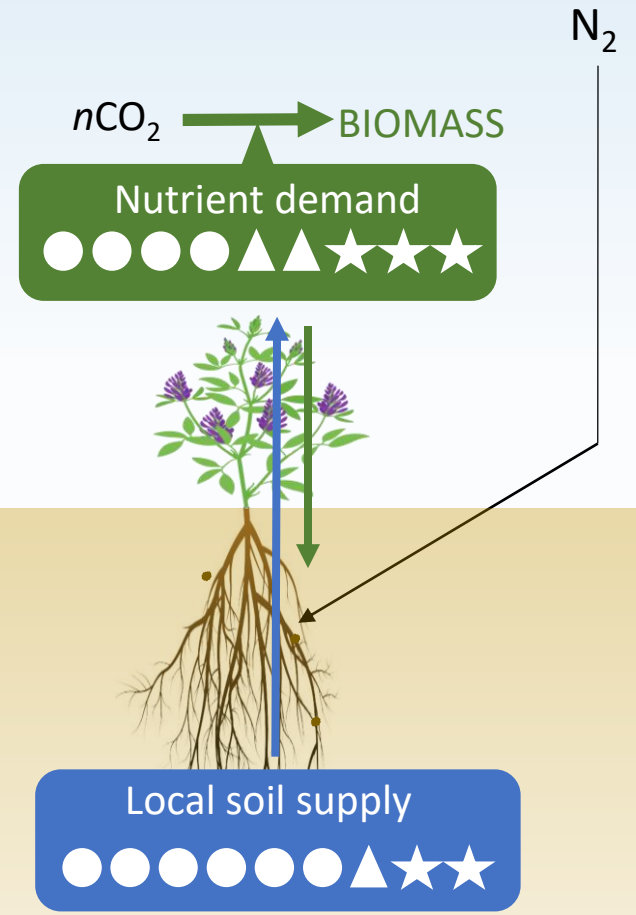
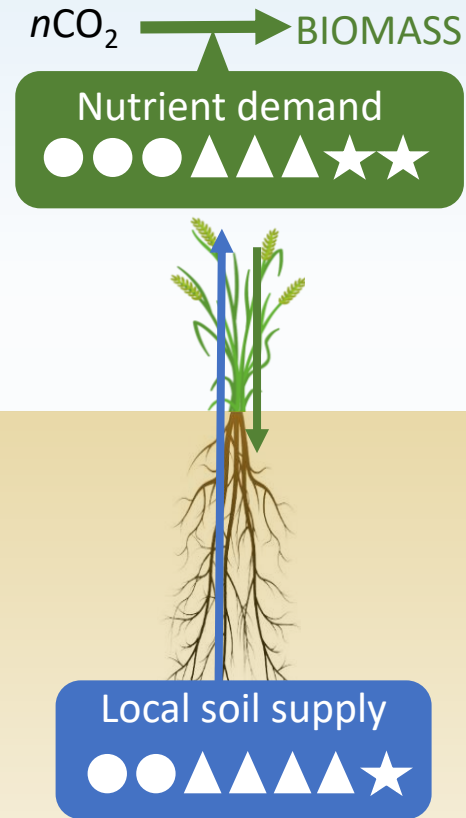
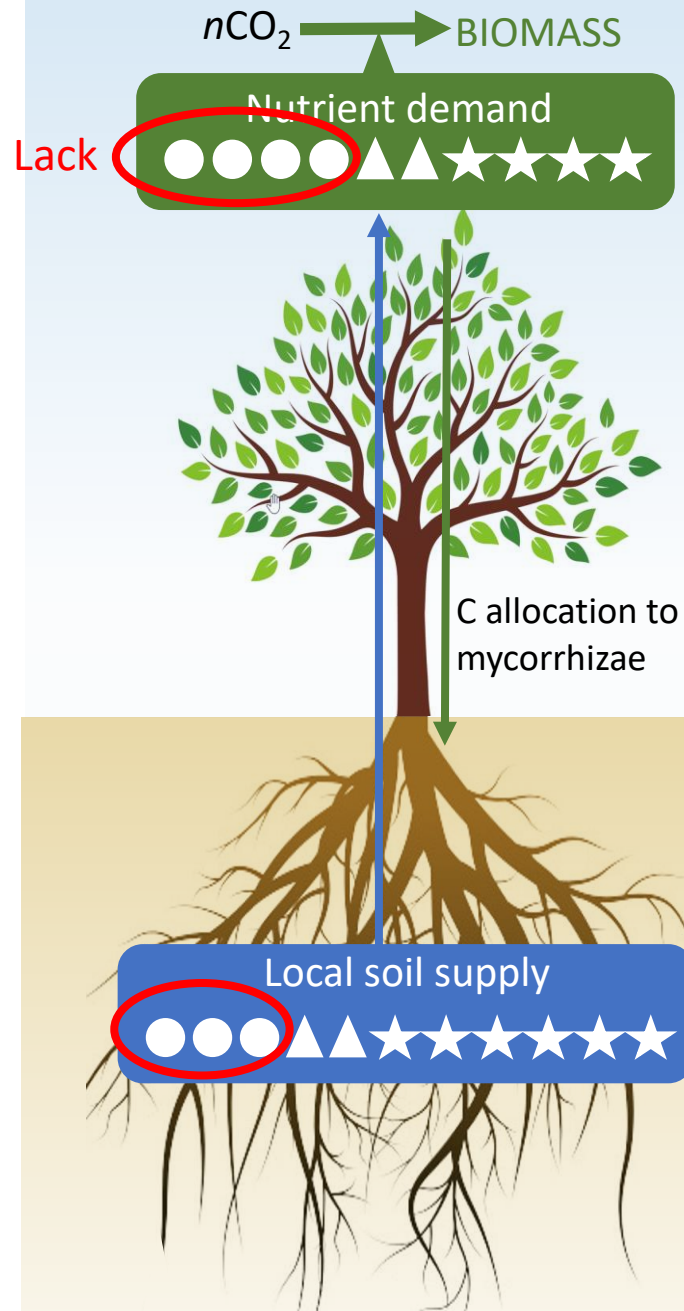
LOW PLANT DEMAND

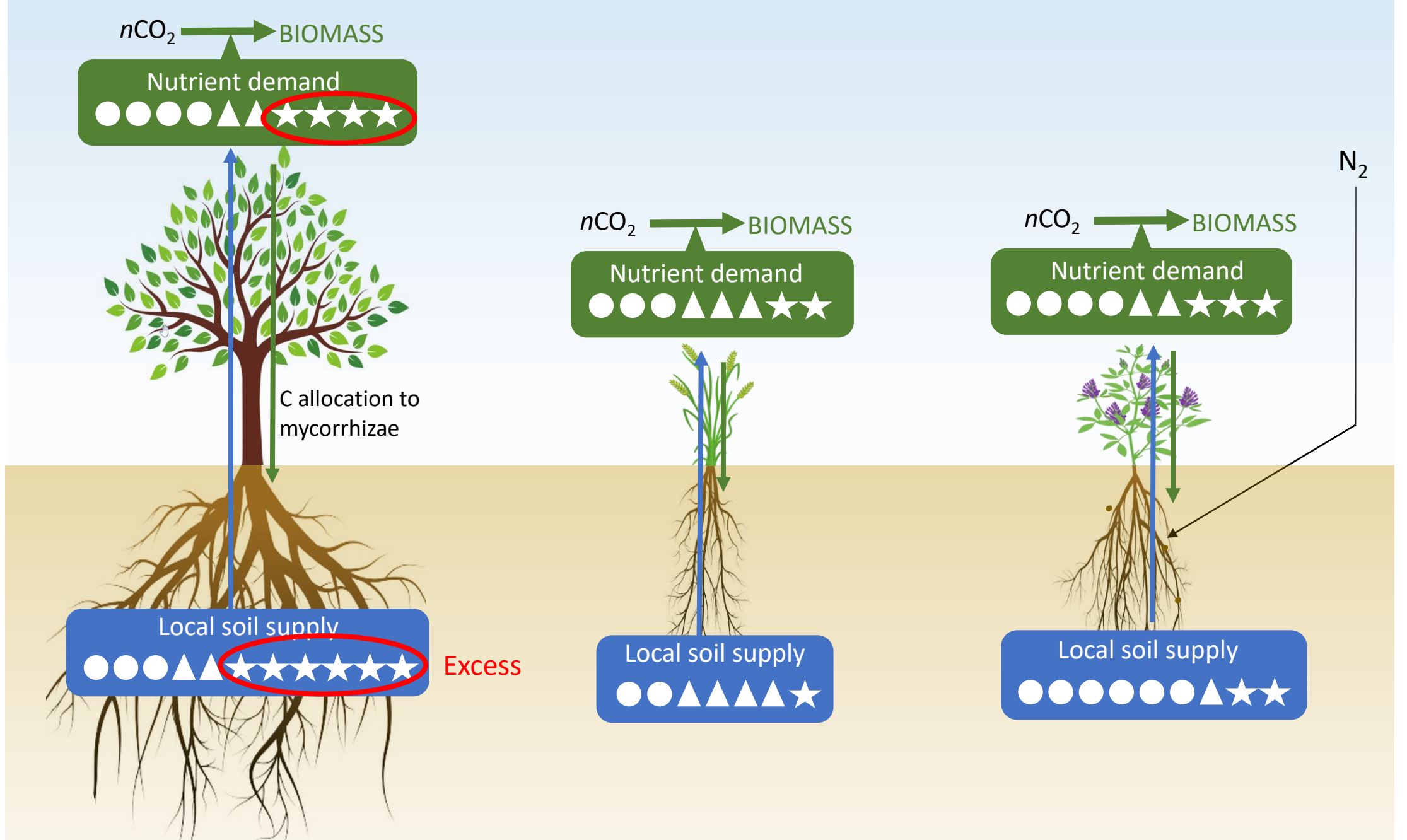


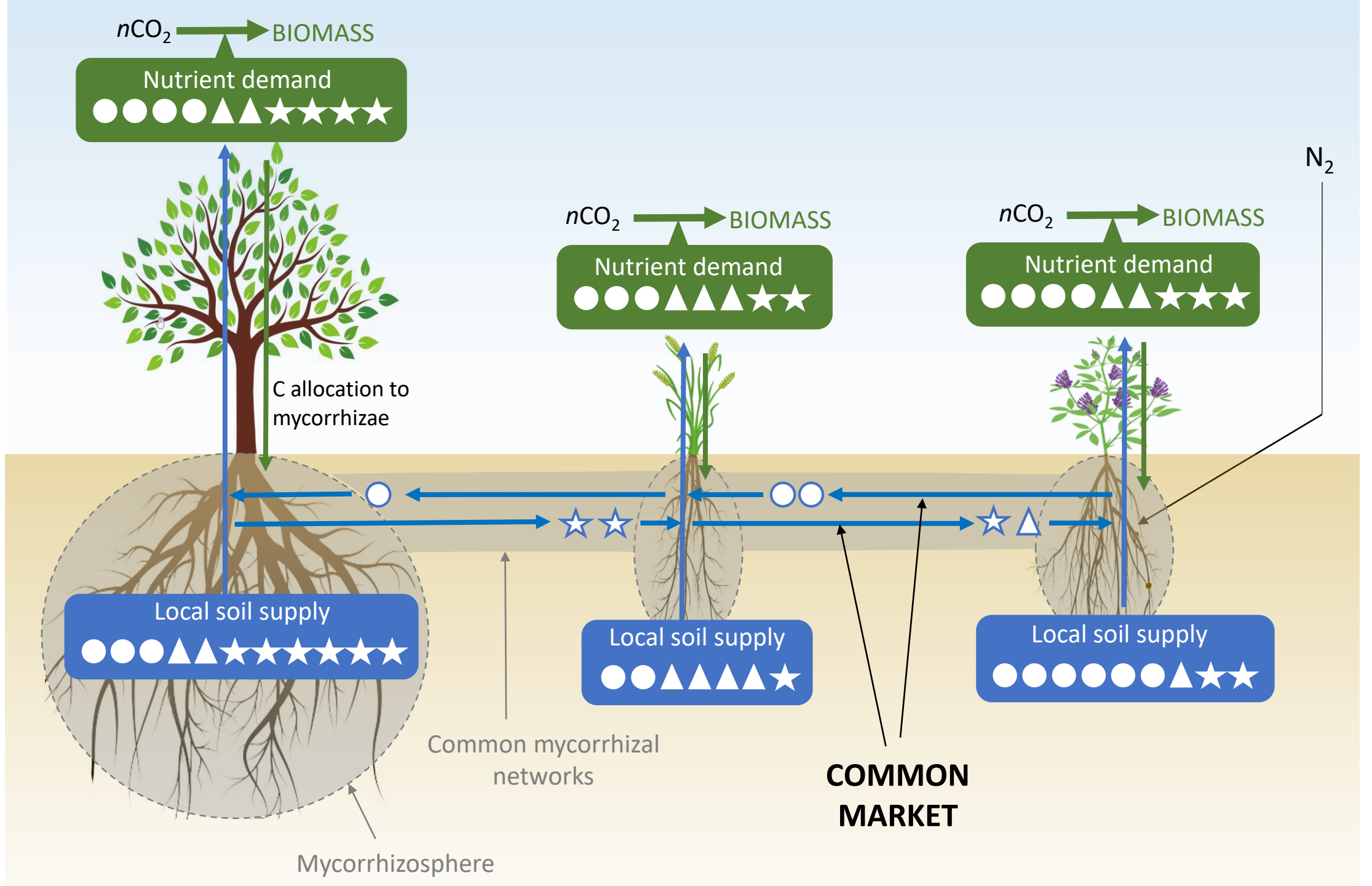
Multi-element synchrony based
on a common nutrient market

(Sync-Market)









Implications for agrosystems

1. Redefining « Soil fertility »

Redefining “Soil fertility”

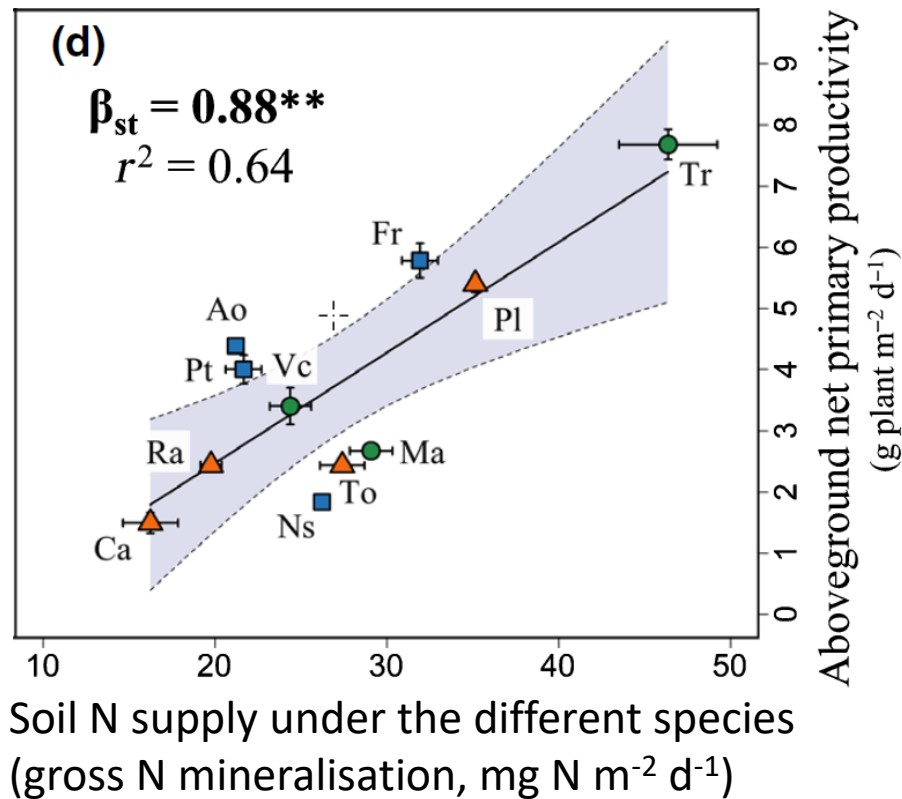


- Fertility is currently defined as an inherent capacity of a soil to sustain plant growth-production by providing nutrients in adequate amounts and in suitable proportion
 - Last advances on synchrony show:
 - Plants control the amount and proportion of nutrients supplied by the soil
 - The soil supply of nutrient must be considered in relation to the fluctuating plant demand.
- Fertility is not an inherent property of soil but is an emerging property of plant-soil interactions

Redefining “Soil fertility”

- Practical consequence : the same soil can support different levels of nutrient supply and biomass production

12 species cultivated on the same soil:



Implications for agrosystems

2. Managing synchrony to ensure both productivity and sustainability

HIGH SYNCHRONY



1. Adapting synchrony systems to local pedoclimatic contexts
2. Coupling synchrony systems with complementary roles
3. Inclusion of plants with high organ reserve and/or plasticity

HIGH SYNCHRONY

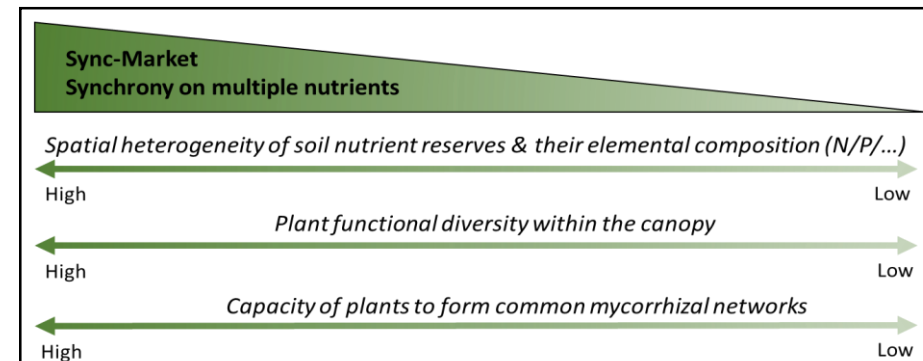
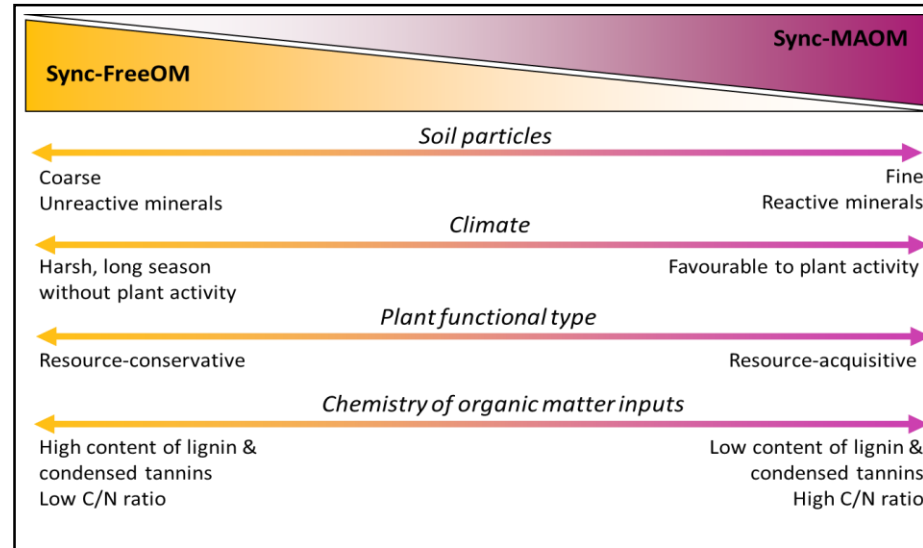
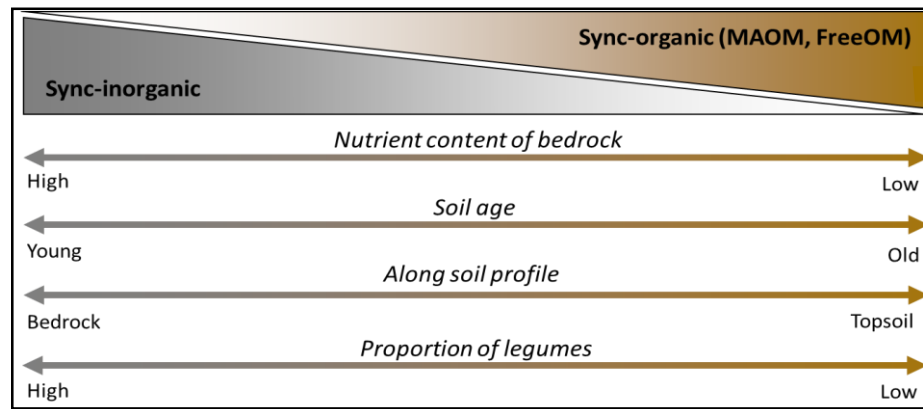


1. Adapting synchrony systems to local pedoclimatic contexts

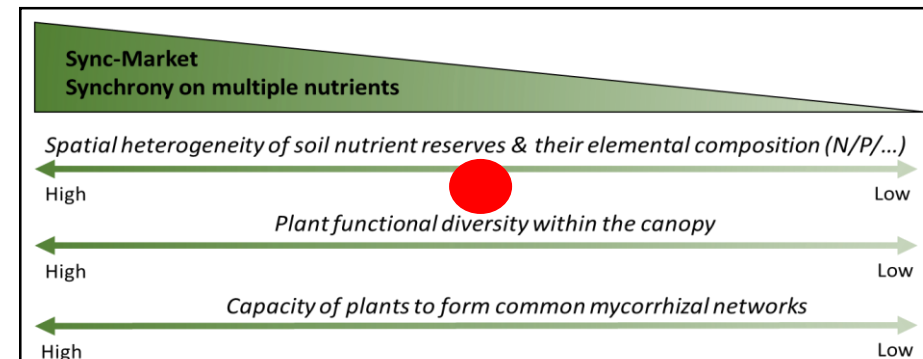
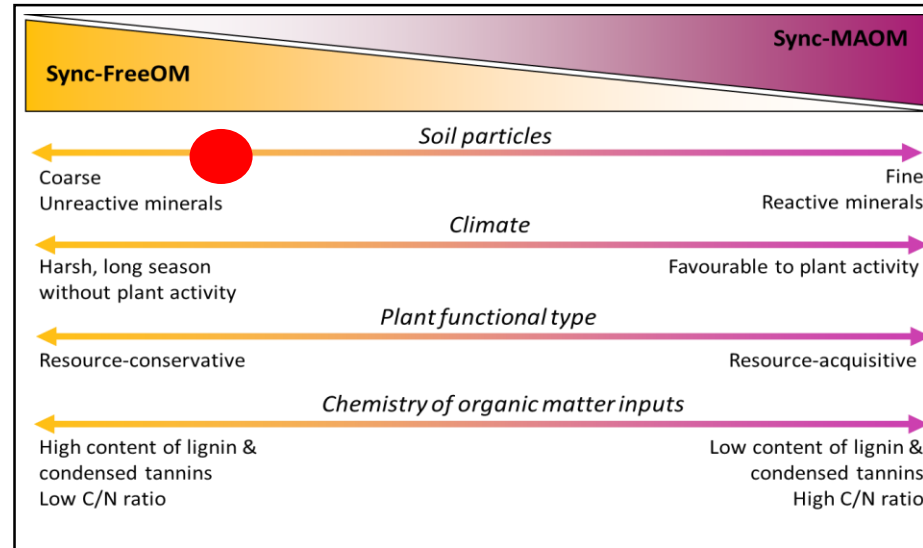
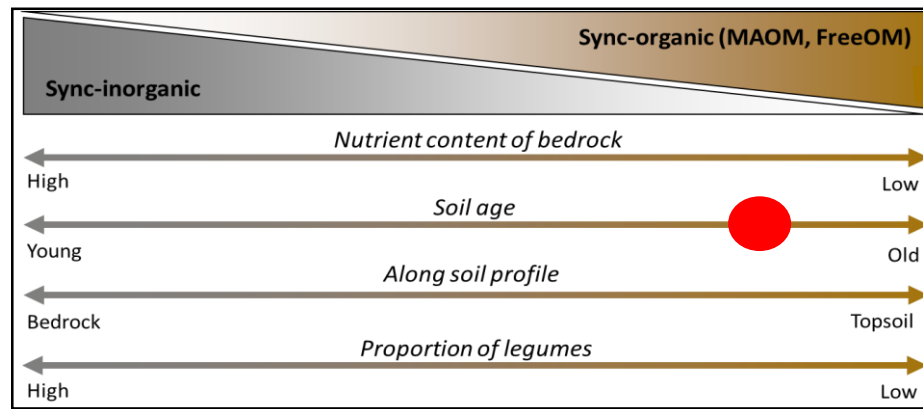
2. Coupling synchrony systems with complementary roles

3. Inclusion of plants with high organ reserve and/or plasticity

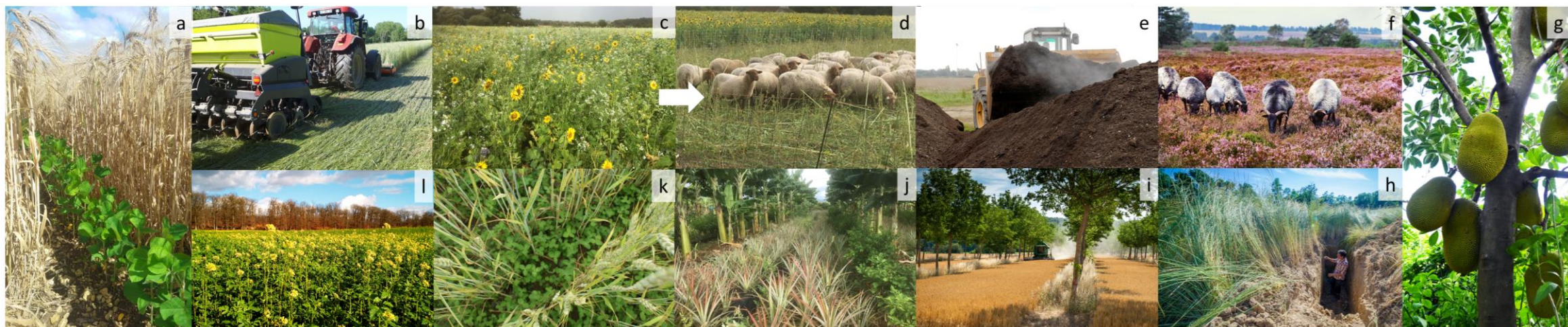
1. Adapting synchrony systems to local pedoclimatic contexts



Let's take an example



| Synchrony | Conditions of synchrony | Combination of practices to set up for promoting the targeted synchrony |
|------------------------------|--|--|
| Sync-MAOM | <ul style="list-style-type: none"> -Acquisitive plant species -Continuous activity of microbes M & I -Reserve of MAOM in soil | <ul style="list-style-type: none"> - Insertion/breeding of acquisitive species with strong capacity of stimulating nutrient mineralization/immobilization (e.g., high C rhizodeposition) - The carbon:nutrient ratio of plant species or organic residues must be high enough to induce nutrient immobilization by I-Microbes. Ideally, the different plant species have contrasting carbon:nutrient ratios (a, c, l, j, k) - Maintaining a continuous cover of active plants fueling microbes in energy-rich C (all pictures but e) - Recycling organic nutrients at local scale (farm-watershed) to preserve soil organic reserve on the long-term (d, e, f) |
| Sync-FreeOM | <ul style="list-style-type: none"> -Conservative plant species -Mycorrhizal fungi -Reserve of FreeOM in soil | <ul style="list-style-type: none"> - Insertion/breeding of conservative species producing recalcitrant litter with reactive compounds fixing organic nutrients (e, f)* - Or/and amendment of recalcitrant organic residues harboring reactive compounds more or less charged in organic nutrients (e) - Recycling organic nutrients at local scale (farm-watershed) to preserve soil organic reserve on the long-term (d, e, f) |
| Sync-Inorganic | <ul style="list-style-type: none"> -Plant symbiosis with mycorrhizal fungi & N₂ fixing bacteria -Nutrients stored in bedrock, soil minerals and/or precipitates | <ul style="list-style-type: none"> - Insertion/breeding of species with strong capacity of mobilizing nutrients from rock and soil minerals (e.g., mycorrhized roots exerting strong mechanic pressure on minerals, secreting high amount of organic acids & ligands) - Insertion of plant with deep roots colonizing bedrock (g, h, i) - Insertion of legumes (a, c, k) - Inoculation with mixed mycorrhizal fungi & N₂ fixing bacteria in highly degraded soils |
| Sync-Market | <ul style="list-style-type: none"> -Plant species with complementary nutritional needs -Common mycorrhizal networks | <ul style="list-style-type: none"> - Mixing plant species with different nutrient acquisition strategies and carbon:nutrient ratios (a, c, l, j, k) - Promoting perennial plants (f, g, h, l, k) and/or permanent plant cover (all pictures but e) to fuel mycorrhizae in energy-rich carbon - No or limited use of soil tillage (b) and pesticides to preserve mycorrhizae networks - Inoculation with mixed mycorrhizal fungi in highly degraded soils |
| Increasing overall synchrony | <ul style="list-style-type: none"> -Synchrony systems adapted to pedoclimatic context -Complementary synchrony systems -Plant plasticity & reserve | <ul style="list-style-type: none"> - Analyzing the soil profile and climate, defining the most adapted synchrony systems - Mixing plant species with different nutrient acquisition strategies (a, c, l, j, k) - Breeding crops species on their suitability to association - Promoting perennial plants with high reserve and organ plasticity (f, g, h, l, j, k) |



Thank you for your attention



Let's continue to play the synchrony's doctor