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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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Agronomy Webinar 25th January

"The Resilience of Grasslands in a Changing World and Their Role in Supporting the Agro-Ecological Transition"

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 CO_2/kg NH_3
- 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

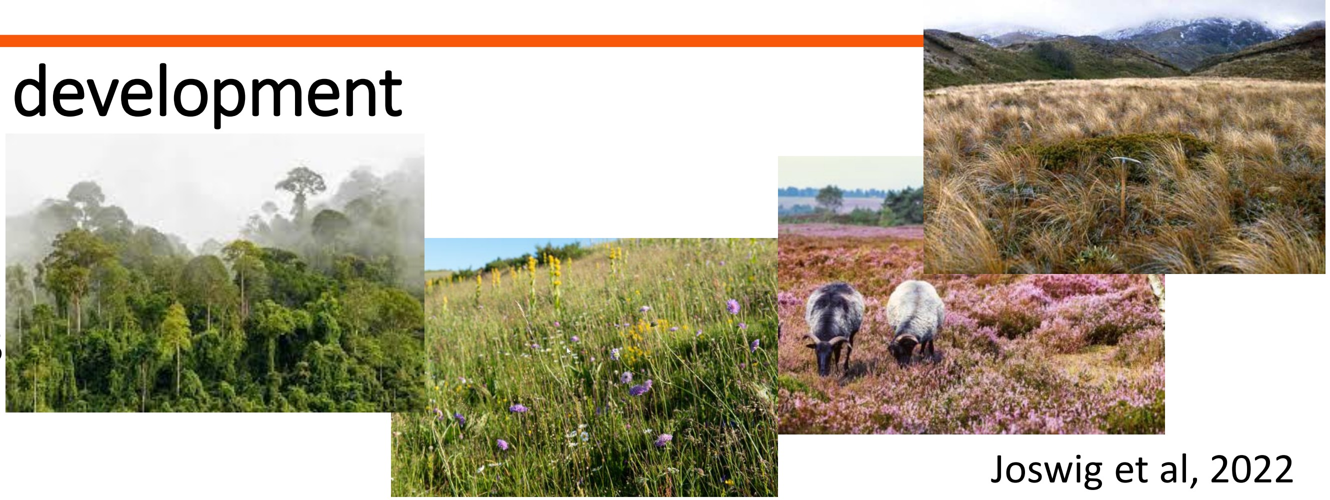
How to develop efficient agroecological strategies ?

- 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 N_2 fixation, C input to soil.

Current difficulties/limits for agroecology development

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

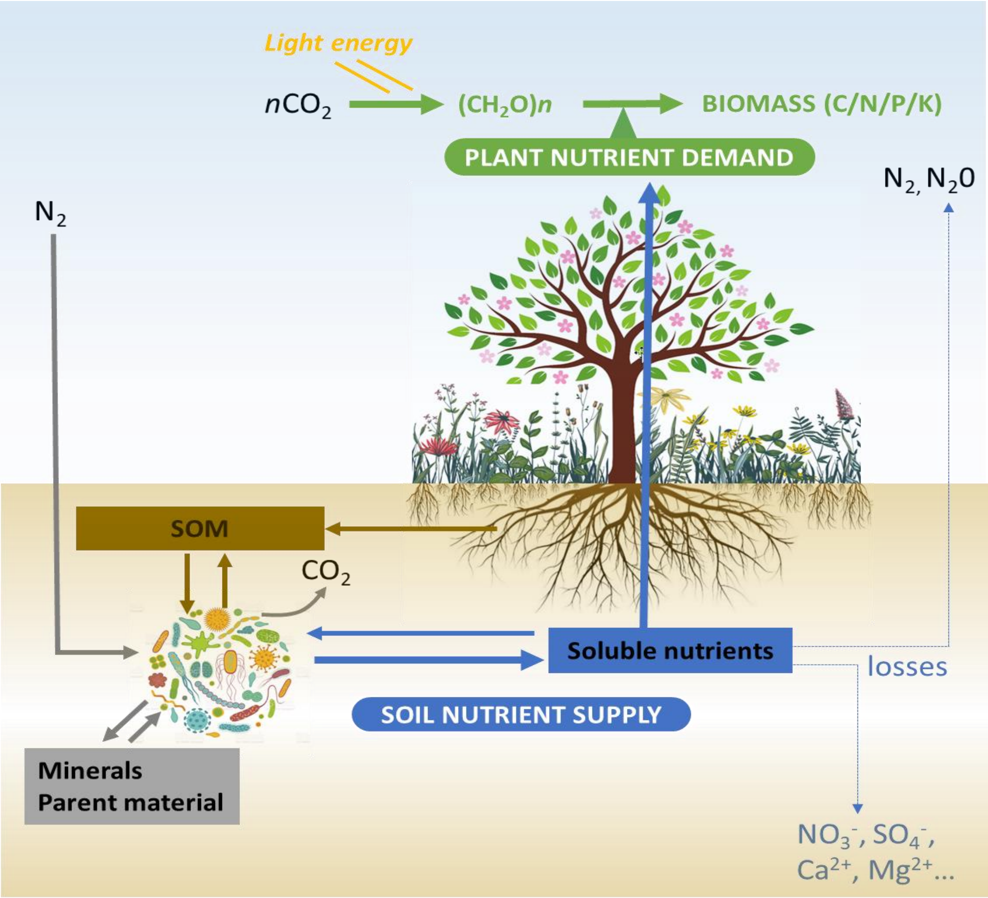


Joswig et al, 2022

- 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)

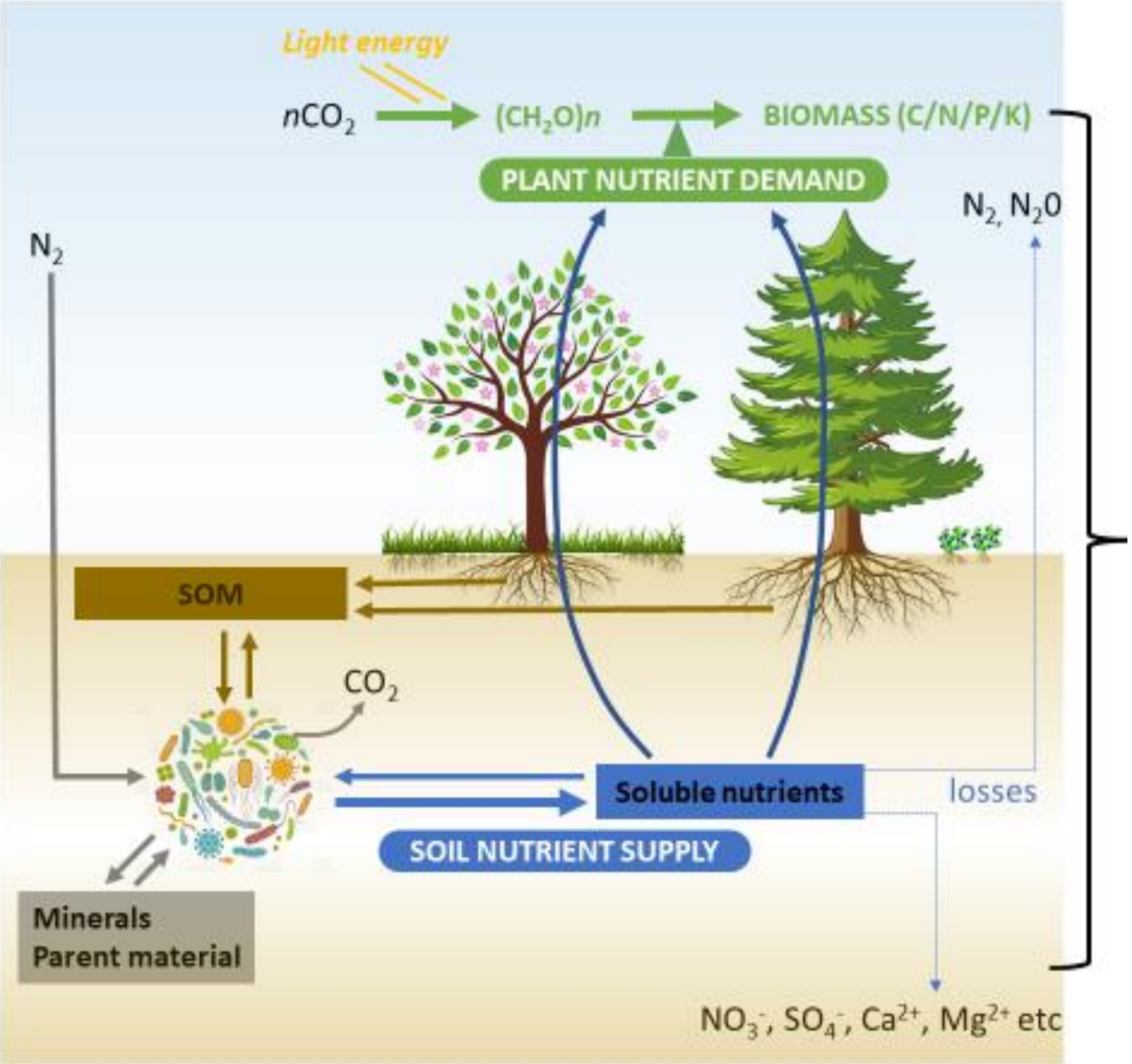
Need of a more systemic approach considering:

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



Introduction of the plant-soil synchrony concept

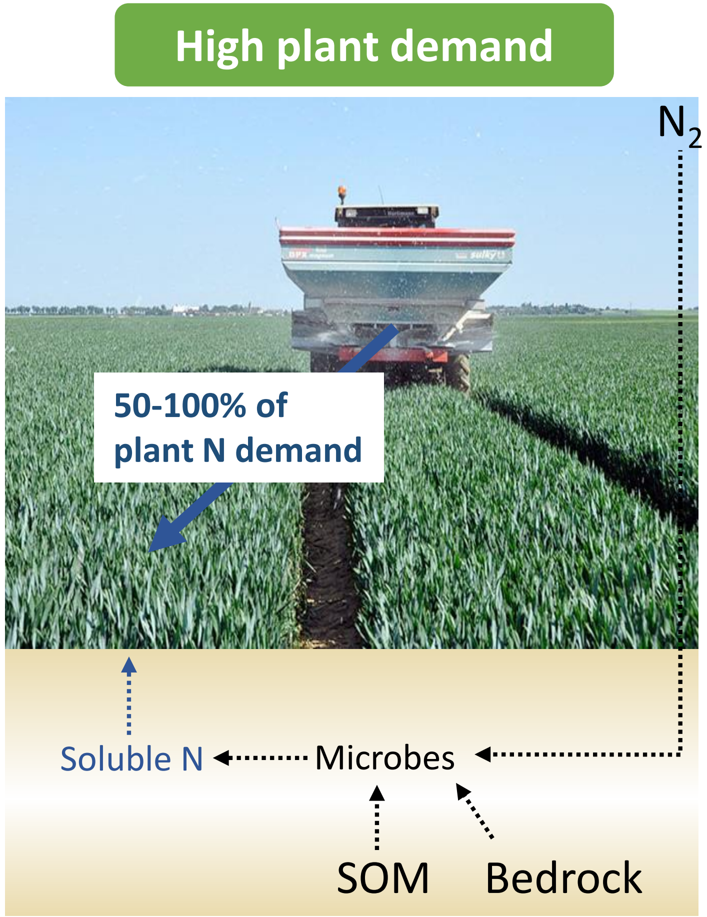
Ecosystem productivity & sustainability linked to the level of synchrony between plant N demand and soil supply



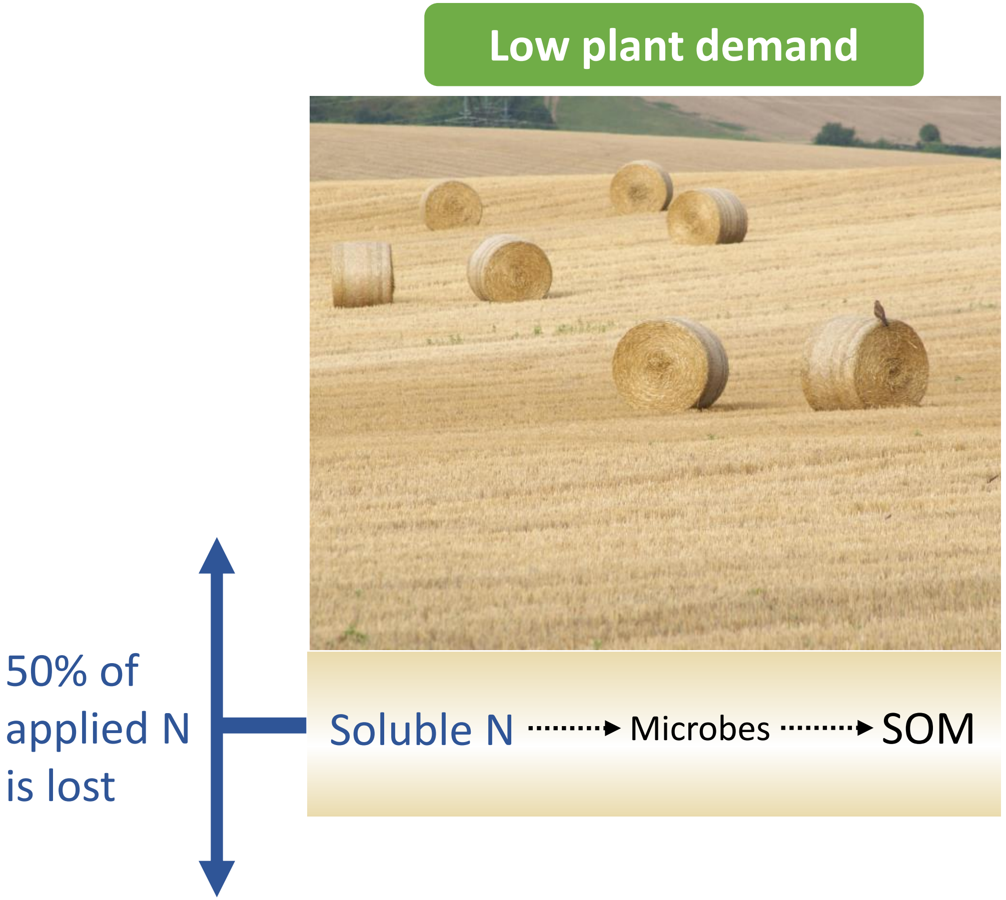
High level of synchrony promotes

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

Intensive agrosystems characterized by a low demand/supply synchrony



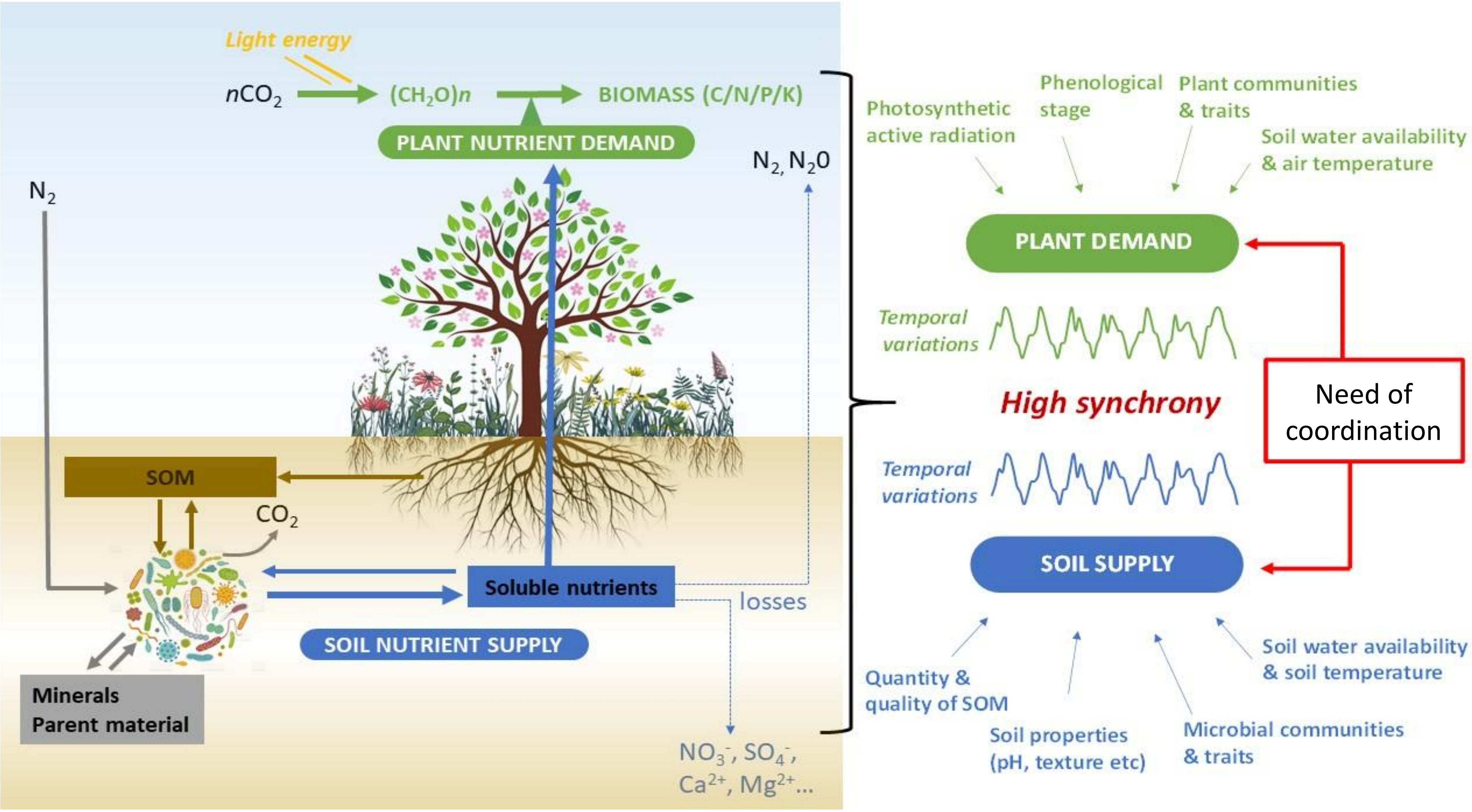
- ➢ Dependence to fertilizers



- ➢ High loss of nutrient and SOM

Robertson et al., 2012; Fowler et al., 2017; Zhang et al., 2021

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

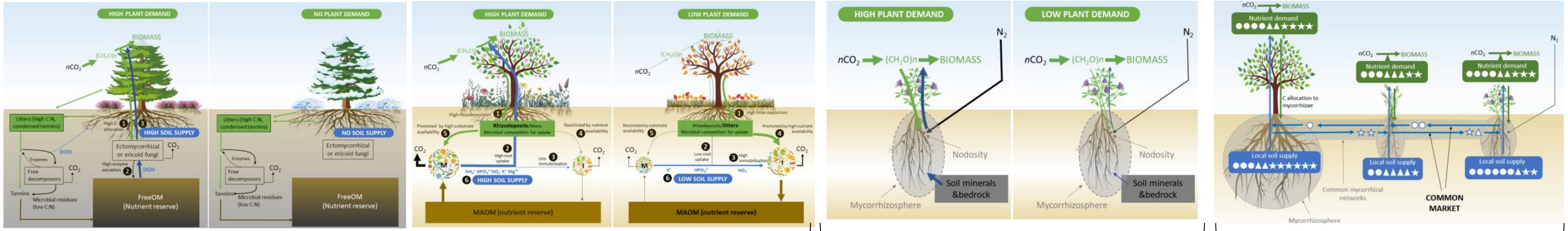


➢ **Synchrony requires the coordination of many plant-soil processes**

Review of latest advances in ecology, biogeochemistry & agronomy

Identification of 4 systems of synchrony (coordination of processes)

1 2 3 4



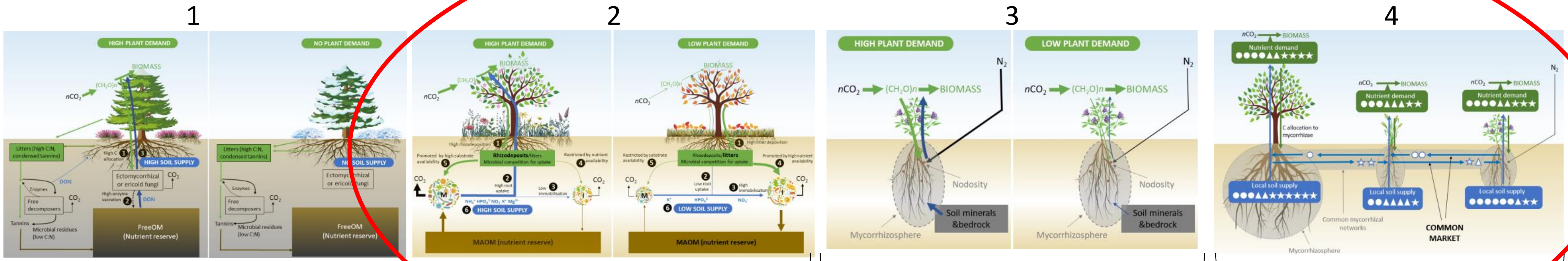
Soil organic nutrient reserves

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)



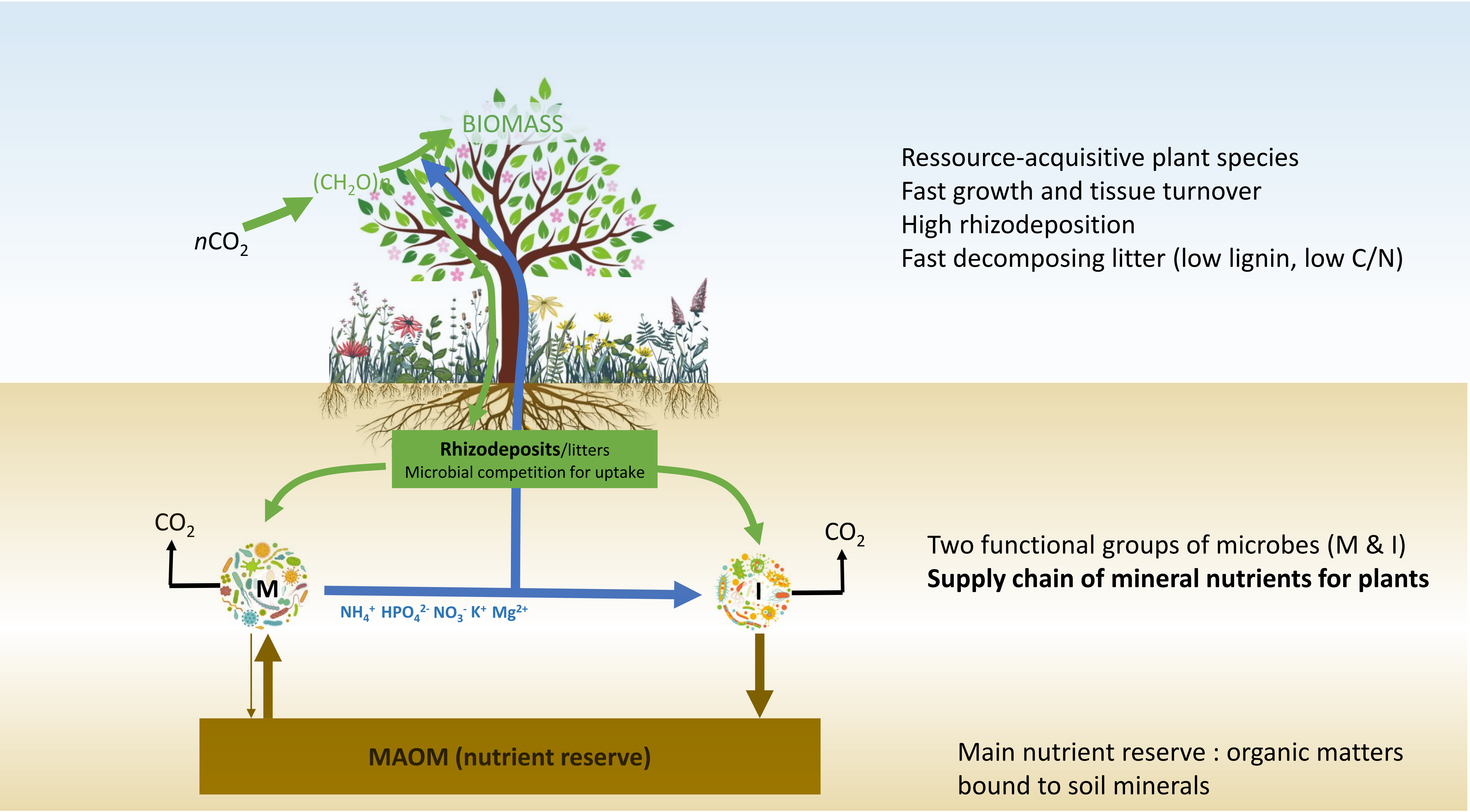
Soil organic nutrient reserves

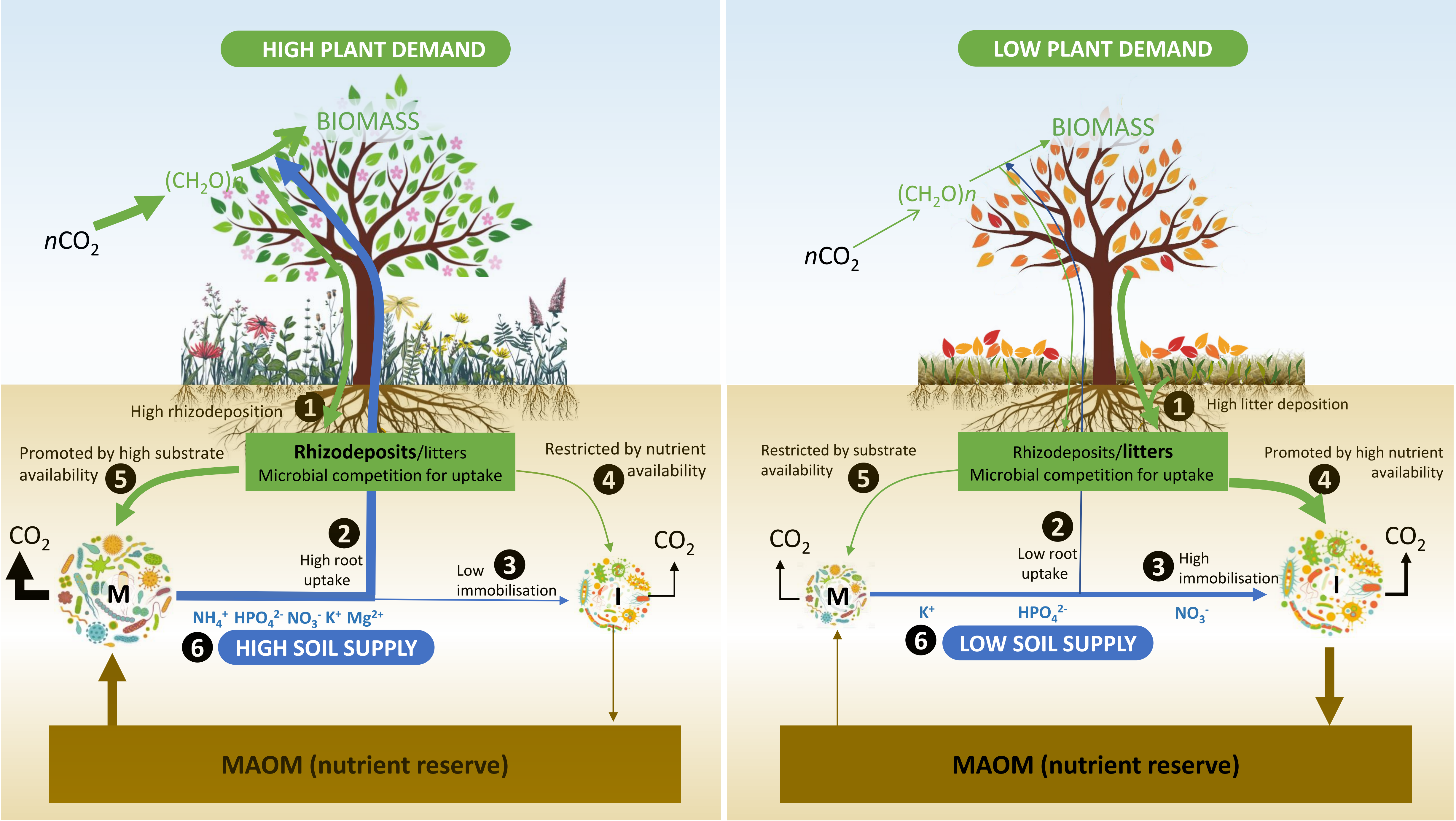
Nutrient retrieved from Atmosphere and soil minerals

Common nutrient market

Synchrony based on organic nutrient reserve

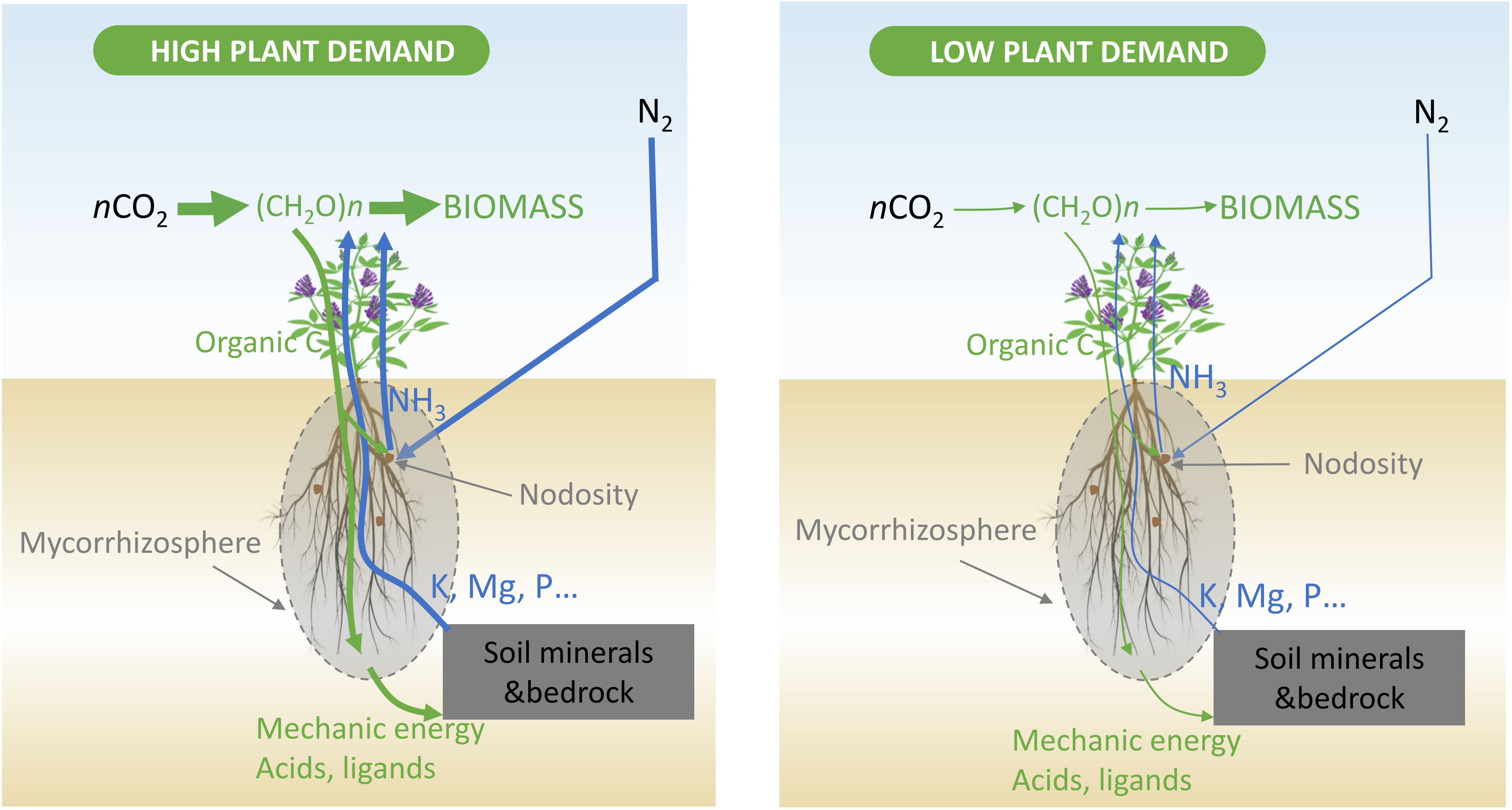
1. MAOM-based synchrony (Sync-MAOM)


BIOMASS
(CH2O)n
nCO2
Ressource-acquisitive plant species
Fast growth and tissue turnover
High rhizodeposition
Fast decomposing litter (low lignin, low C/N)
Rhizodeposits/litters
Microbial competition for uptake
CO2
M
I
CO2
NH4+ HPO42- NO3- K+ Mg2+
Two functional groups of microbes (M & I)
Supply chain of mineral nutrients for plants
MAOM (nutrient reserve)
Main nutrient reserve : organic matters
bound to soil minerals


HIGH PLANT DEMAND
BIOMASS
$(CH_2O)n$
nCO_2
High rhizodeposition
1
Rhizodeposits/litters
Microbial competition for uptake
Promoted by high substrate availability
5
Restricted by nutrient availability
4
CO_2
M
2
High root uptake
Low immobilisation
3
CO_2
I
NH_4^+ HPO_4^{2-} NO_3^- K^+ Mg^{2+}
6
HIGH SOIL SUPPLY
MAOM (nutrient reserve)
LOW PLANT DEMAND
BIOMASS
$(CH_2O)n$
nCO_2
1
High litter deposition
Restricted by substrate availability
5
Rhizodeposits/litters
Microbial competition for uptake
Promoted by high nutrient availability
4
CO_2
M
2
Low root uptake
3
High immobilisation
CO_2
I
K^+
HPO_4^{2-}
NO_3^-
6
LOW SOIL SUPPLY
MAOM (nutrient reserve)

Synchrony based on nutrient retrieved from atmosphere and soil minerals

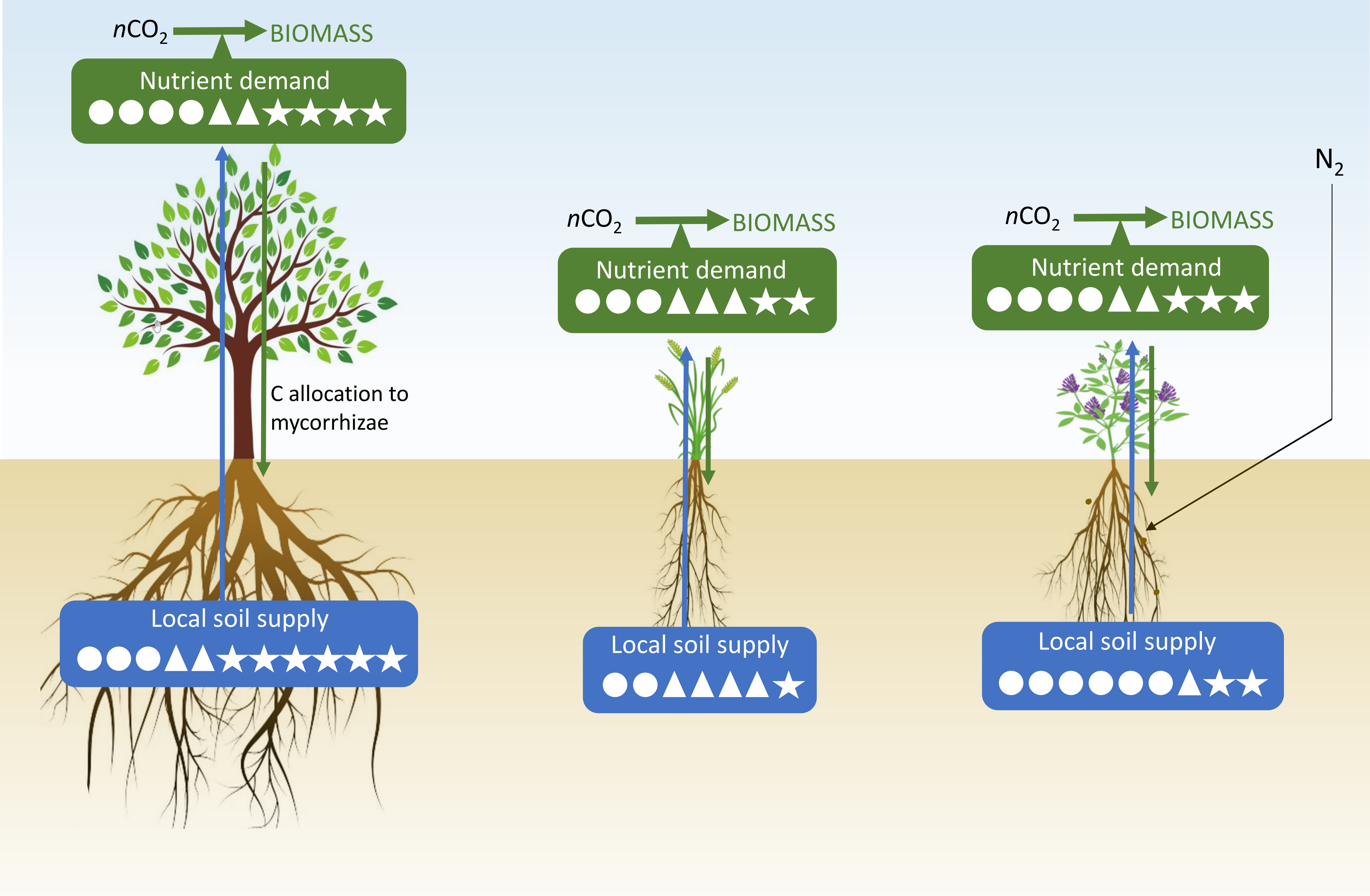
(Sync-Inorganic)



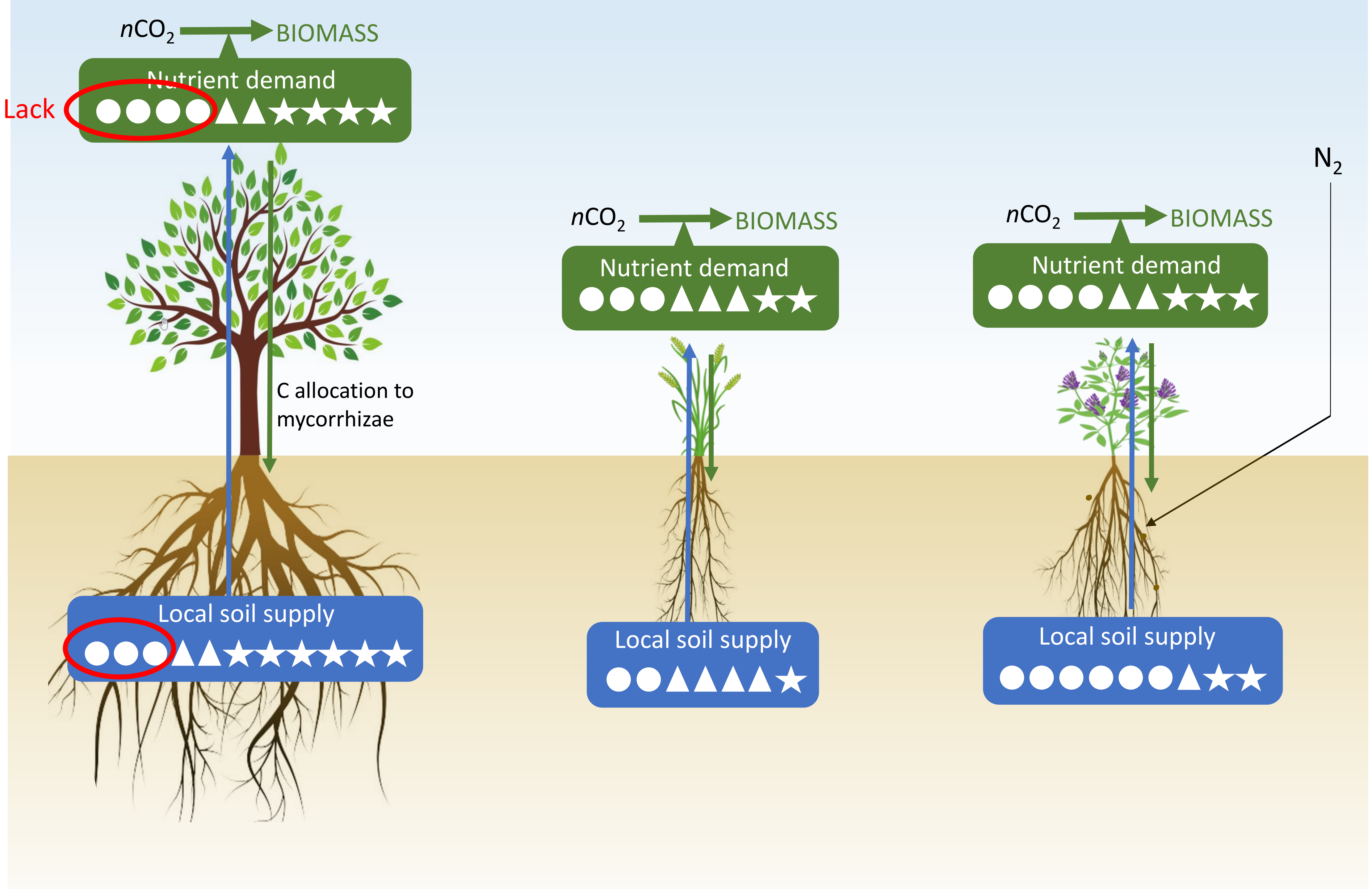
HIGH PLANT DEMAND
N2
nCO2
(CH2O)n
BIOMASS
Organic C
NH3
Nodosity
Mycorrhizosphere
K, Mg, P…
Soil minerals &bedrock
Mechanic energy
Acids, ligands
LOW PLANT DEMAND
N2
nCO2
(CH2O)n
BIOMASS
Organic C
NH3
Nodosity
Mycorrhizosphere
K, Mg, P…
Soil minerals &bedrock
Mechanic energy
Acids, ligands

Multi-element synchrony based on a common nutrient market

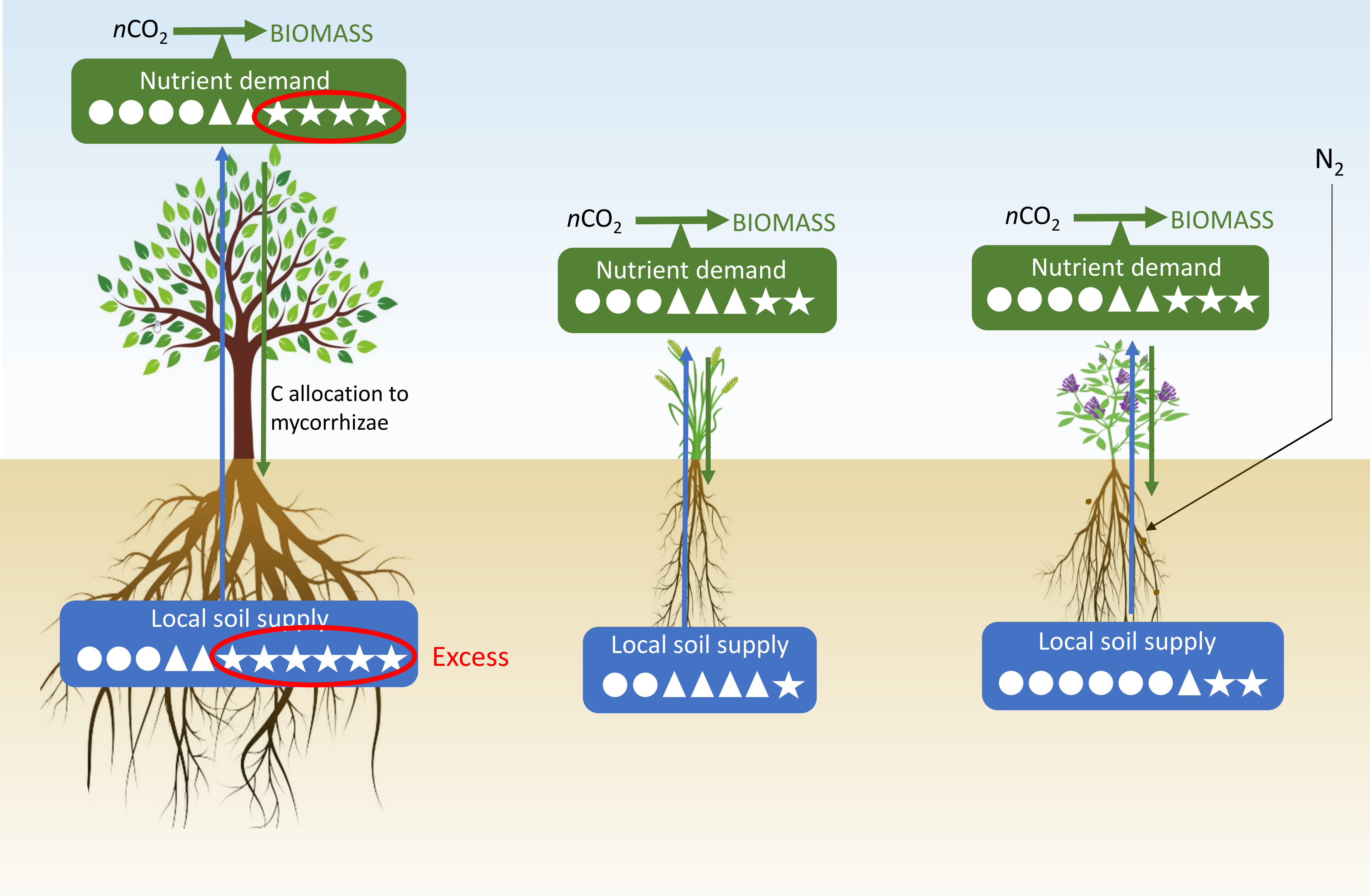
(Sync-Market)



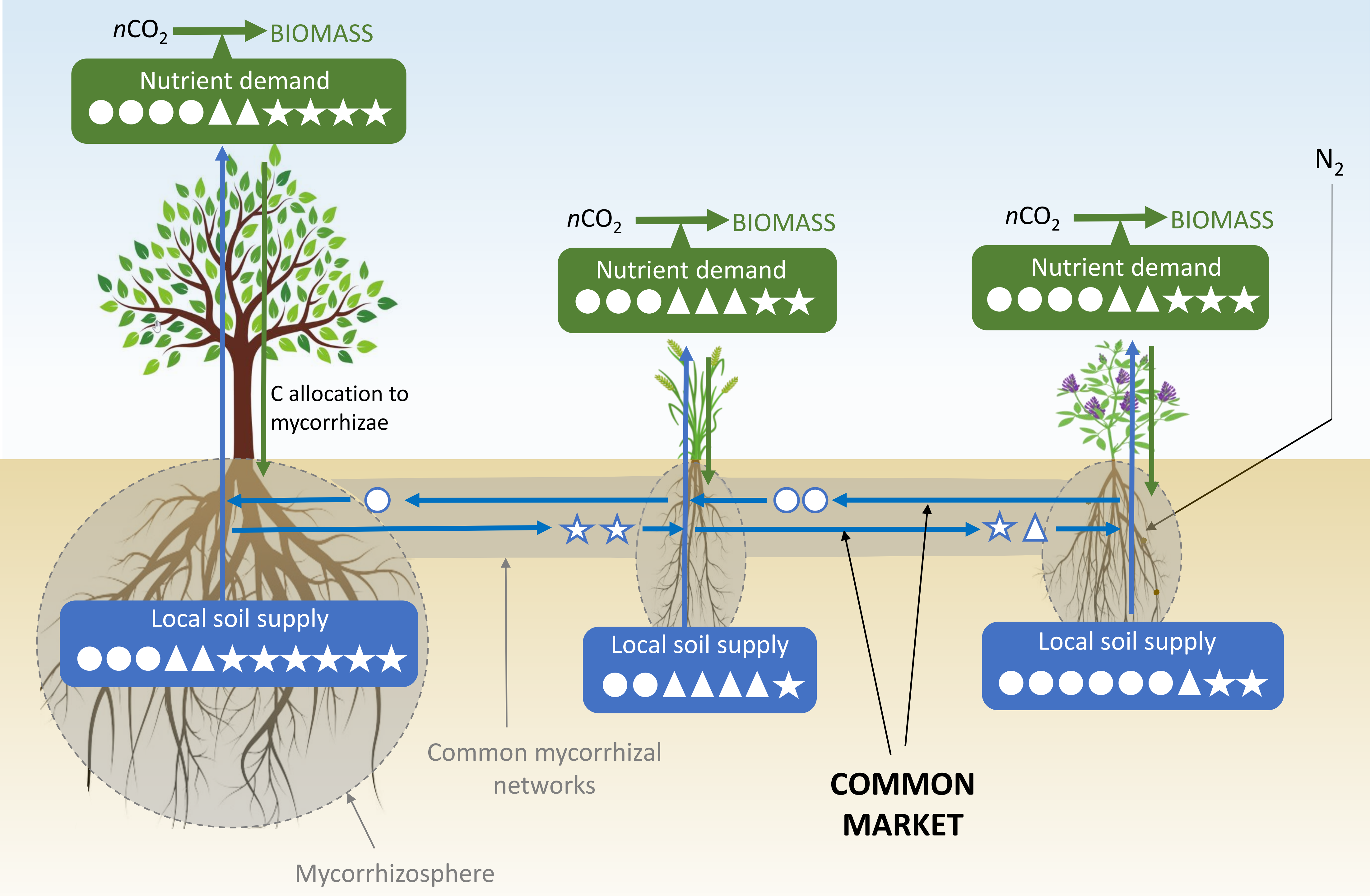
nCO2
BIOMASS
Nutrient demand
Local soil supply
C allocation to mycorrhizae
nCO2
BIOMASS
Nutrient demand
Local soil supply
N2
nCO2
BIOMASS
Nutrient demand
Local soil supply



nCO_2
BIOMASS
Nutrient demand
Lack
C allocation to
mycorrhizae
Local soil supply
nCO_2
BIOMASS
Nutrient demand
Local soil supply
N_2
nCO_2
BIOMASS
Nutrient demand
Local soil supply



nCO2
BIOMASS
Nutrient demand
C allocation to mycorrhizae
Local soil supply
Excess
nCO2
BIOMASS
Nutrient demand
Local soil supply
N2
nCO2
BIOMASS
Nutrient demand
Local soil supply



nCO2
BIOMASS
Nutrient demand
nCO2
BIOMASS
Nutrient demand
nCO2
BIOMASS
Nutrient demand
N2
C allocation to mycorrhizae
Local soil supply
Local soil supply
Local soil supply
Common mycorrhizal networks
COMMON MARKET
Mycorrhizosphere

Implications for agrosystems

1. Redefinying « Soil fertility »

Redefinying “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

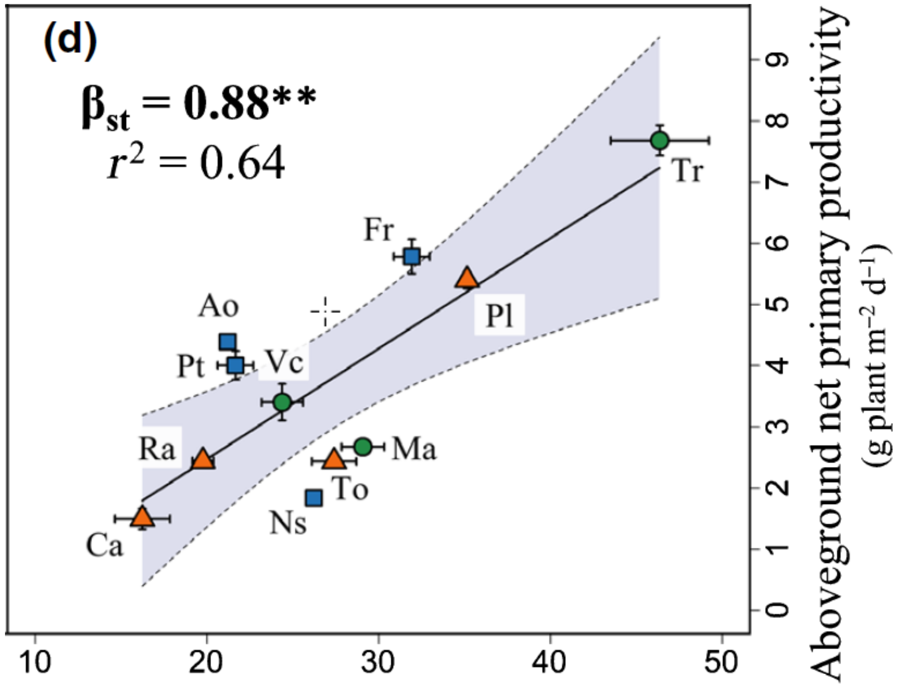
  - The soil supply of nutrient must be considered in relation to the fluctuating plant demand.

➢ Fertility is not an inherent property of soil but is an emerging property of plant-soil interactions

Redefinying “Soil fertility”

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

<u>12 species cultivated on the same soil:</u>



Soil N supply under the different species
(gross N mineralisation, mg N m^{-2} d^{-1})

Henneron et al 2020

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. Inlusion of plants with high organ reserve and/or plasticity

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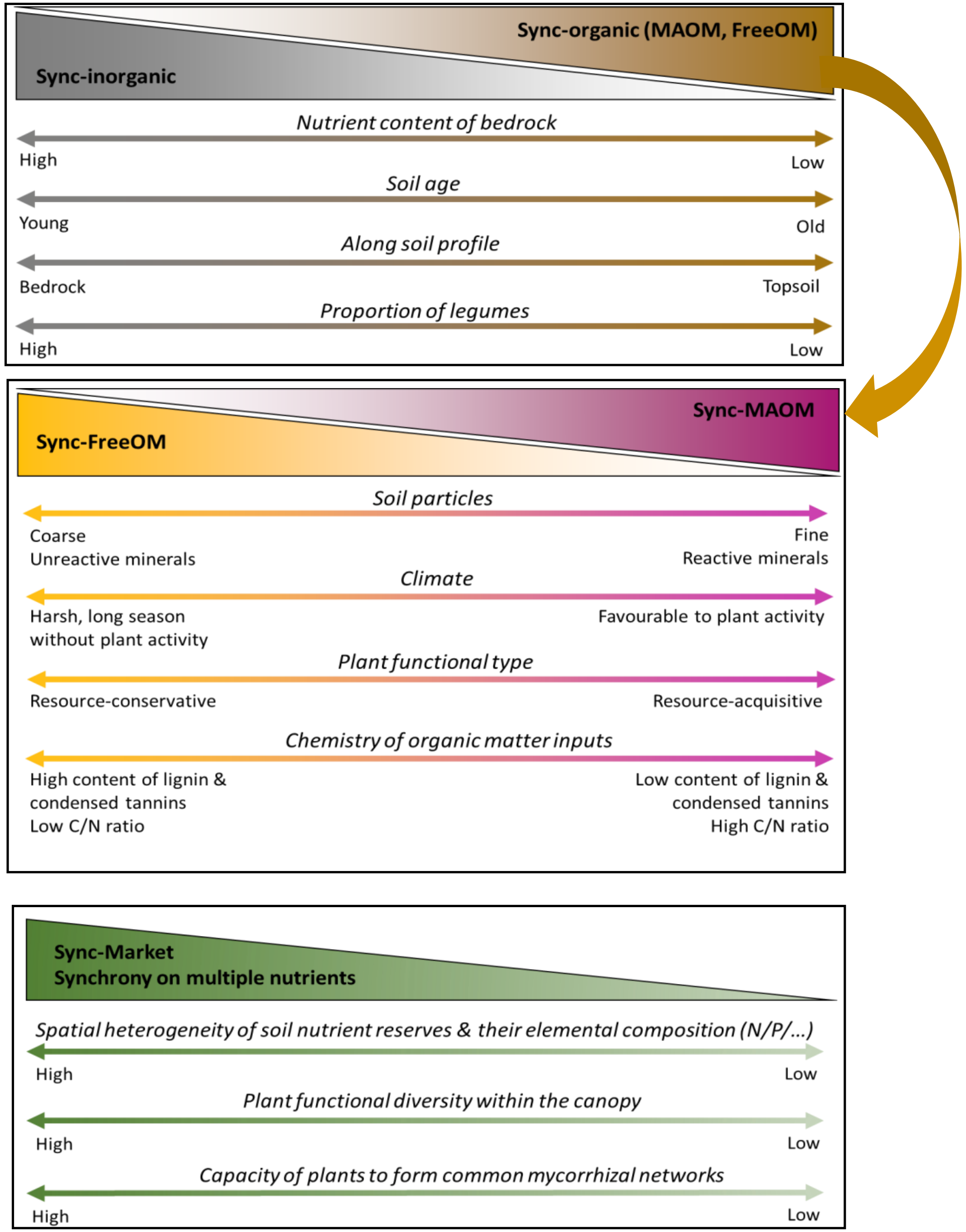
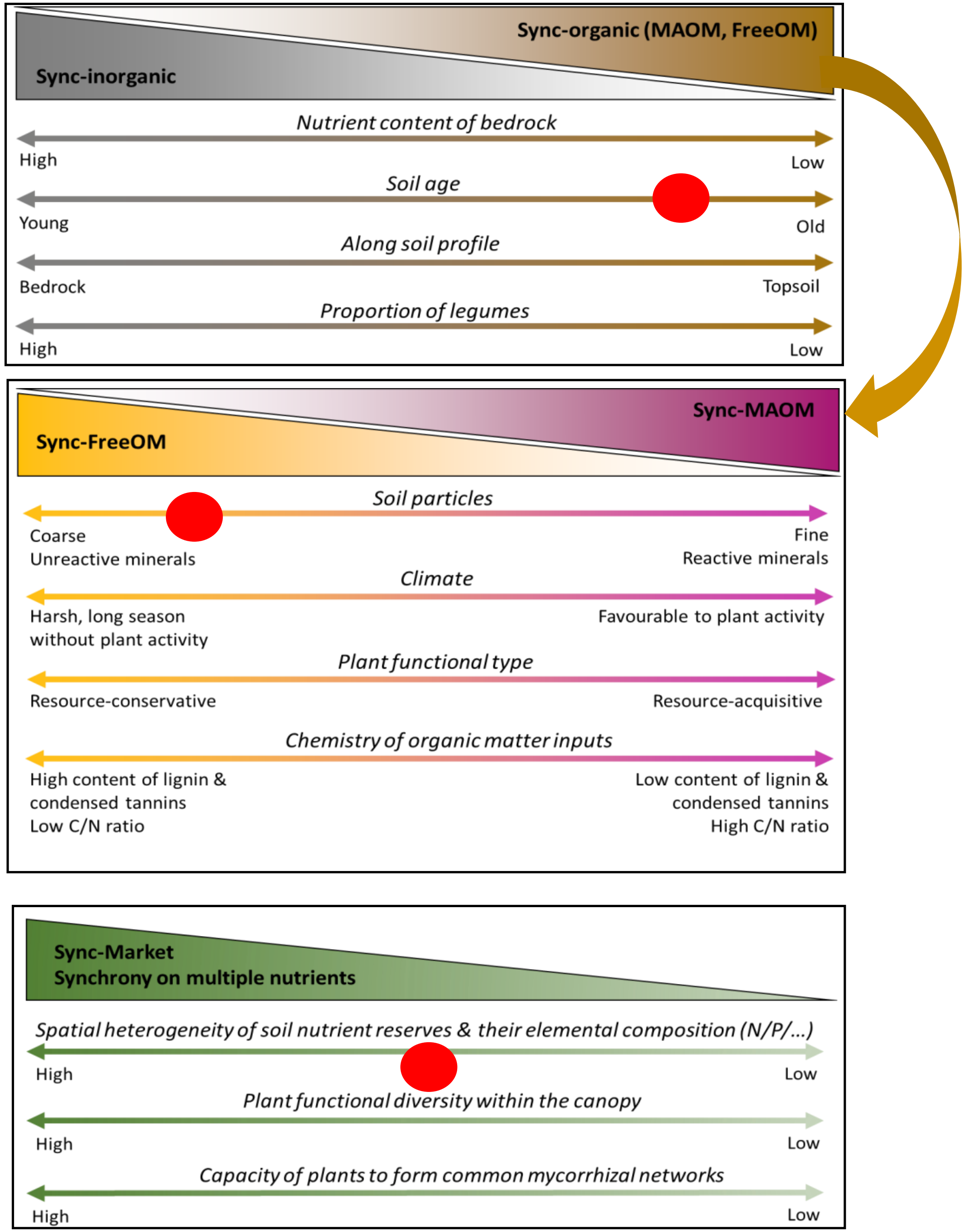
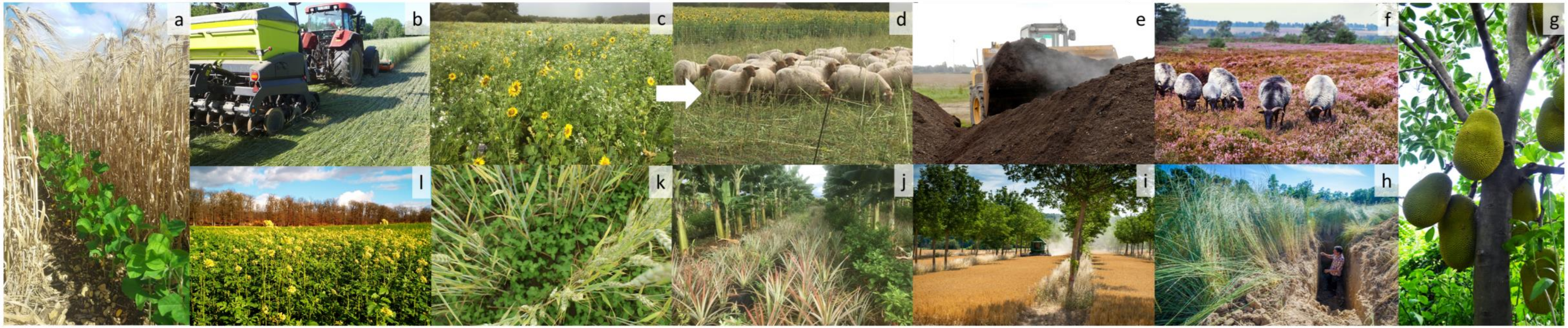


Let’s take an example



Synchrony	Conditions of synchrony	Combination of practices to set up for promoting the targeted synchrony
Sync-MAOM	-Acquisitive plant species -Continuous activity of microbes M & I -Reserve of MAOM in soil	- 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, I, 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	-Conservative plant species -Mycorrhizal fungi -Reserve of FreeOM in soil	- 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	-Plant symbiosis with mycorrhizal fungi & N_2 fixing bacteria -Nutrients stored in bedrock, soil minerals and/or precipitates	- 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 & N_2 fixing bacteria in highly degraded soils
Sync-Market	-Plant species with complementary nutritional needs -Common mycorrhizal networks	- Mixing plant species with different nutrient acquisition strategies and carbon:nutrient ratios (a, c, I, j, k) - Promoting perennial plants (f, g, h, I, 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	-Synchrony systems adapted to pedoclimatic context -Complementary synchrony systems -Plant plasticity & reserve	- Analyzing the soil profile and climate, defining the most adapted synchrony systems - Mixing plant species with different nutrient acquisition strategies (a, c, I, j, k) - Breeding crops species on their suitability to association - Promoting perennial plants with high reserve and organ plasticity (f, g, h, I, j, k)



Thank you for your attention

Let’s continue to play the synchrony’s doctor