Prof Philippe Vandenkoornhuyse

The holobiont and hologenome concepts and related emerging ideas for the next agriculture

Université de Rennes
Campus de Beaulieu
CNRS
UMR6553 EcoBio,
Rennes, France

Université de Rennes

cnrs dépasser les frontières

@symbioticworld

ECOBIO Rennes

Microorganisms can promote evolutionary advantages to its host over generations

A number of examples…

Microorganisms can promote evolutionary advantages to its host over generations

A number of examples…

Acremonium coenophialum **associated with** *Festuca arundinacea*

Festuca arundinacea, Kentucky31 (1971 by E. N. Fergus),

Poor soils,
Resistant to pest and drought.

→ *Kentucky 31 = invasive*

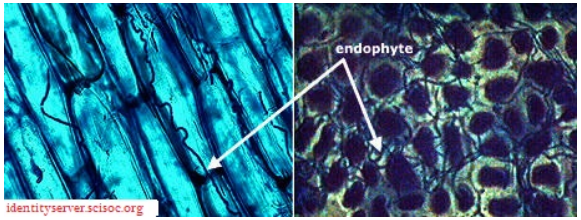
https://www.walmart.com

Festuca arundinacea, Kentucky31 (1971 by E. N. Fergus),

Acremonium coenophialum

Synthesis of Ergovaline + Loline → grazing resistance

alcaloids



+

=

Grazers

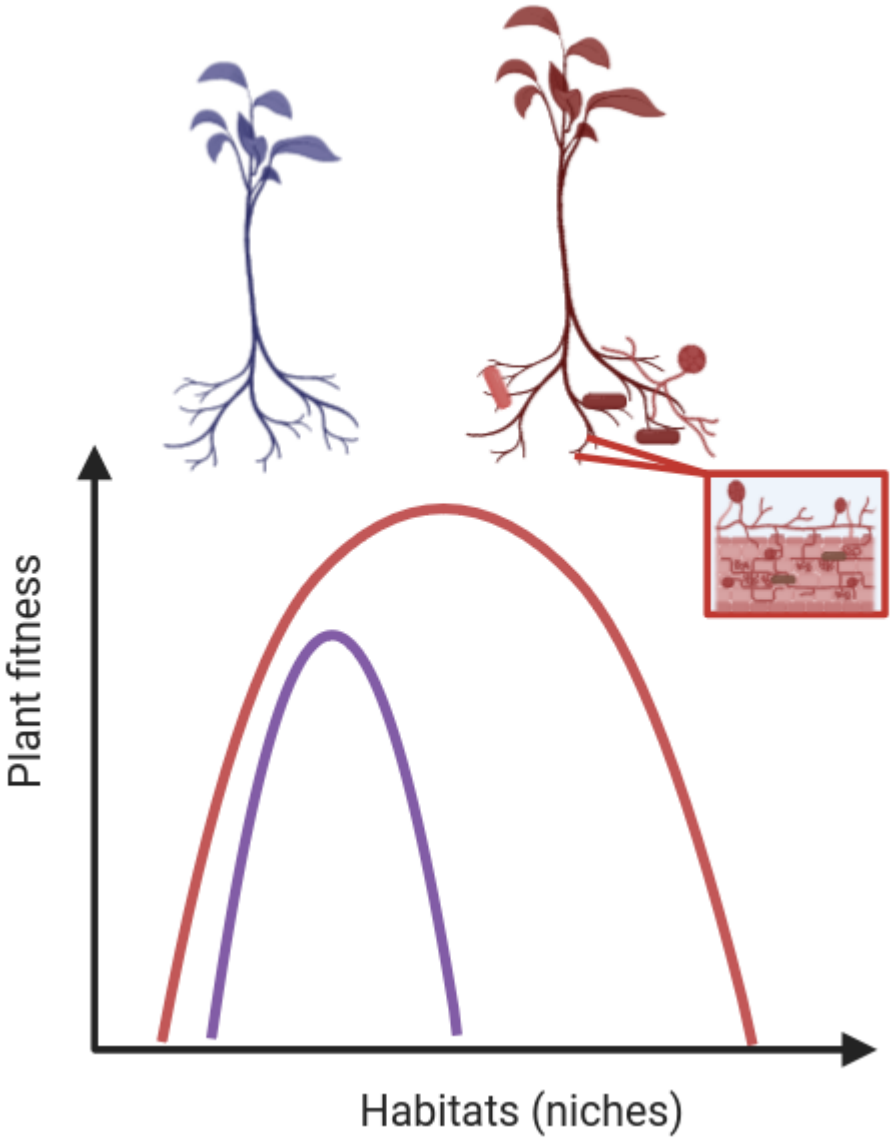
-Weight loss

-Abortion

-other negative effects

Université de Rennes

1-Macro-organisms



Université de Rennes

Plant fitness

Not necessarily a consequence of plant genome itself !

P ≠ G

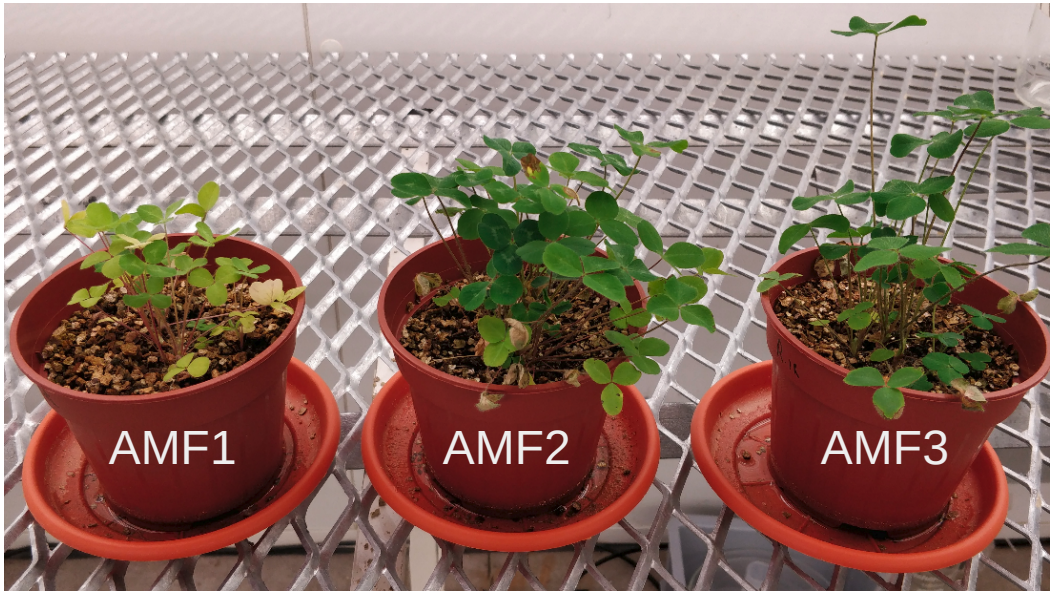
Microbiota do matter

Plant fitness

Not necessarily a consequence of plant genome itself !

P ≠ G

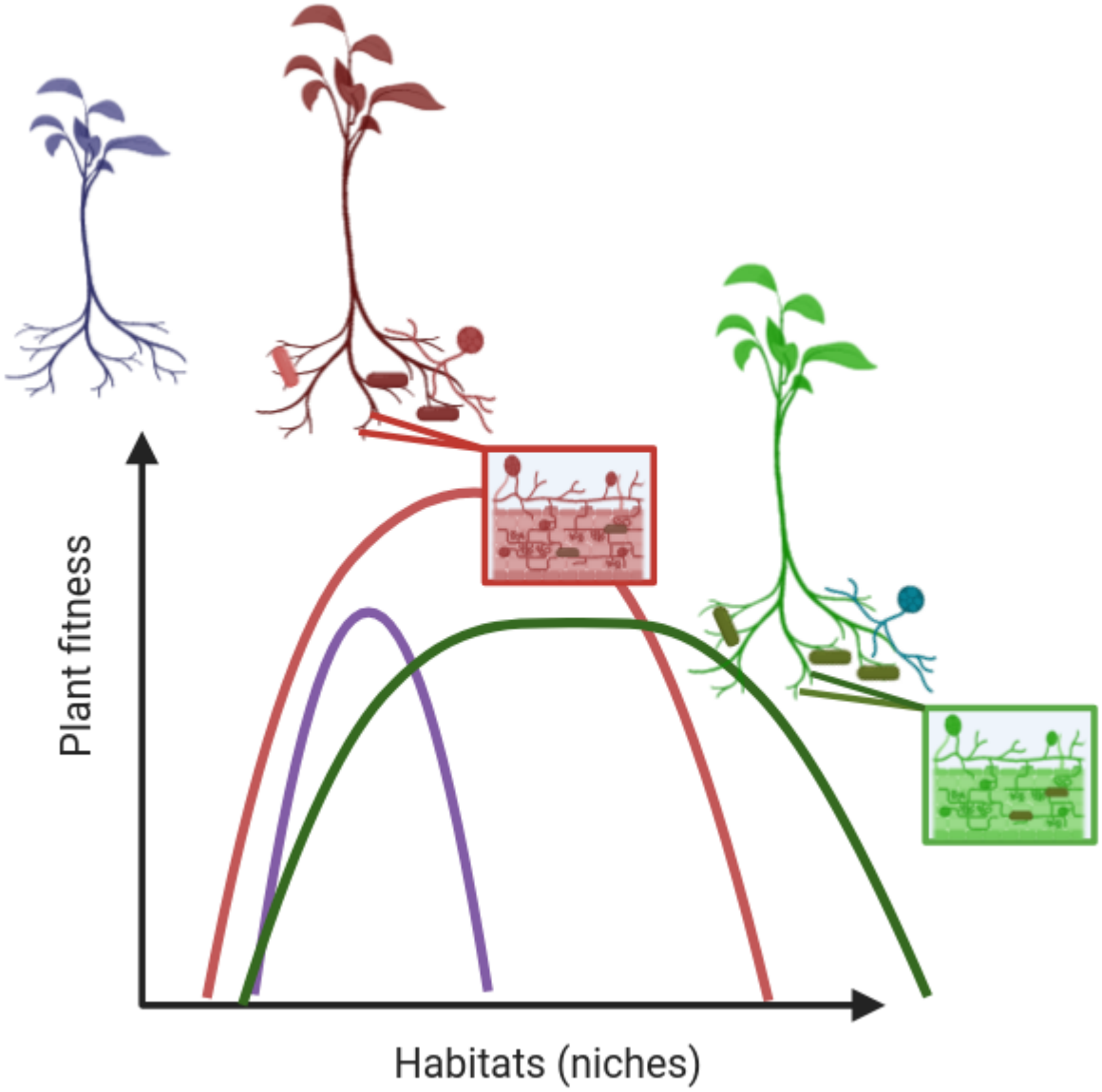
Microbiota do matter



Trifolium pratense
same growth conditions and duration
3 different mycorrhizal inocula
→ reproducible

Ricono et al, unpublished

1-Macro-organisms



Université de Rennes

Plant fitness

Not necessarily a consequence of plant genome itself !

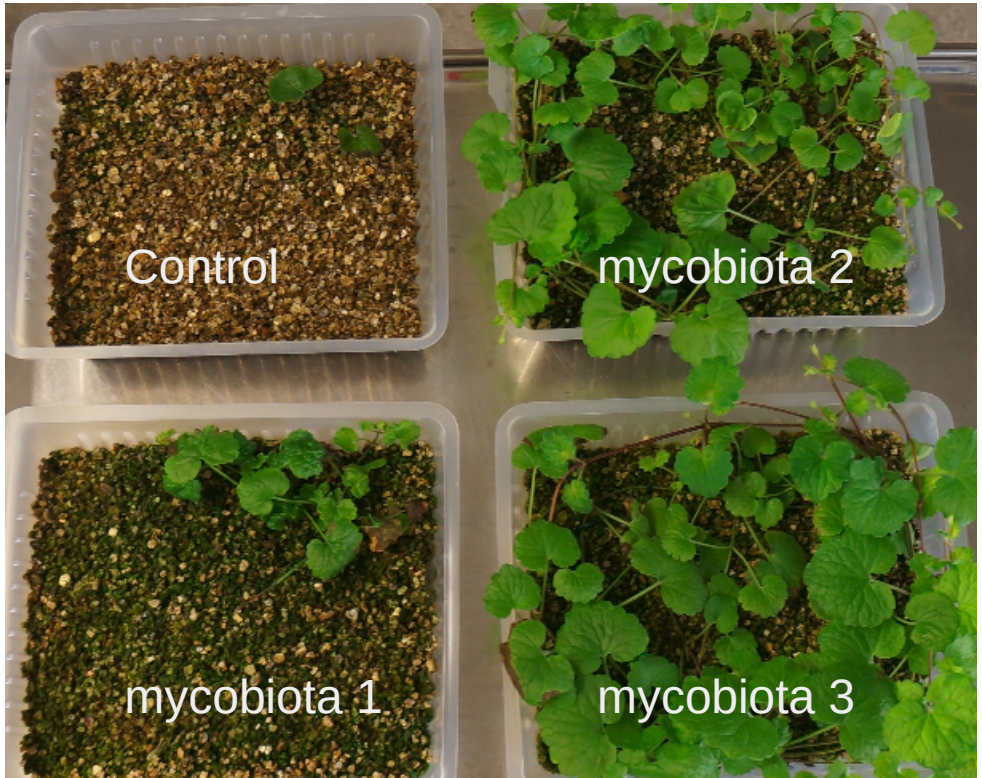
Microbiota do matter

Plant fitness

Not necessarily a consequence of plant genome itself !

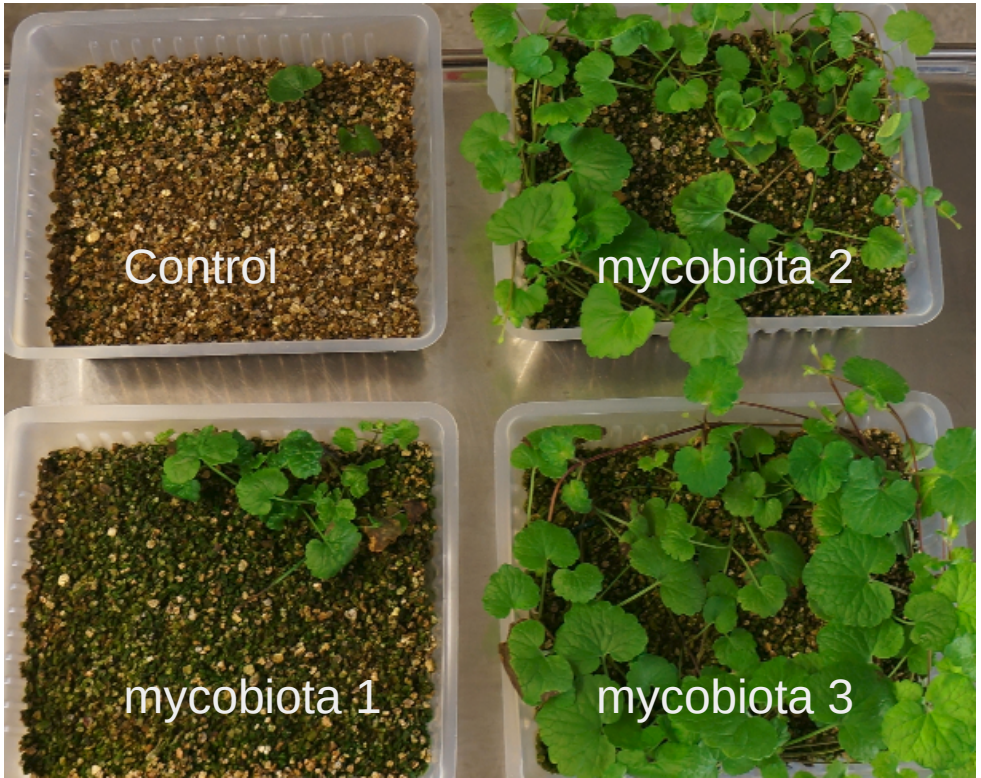
Microbiota do matter

Single genotype of the clonal *Glechoma hederacea*
same growth conditions and duration
3 different mycobiota inocula
→ reproducible



Wang et al, unpublished

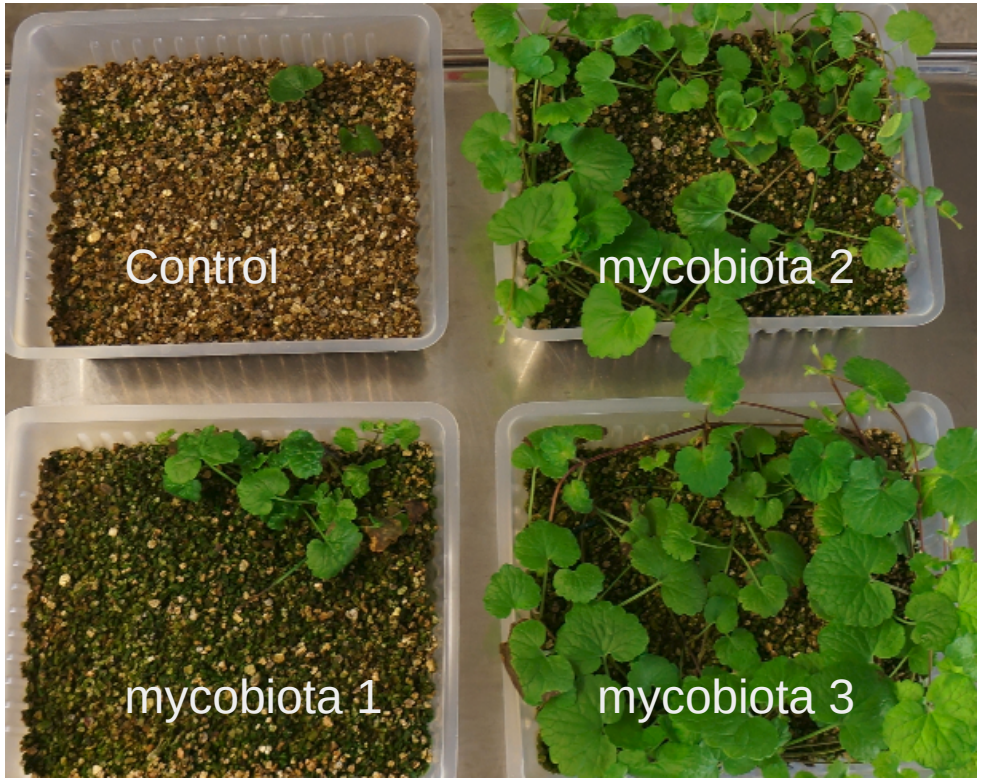
Plant fitness



Wang et al, unpublished

Plant fitness

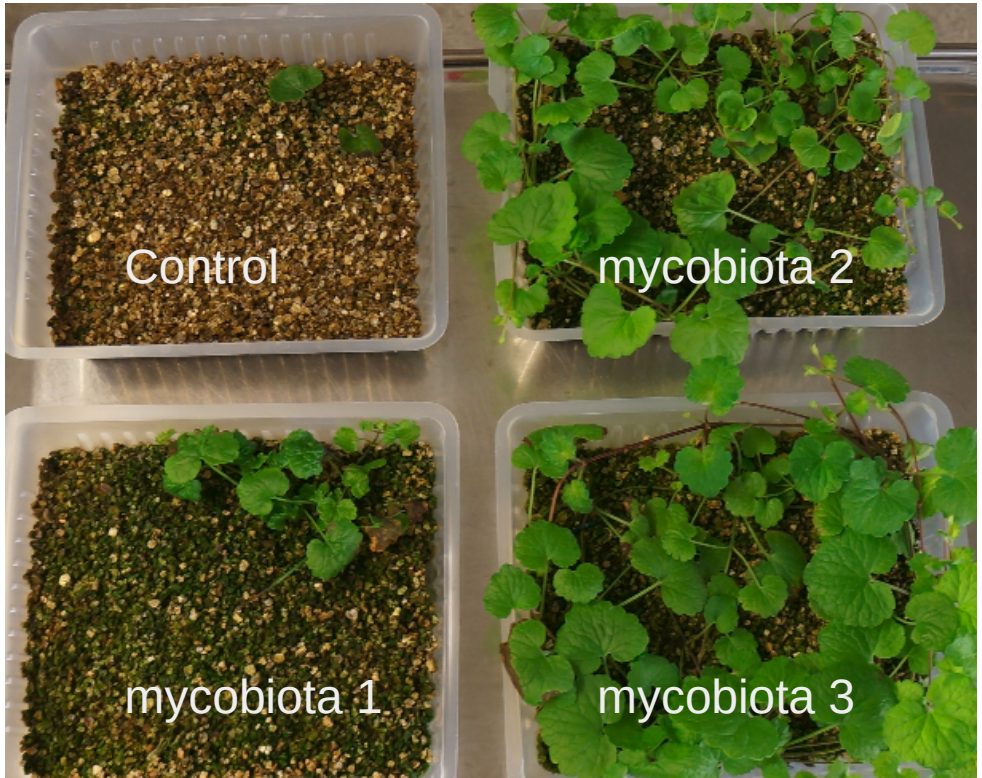
P ≠ G P ≠ GxE



Wang et al, unpublished

Plant fitness

P ≠ G P ≠ GxE but P ~ M



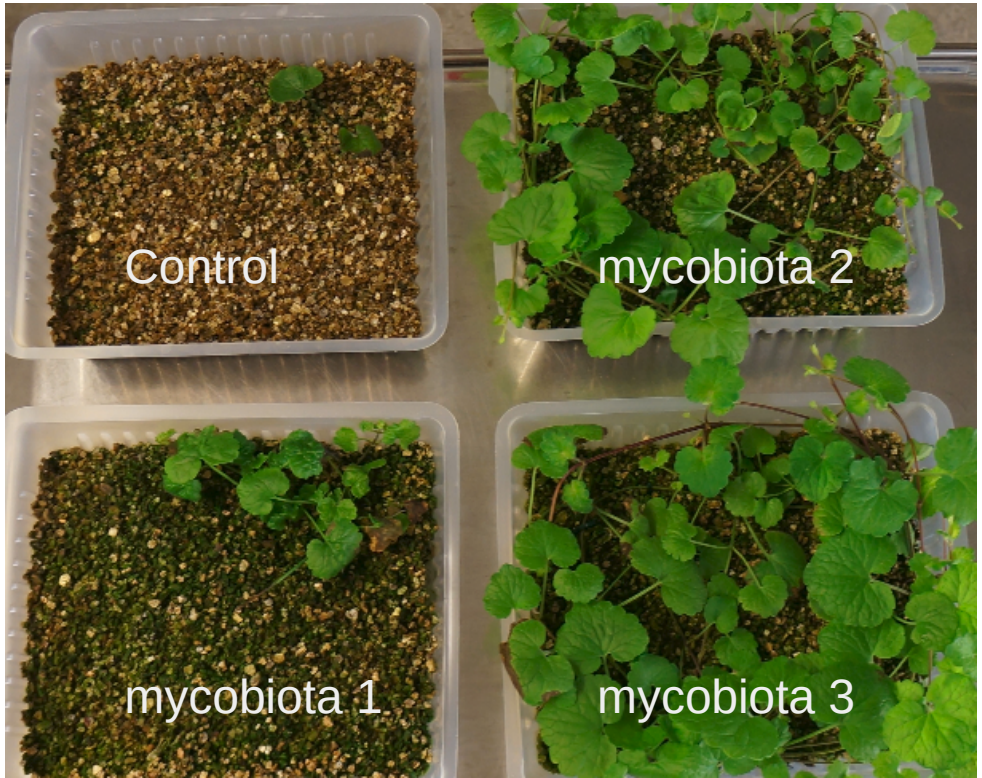
Wang et al, unpublished

Plant fitness

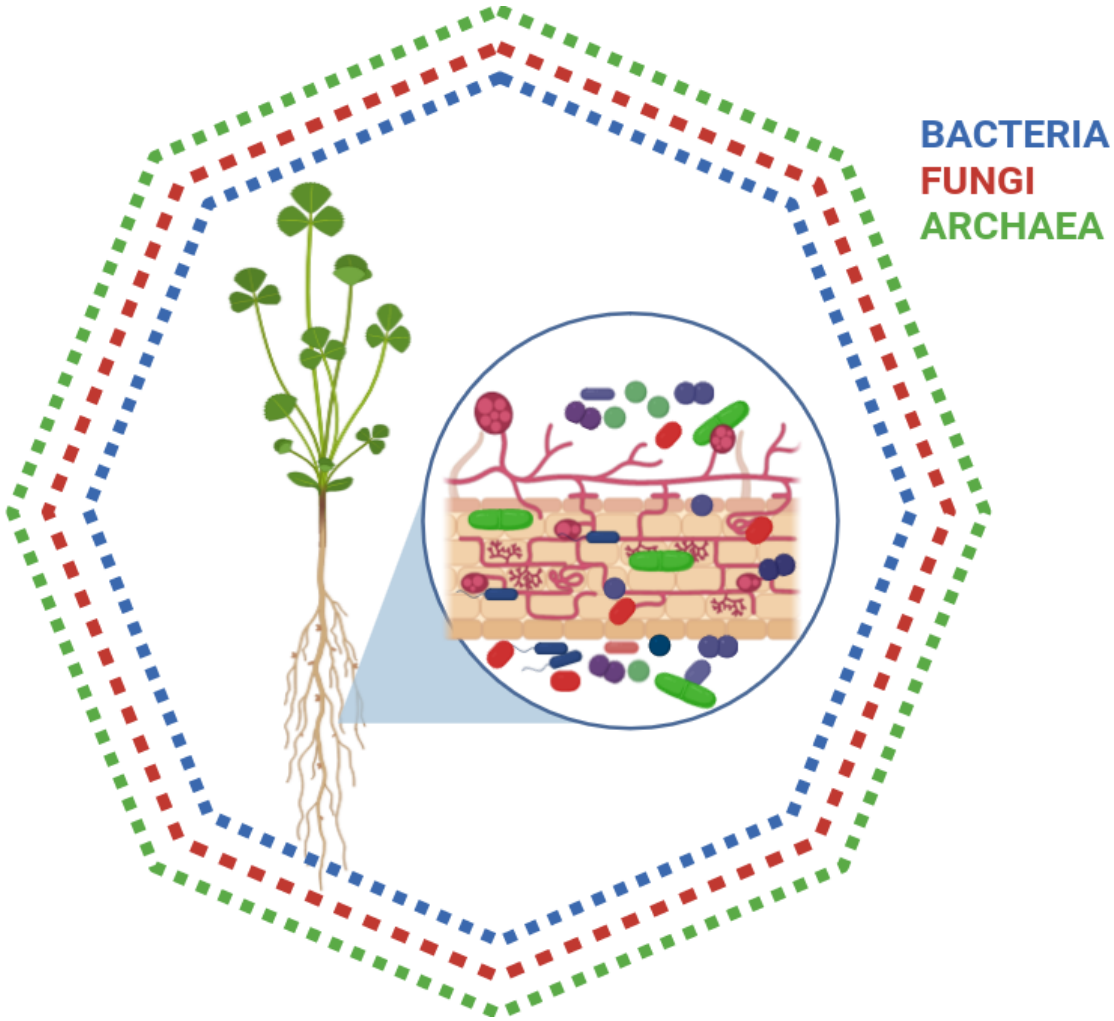
P ≠ G P ≠ GxE but P ~ M

Or, if natural conditions
(→ 'E' effect)

P ~ GxExM or
P ~ G+E+M+GxE+GxM+GxExM



Wang et al, unpublished

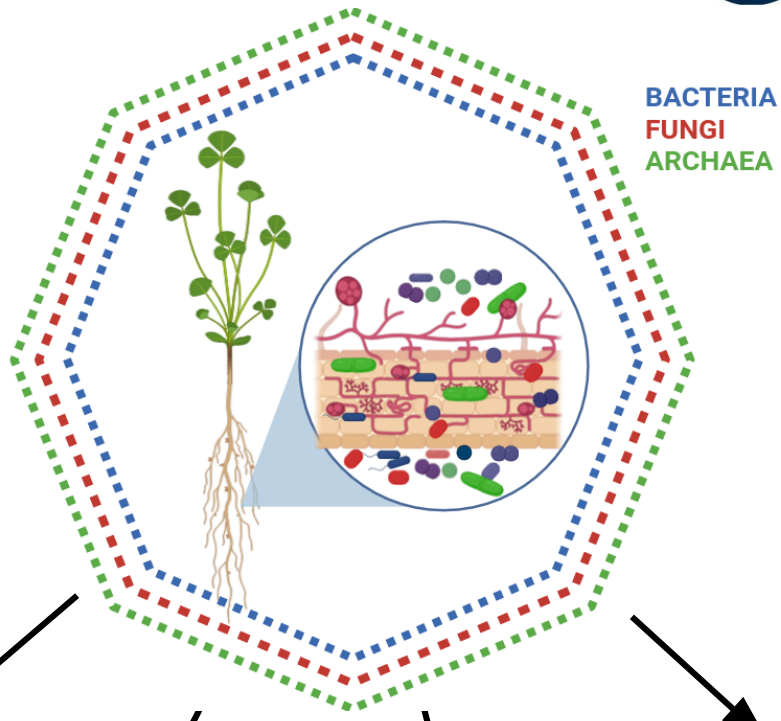


The microorganisms functions (microbiota) extend the plant adaptive abilities = add-on genetic components

Université de Rennes

e.g. Vandenkoornhuyse et al., 2015 ; Vannier *et al., Frontiers in Microb* 2015

Microorganisms transmission between generations



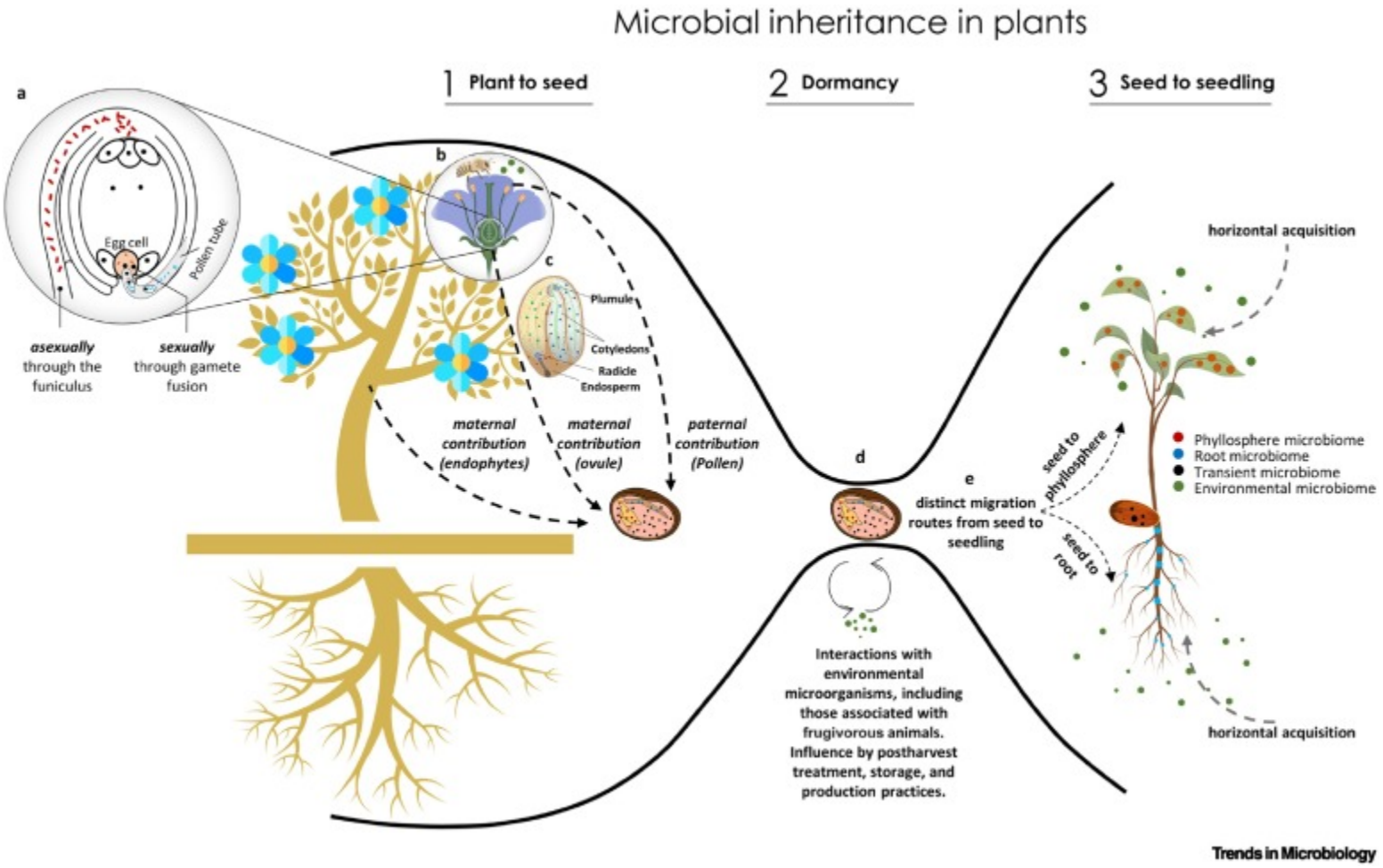
Avoids the cost of searching for symbionts

Ensures habitat quality

Fitness

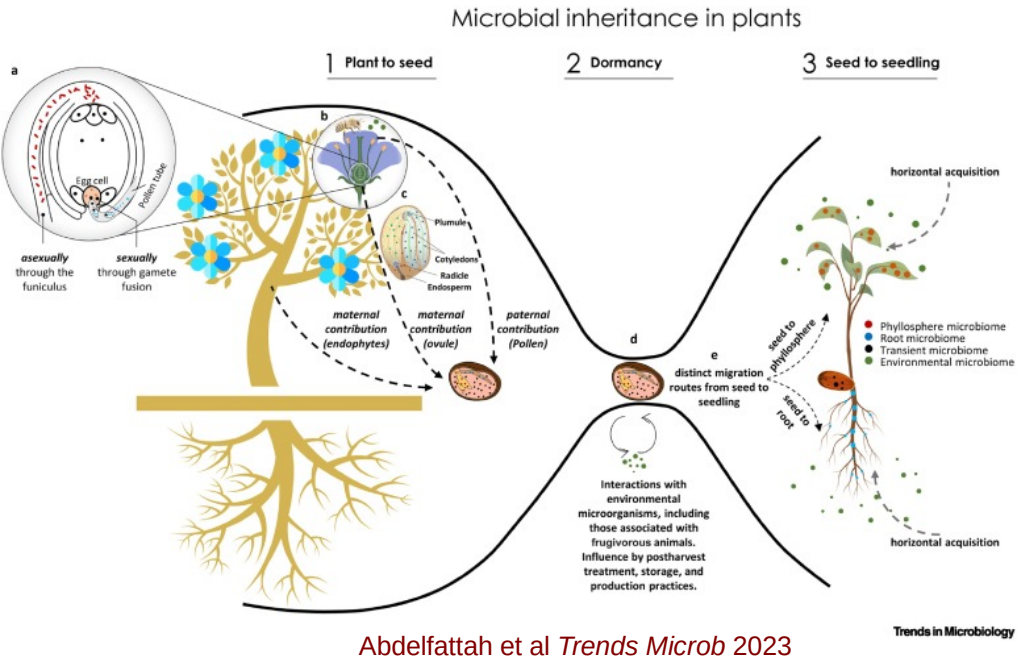
Constitutes a continuity of partnership

Seed-borne microorganisms (i.e. vertical transmission):



e.g. Guo et al., *New Phytol* 2022 ; Abdelfattah et al *Trends in Microb* 2023 ;

Seed-borne microorganisms (i.e. vertical transmission):



Abdelfattah et al *Trends Microb* 2023

Bacillus subtilis *Pseudomonas putida*	phytoprotection
Azoarcus sp *Gluconacetobacter diazotrophicus* *Burkholderia phytofirmans* *Pseudomonas fluorescens*	*growth*
Herbaspirillum seropedicae	*rooting*
Acremonium coenophialum	drought, grazers

And also pathogens reported …

e.g. Kandel et al., *Microorganisms* 2017 ; Chesneau et al., *MBio* 2022 ; Guo et al., *New Phytol* 2022 ; Abdelfattah et al *Trends Microb* 2023 ;

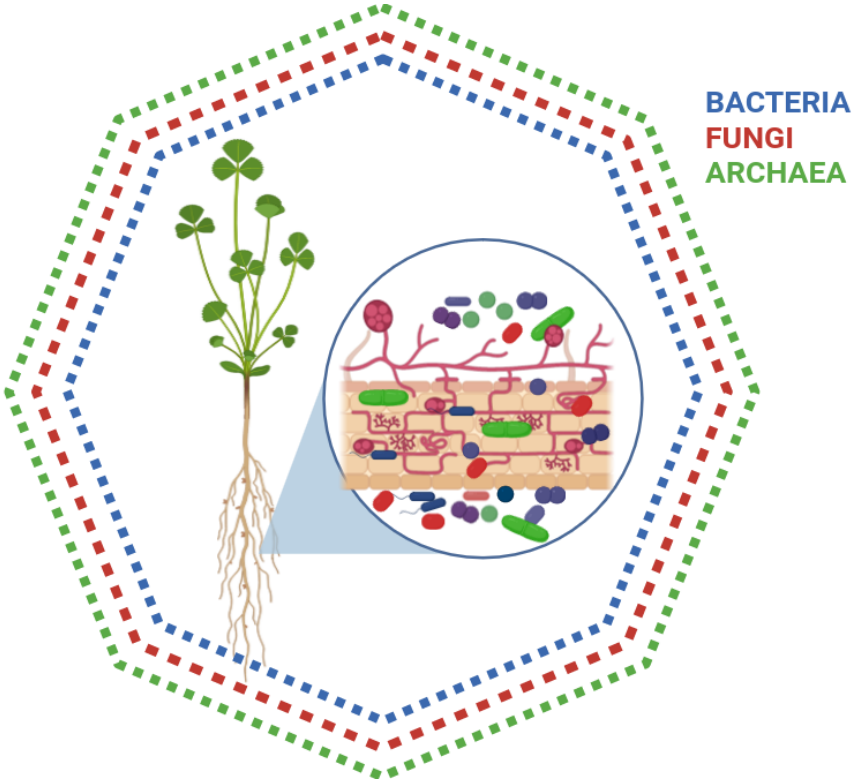
Microorganisms transmission between generations

Avoids the cost of searching for symbionts

Ensures habitat quality

Constitutes a continuity of partnership

<u>Different ways of heritability</u> :
-Vertical through seeds
-Pseudo-vertical (seeds germinating nearby the mother plant)
-Vertical transmission from mother to daughter ramets in clonal plants



Wilkinson & Sherratt, Oikos 2001; Selosse et al., CR Biol 2004
Truyans et al. Env Microb Rep 2015 ; Vannier et al., Sci Rep 2016 ; Microbiome 2018

The holobiont & hologenome

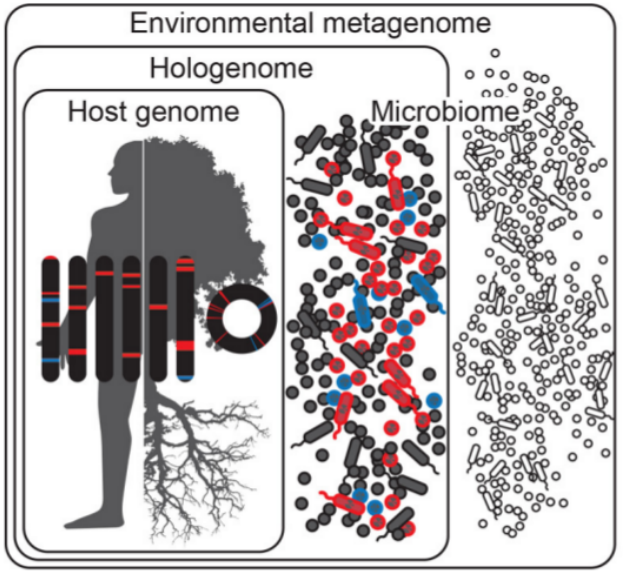
Tenets of the hologenome concept of evolution

1- Hosts ubiquitously associate with symbiotic microbes

2- These associations can affect the fitness of the Holobiont *In both positive and negative ways*

3- Microbial alleles can be reliably associated with hosts across generations (vertical or pseudo-vertical transmission)

4- Variation among hologenomes can arise via changes in hosts' or microbes' genomes



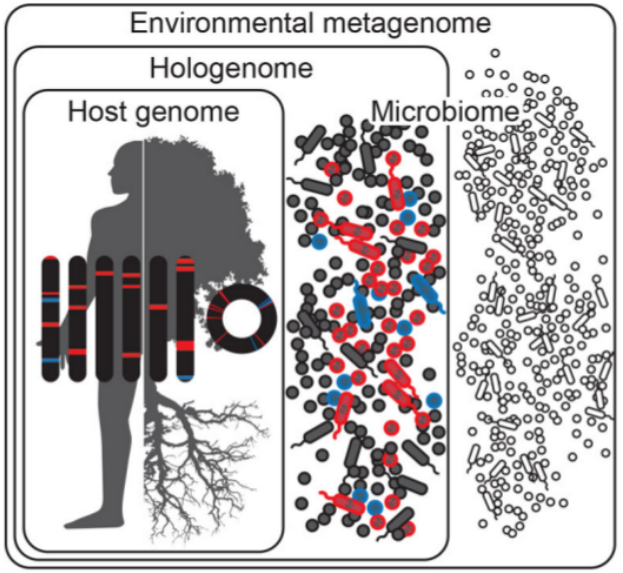
Theis et al. *mSystems* 2016

Université de Rennes

Zilber-Rosenberg, Rosenberg *FEMS Microbiol Rev* 2008 ; Vandenkoonhuyse et al, *New Phytol* 2015
Bordenstein & Theis *PLoS Biology* 2015; Theis et al. *mSystems* 2016

Testing the validity of the hologenome concept

1- Hypothesis H0 : if hologenome is just an intellectual concept not existing in the true life, pattern of recruitment are expected to be passive, **stochastic** differences in the microbiota community among plants are expected.



Rosenberg & Zilber-Rosenberg 2013; Vandenkoonhuyse et al, *New Phytol* 2015
Bordenstein & Theis PLoS Biology 2015; Theis et al. *mSystems* 2016

Testing the validity of the hologenome concept

iScience

CellPress
OPEN ACCESS

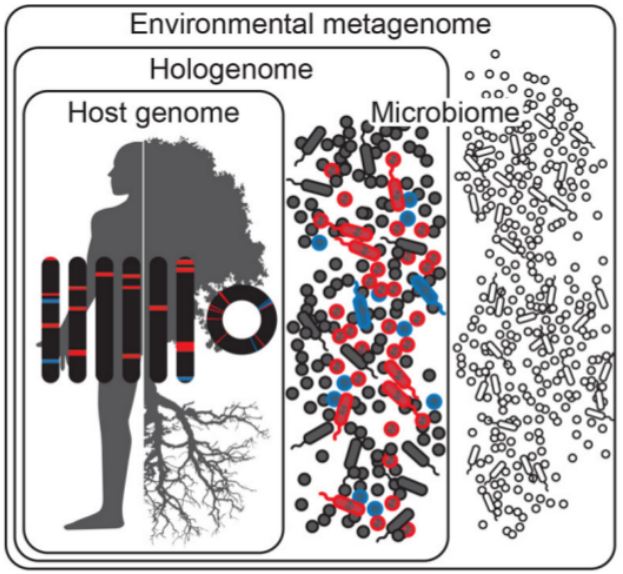
Article

Evaluating the hologenome concept by analyzing the root-endosphere microbiota of chimeric plants

Marine Biget,[1,5,6] Tingting Wang,[1,2,6] Cendrine Mony,[1] Qicheng Xu,[2] Lucie Lecoq,[1] Véronique Chable,[3] Kevin R. Theis,[4] Ning Ling,[2,*] and Philippe Vandenkoornhuyse[1,7,*]

Testing the validity of the hologenome concept

1- Hypothesis H0 : if hologenome is just an intellectual concept, pattern of recruitment are expected passive, **stochastic** differences in the microbiota community among plants are expected.



Hypothesis REJECTED
Pattern of recruitment is not stochastic
and hologenome is most likely not just an intellectual concept

Determinism in microbial recruitment & homeostasis
Variations mostly related to heterogenity in the soil microbial reservoir

Biget, Wang et al. *iScience* 2023

Hologenome concept opens opportunities to see life in a different way

Hologenome / holobiont :
a new level of biological organization

=A breakup paradigm in the understanding of the world around us, that transforms scientific methods and philosophical ideas

A Copernican revolution (E Kant)

Witness/actors of this deep paradigm and philolophical shift

Hologenome concept opens opportunities to see life in a different way

Hologenome / holobiont :
a new level of biological organization

=A breakup paradigm in the understanding of the world around us, that transforms scientific methods and philosophical ideas

A Copernican revolution (E Kant)

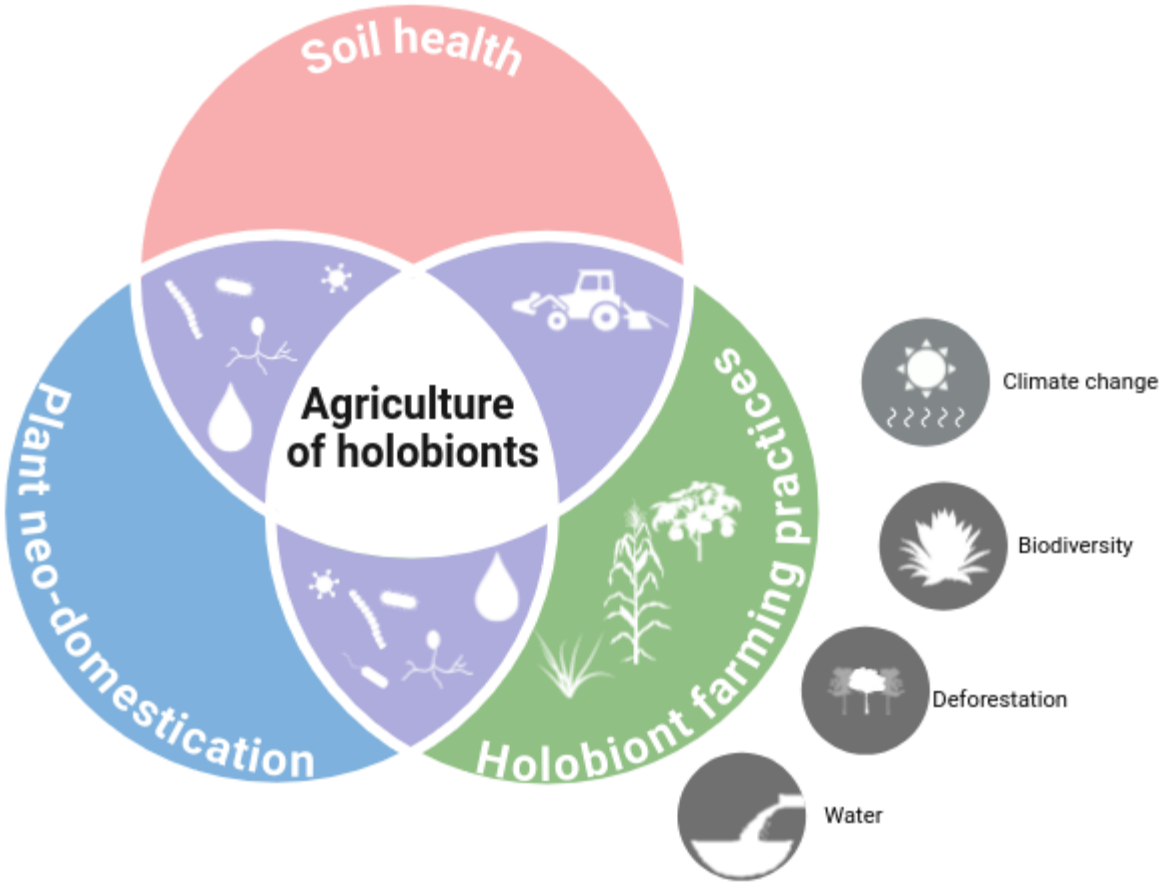
A shift in the ideas for future agriculture :
Rethinking what is key

(taking into account the need of a sustainable and productive agriculture)

Toward an agriculture of holobionts ?

The right way to consider plant individuals

Toward an agriculture of holobionts ? → Three pillars



Toward an agriculture of holobionts ? → Key concern One

A needed soil microorganisms reservoir for plant microbiota recruitment

→ horizontal and pseudo-vertical microbiota transmission

Detrimental effects of current conventional agriculture on soil microbial reservoir ?

Toward an agriculture of holobionts ? → Key concern One

A needed soil microorganisms reservoir for plant microbiota recruitment

→ horizontal and pseudo-vertical microbiota transmission

AMERICAN SOCIETY FOR MICROBIOLOGY | mSystems®

July/August 2020 Volume 5 Issue 4 e00337-20

RESEARCH ARTICLE
Applied and Environmental Science

Long-Term Chemical-Only Fertilization Induces a Diversity Decline and Deep Selection on the Soil Bacteria

Qicheng Xu,[a,b] Ning Ling,[a,b] Huan Chen,[c] Yinghua Duan,[d] Shuang Wang,[e] Qirong Shen,[a] Philippe Vandenkoornhuyse[b]

Toward an agriculture of holobionts ?

A needed soil microorganisms reservoir for plant microbiota recruitment

→ horizontal and pseudo-vertical microbiota transmission

PNAS RESEARCH ARTICLE | AGRICULTURAL SCIENCES OPEN ACCESS

Carbon starvation raises capacities in bacterial antibiotic resistance and viral auxiliary carbon metabolism in soils

Qicheng Xu[a,b,1], He Zhang[a,c,1], Philippe Vandenkoornhuyse[b], Shiwei Guo[a], Yakov Kuzyakov[d,e], Qirong Shen[a,2], and Ning Ling[c,2]

2024 Vol. 121 No. 16 e2318160121

Toward an agriculture of holobionts ?

A needed soil microorganisms reservoir for plant microbiota recruitment

→ horizontal and pseudo-vertical microbiota transmission

Detrimental effects of current conventional agriculture on soil microbial reservoir

Toward an agriculture of holobionts ?

A needed soil microorganisms reservoir for plant microbiota recruitment

→ horizontal and pseudo-vertical microbiota transmission

Detrimental effects of current conventional agriculture on soil microbial reservoir

N inputs to soils and diazotrophy

Toward an agriculture of holobionts ?

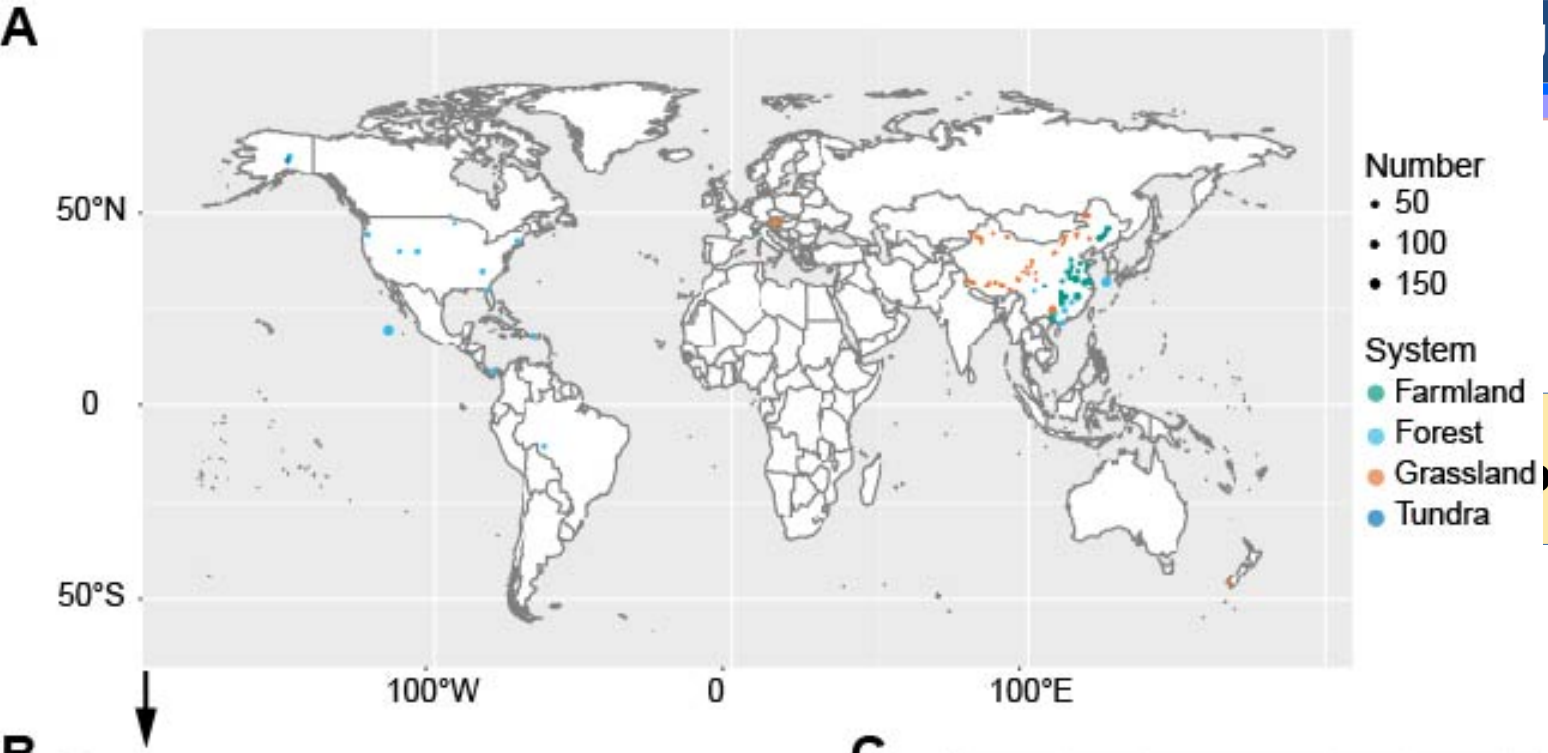
A needed soil microorganisms reservoir for plant microbiota recruitment

→ horizontal and pseudo-vertical microbiota transmission

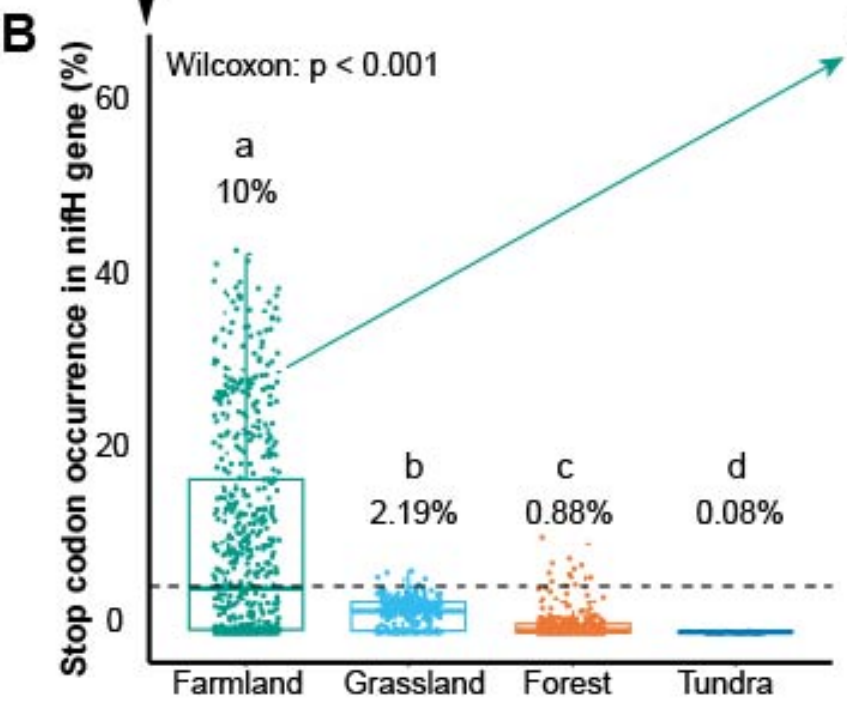
Detrimental effects of current conventional agriculture on soil microbial reservoir

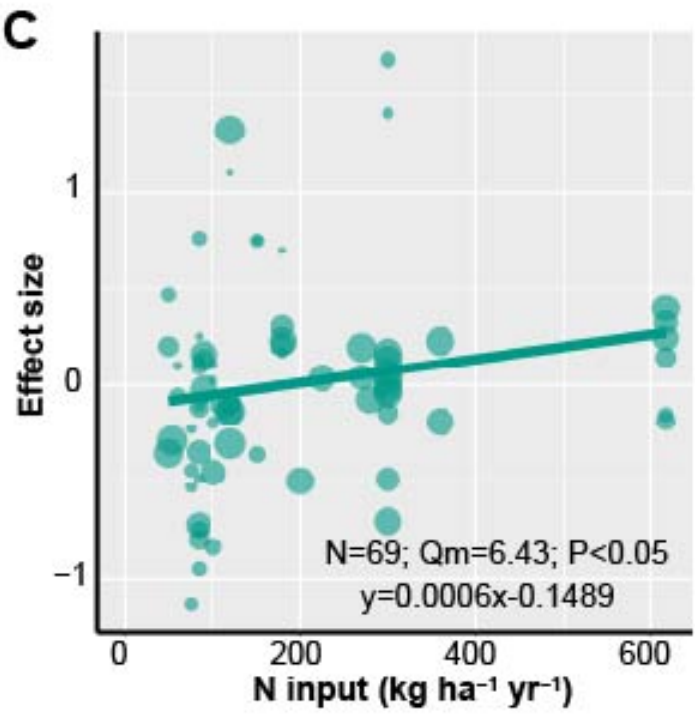
N inputs to soils and diazotrophy

→ Diazotrophs not competitive
No need for N fixation by diazotrophs
=> mitigation of selection pressure on N fixing genes



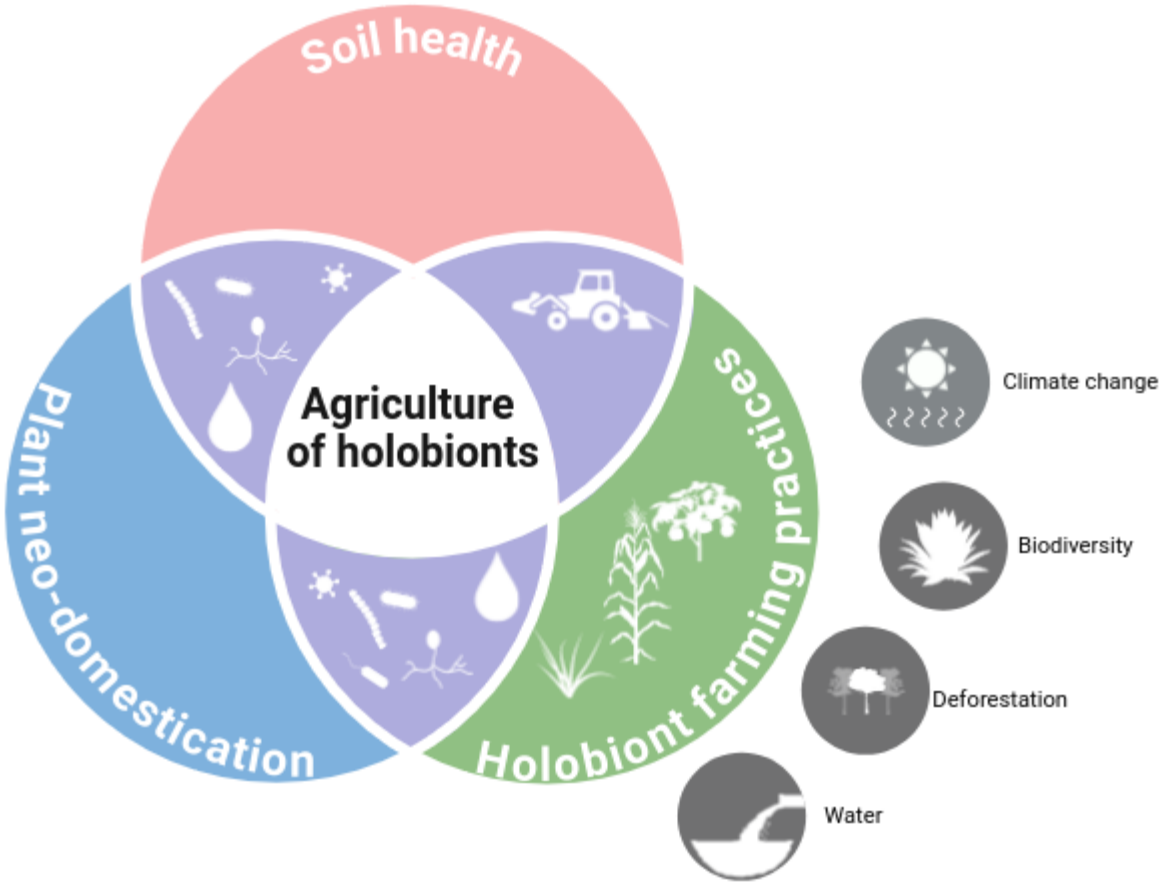
ta recruitment





Zhu et al.,
to submit

Toward an agriculture of holobionts ?



Toward an agriculture of holobionts ?

A needed reconsideration of the plant breeding strategy

Today, breeding for the best possible plant cultivar in the context of conventional farming and artificialization → not holobiont breeding

Detrimental effect on the capacity of plant to interact and control interactions with microorganisms

Toward an agriculture of holobionts ?

A needed reconsideration of the plant breeding strategy

PROCEEDINGS OF THE ROYAL SOCIETY B

Proc. R. Soc. B (2007) **274**, 3119–3126
doi:10.1098/rspb.2007.1187
Published online 17 October 2007

Human selection and the relaxation of legume defences against ineffective rhizobia

E. Toby Kiers[1,4,*], Mark G. Hutton[2] and R. Ford Denison[3,4]

‘Modern’ crop more prone to be colonized by Rhizobia cheaters

Toward an agriculture of holobionts ?

A needed reconsideration of the plant breeding strategy

→ breeding of holobionts NOT host only !

Trends in Ecology & Evolution

Review

Agriculture and the Disruption of Plant–Microbial Symbiosis

Stephanie S. Porter[1] and Joel L. Sachs[2,3,4,*]

Trends in Ecology & Evolution, May 2020, Vol. 35, No. 5 https://doi.org/10.1016/j.tree.2020.01.006

Disruption of the plant traits that regulate symbiosis is selectively neutral under agricultural conditions and related artificialization

Toward an agriculture of holobionts ?

A needed reconsideration of the plant breeding strategy

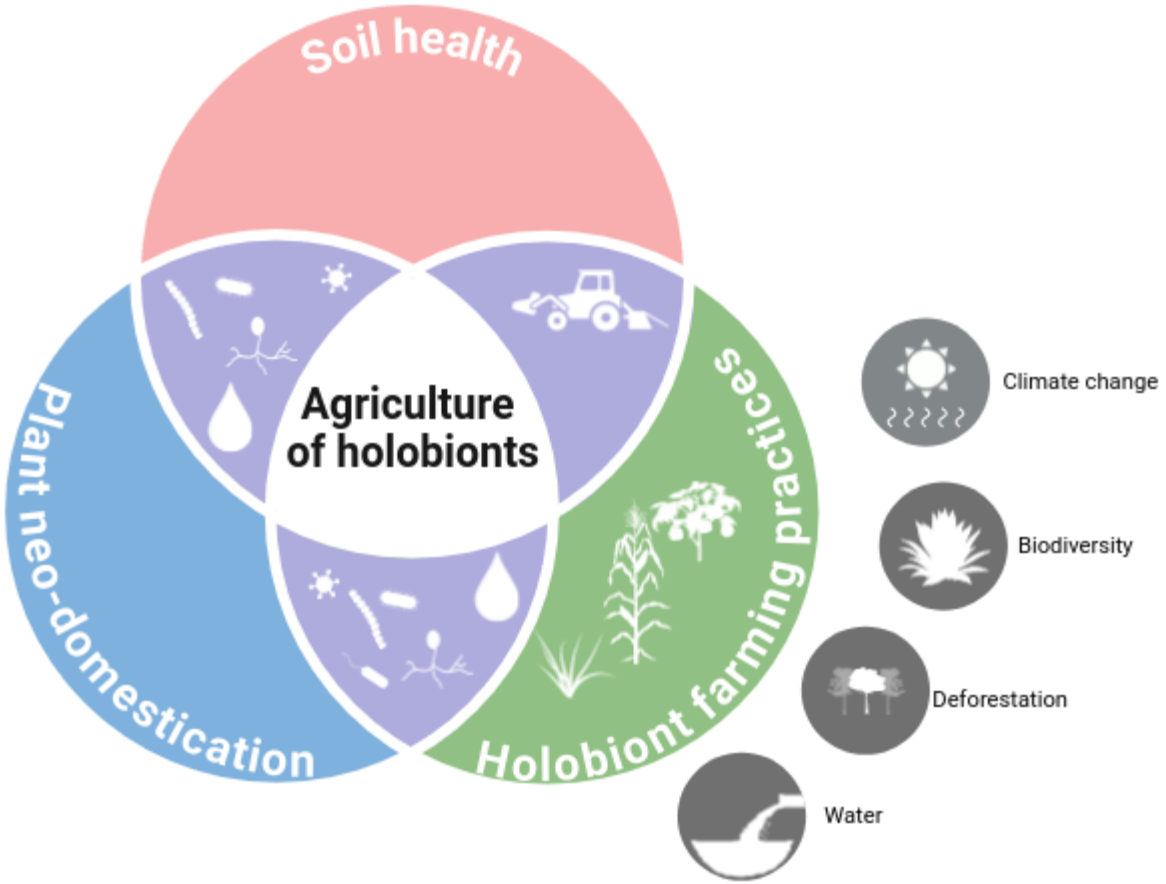
→ breeding of holobionts NOT host only !

Trends in Plant Science November 2013, Vol. 18, No. 11

Sustainable agriculture: possible trajectories from mutualistic symbiosis and plant neodomestication

Marie Duhamel[1,2] and Philippe Vandenkoornhuyse[1]

Toward an agriculture of holobionts ?



Beyond the 3 identified pillars...

An agriculture of holobionts …

A needed reconsideration of plant diseases

An agriculture of holobionts …

A needed reconsideration of plant diseases

If holobionts exist, diseases ?
Microbiota can be at the origin of a disease
= Disease as a consequence of a disorder of host-microorganisms and/or microorganisms-microorganisms interactions

→ **concept of dysbiosis**

Trends in Plant Science, January 2023, Vol. 28, No. 1 https://doi.org/10.1016/j.tplants.2022.08.012

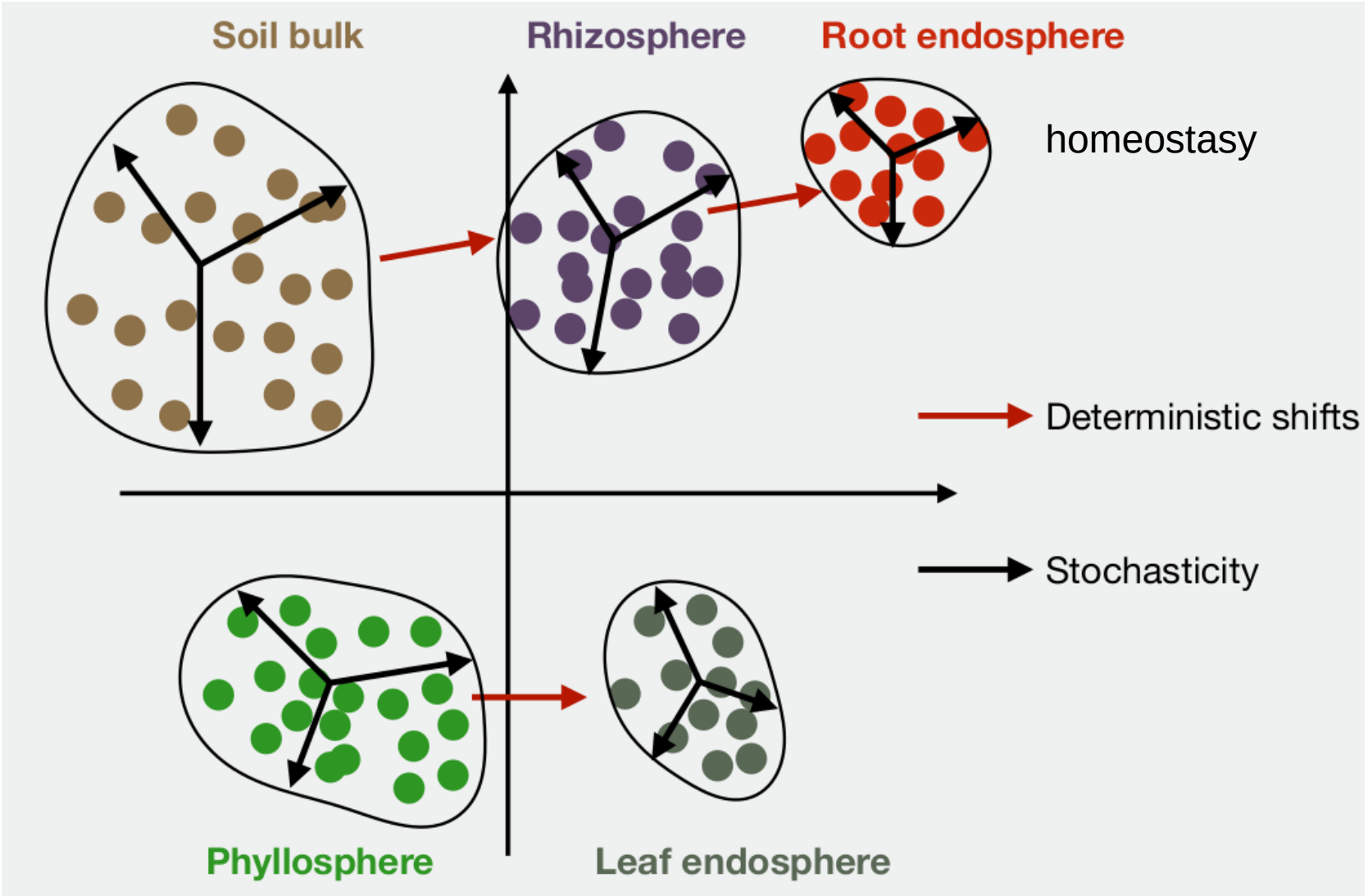
CellPress

Trends in Plant Science

Opinion

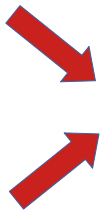
Plant microbiota dysbiosis and the Anna Karenina Principle

Gontran Arnault [1,2] Cendrine Mony [1] and Philippe Vandenkoornhuyse [1,*]



Arnault et al Trends Plant Sci 2023

Disease and microbiota



α-diversity

β-diversity

-loss of a microbiota part +
-development of the pathogen

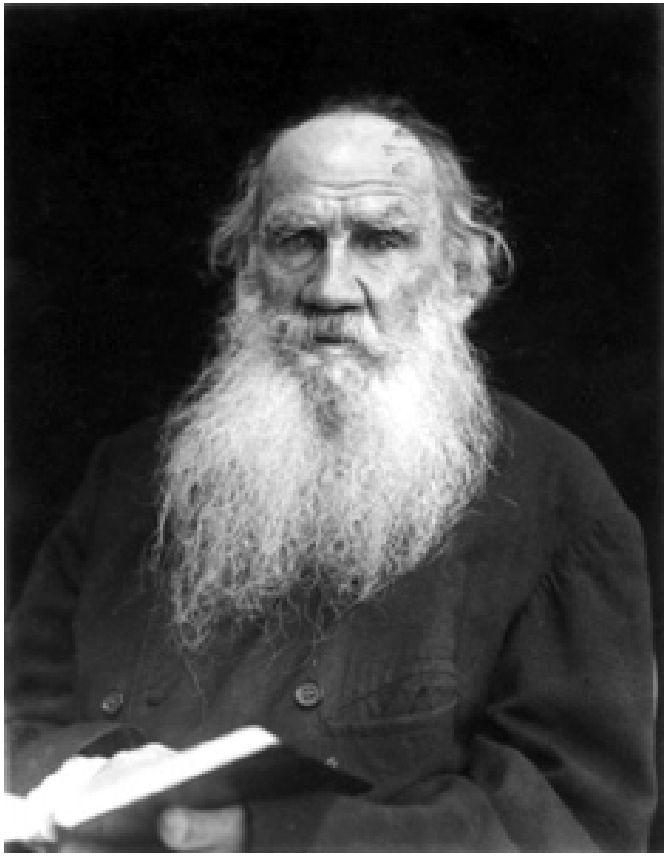
-divergence from the homeostatic steady state
-loss of a cooperative fraction of the microbiota → spread of pathogen
- …

-Loss of a cooperative fraction of the microbiota and spread of pathogen
- …

Anna Karenina Principle

‘All happy families are all alike; each unhappy family is unhappy in its own way’

(first sentence of the book)



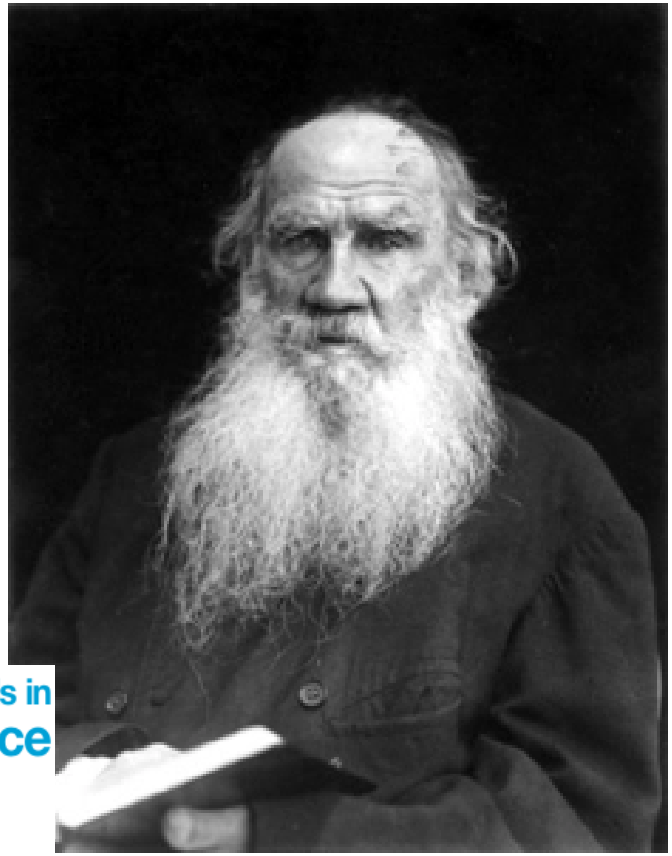
Arnault et al *Trends Plant Sci* 2023

-Loss of a cooperative fraction of the microbiota and spread of pathogen …

Anna Karenina Principle

Transposed to microbiome…

All healthy microbiomes are alike; All microbiome associated to a disease is sick in its own way



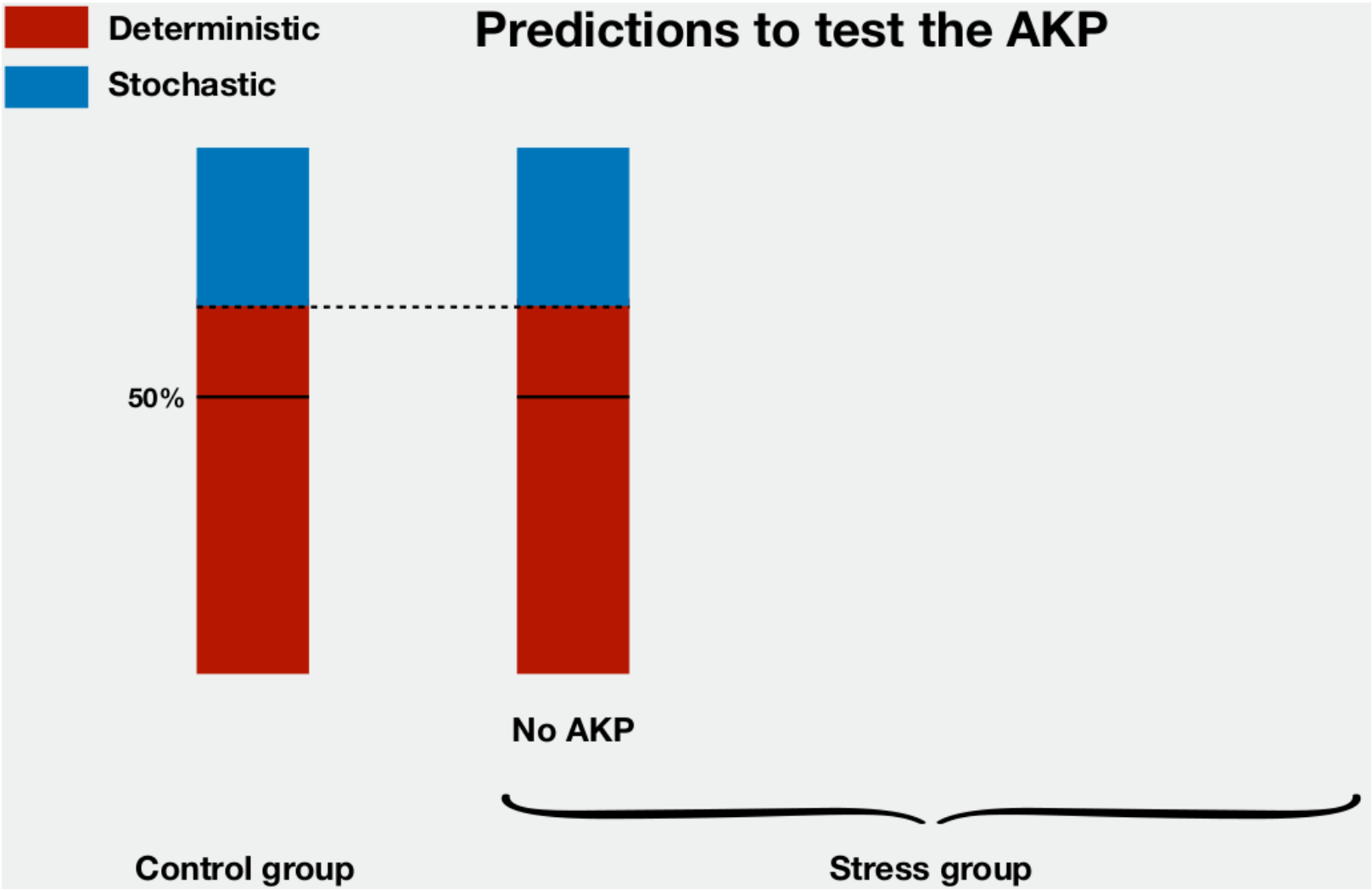
CellPress

Trends in Plant Science

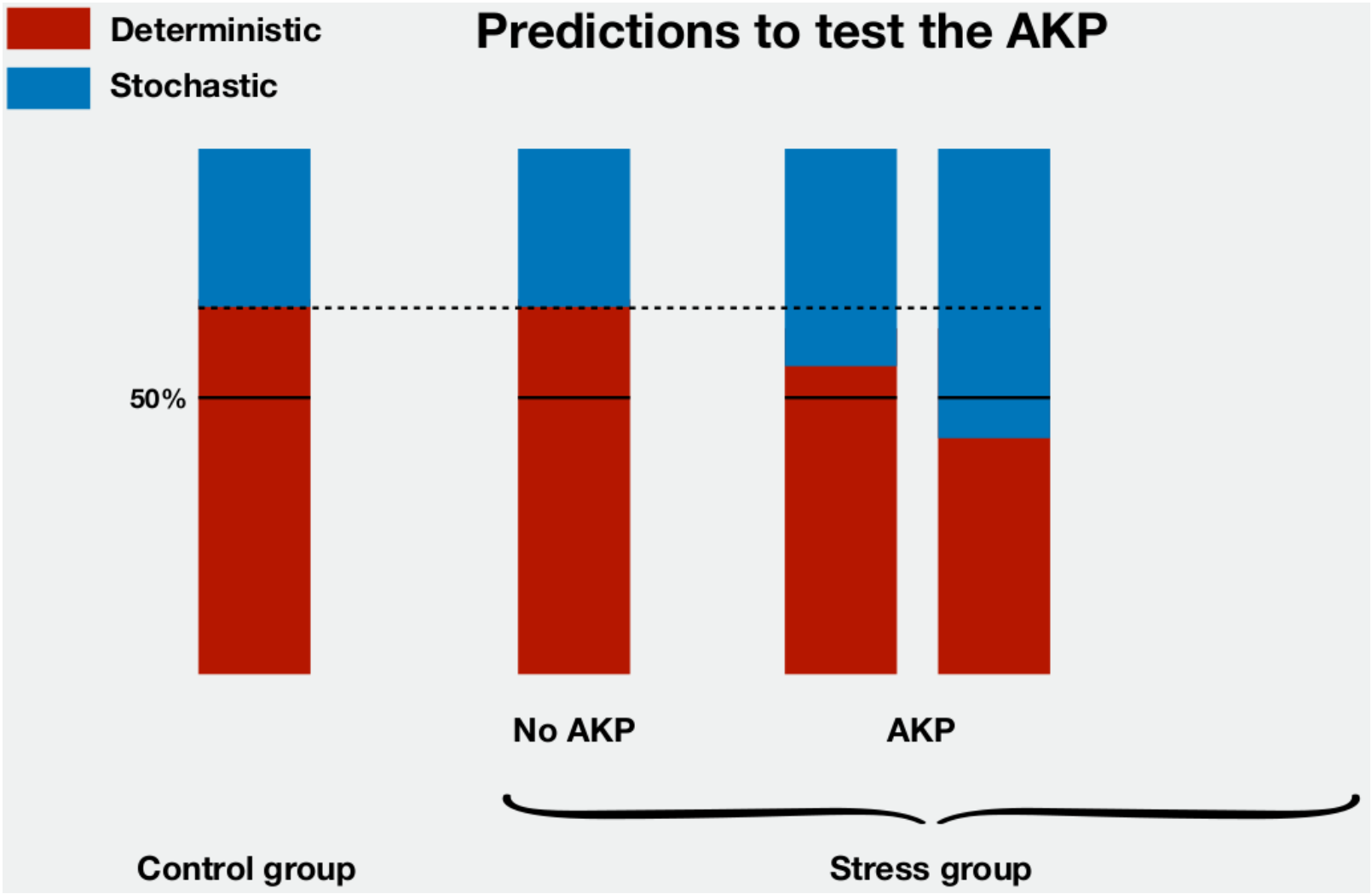
Opinion

Plant microbiota dysbiosis and the Anna Karenina Principle

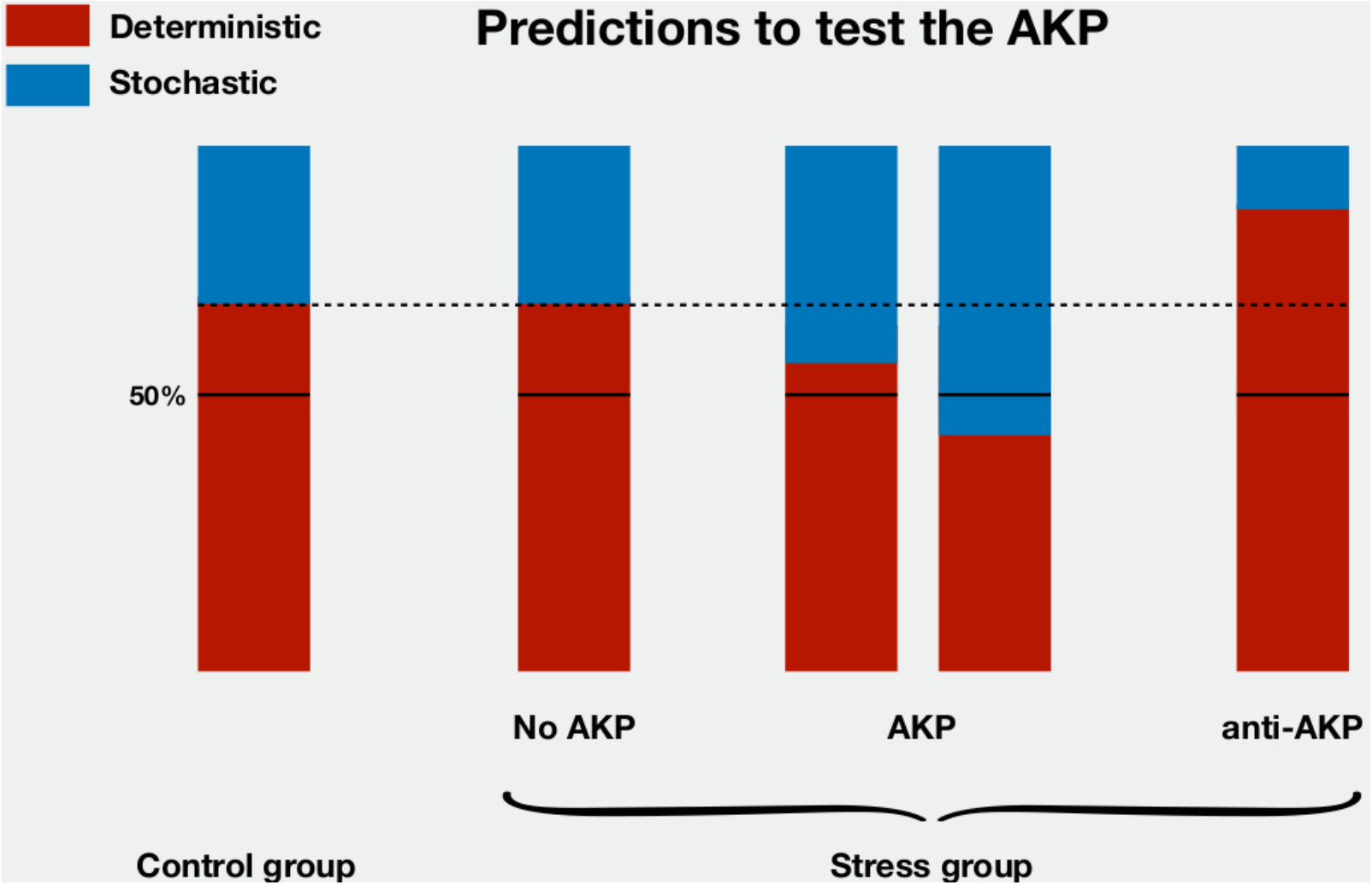
Gontran Arnault [1,2] Cendrine Mony [1] and Philippe Vandenkoornhuyse [1,*]



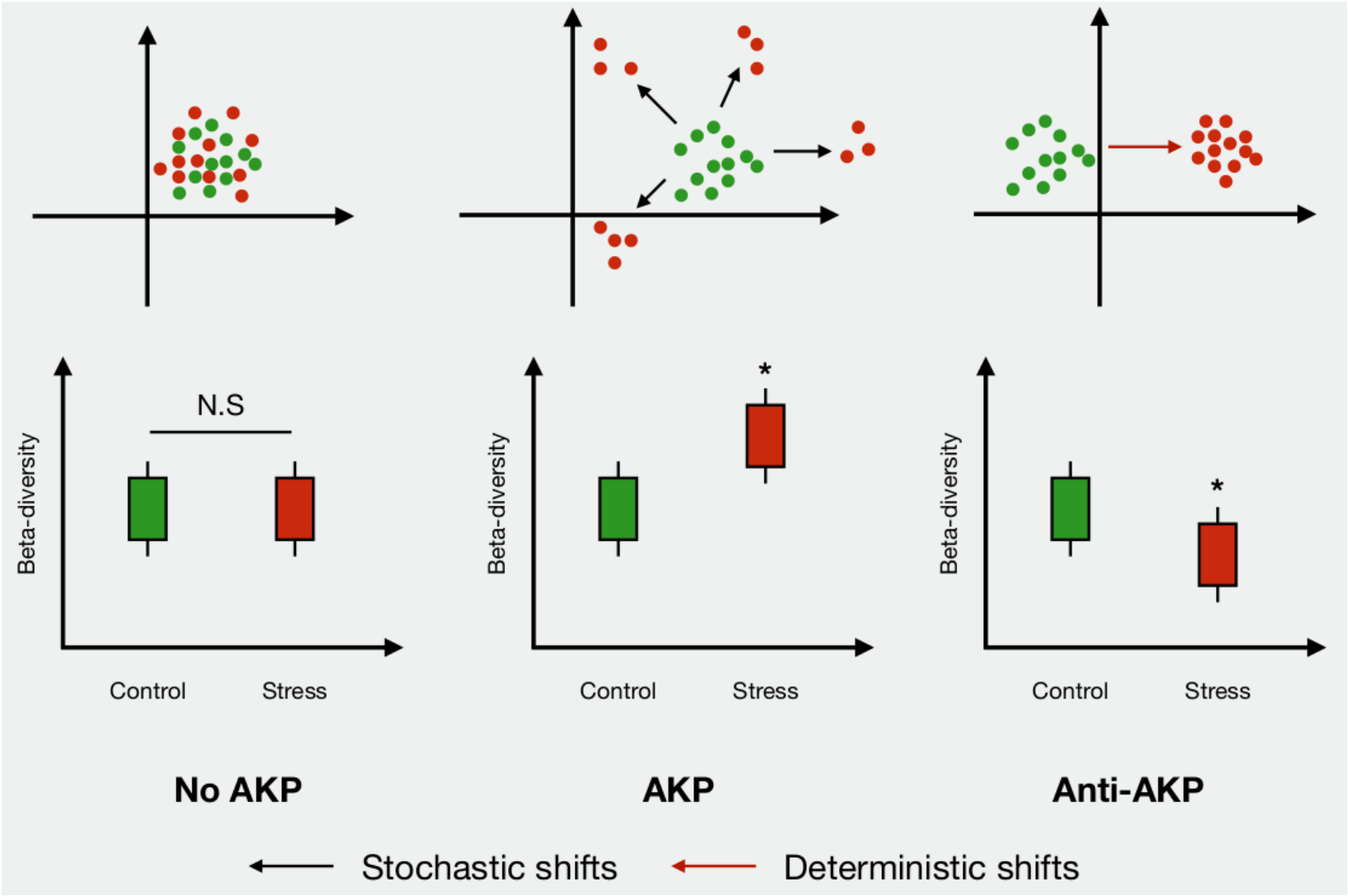
Arnault et al *Trends Plant Sci* 2023



Arnault et al Trends Plant Sci 2023

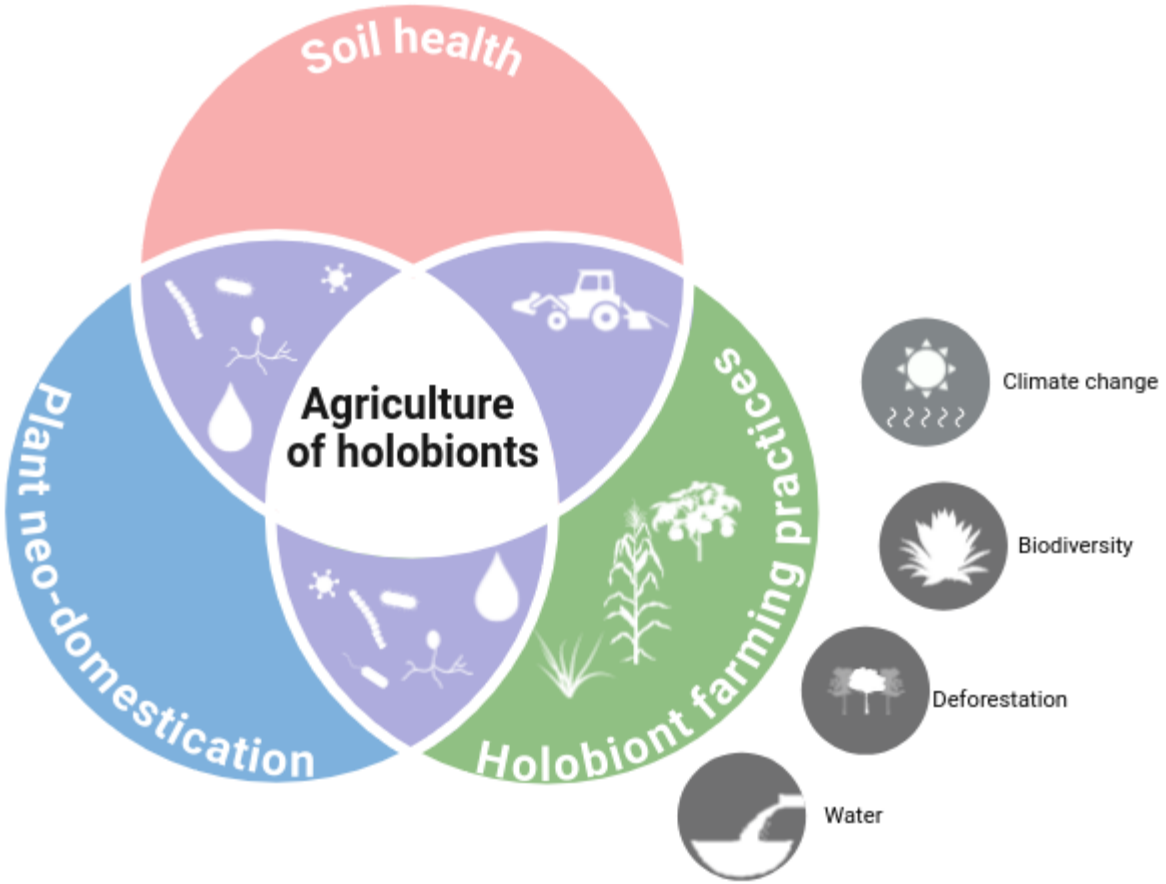


Arnault et al *Trends Plant Sci* 2023



Arnault et al *Trends Plant Sci* 2023

Toward an agriculture of holobionts ?



Beyond the 3 identified pillars...

An agriculture of holobionts ...

A needed reconsideration of seeds and seedlings

A vertical transmission of microorganisms related to the growth conditions of the mother plant

→ **seed microbiota has consequences on the plant growth**

New Phytologist

New Phytologist (2021) **230**: 2047–2060

Research

Seed-borne, endospheric and rhizospheric core microbiota as predictors of plant functional traits across rice cultivars are dominated by deterministic processes

Junjie Guo[1], Ning Ling[1,2], Yong Li[3], Kaisong Li[1], Huiling Ning[1], Qirong Shen[1], Shiwei Guo[1] and Philippe Vandenkoornhuyse[2]

An agriculture of holobionts ...

A needed reconsideration of seeds and seedlings

→ **seed microbiota has consequences on the plant growth and susceptibility to both biotic and abiotic stresses**

www.nature.com/ismej

ISME

ARTICLE OPEN

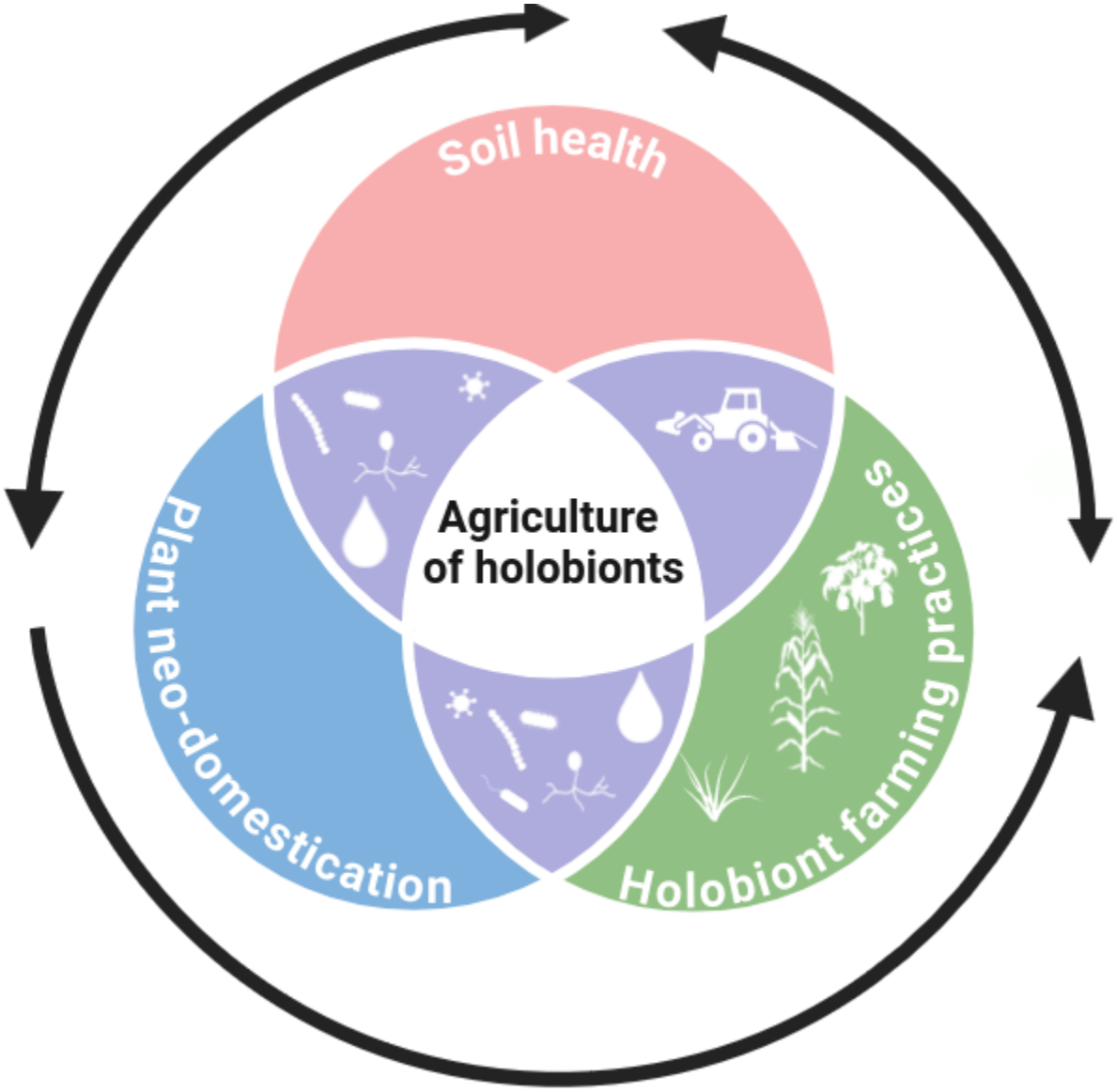
Check for updates

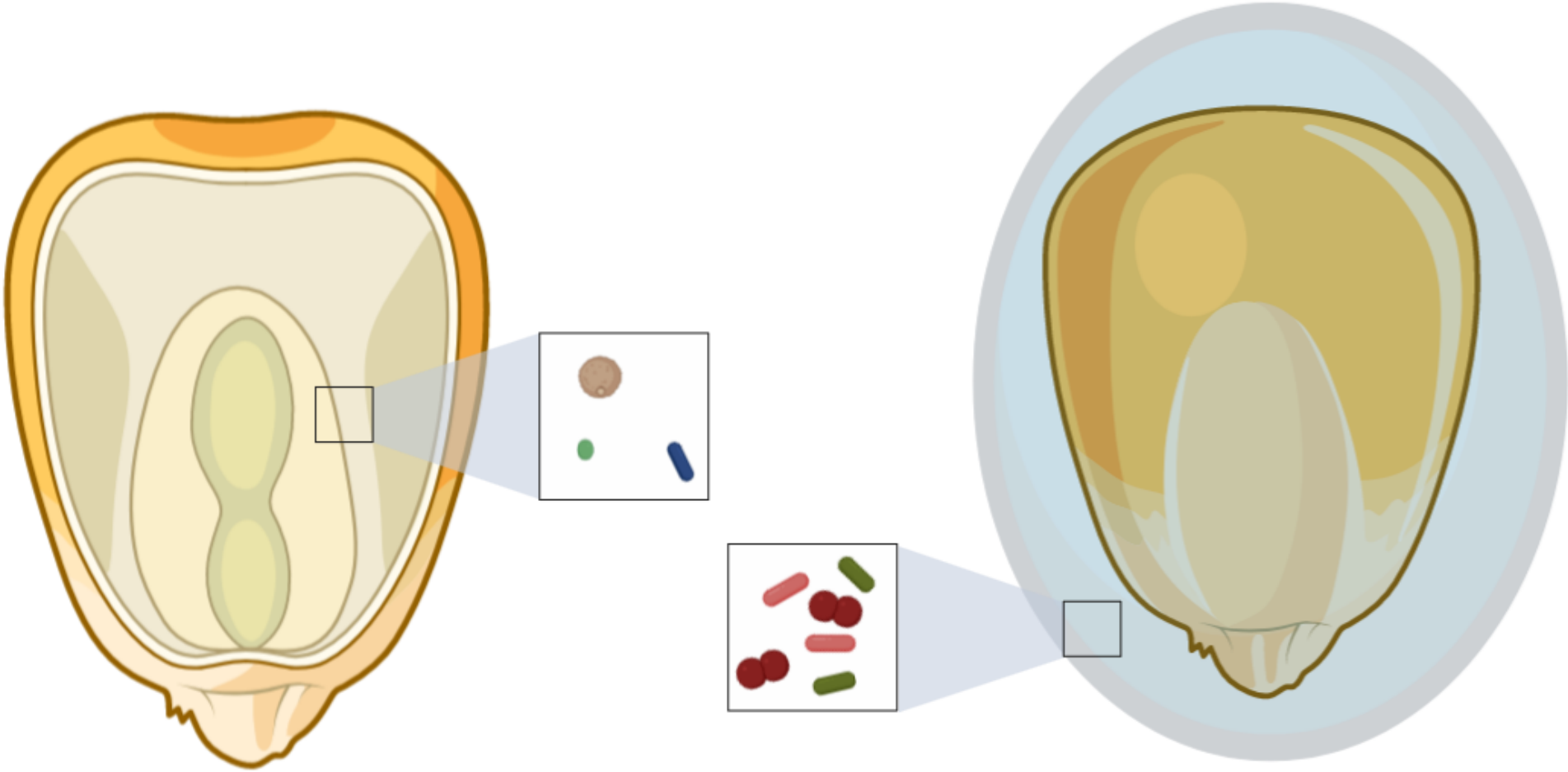
Small changes in rhizosphere microbiome composition predict disease outcomes earlier than pathogen density variations

Yian Gu[1,2], Samiran Banerjee[3], Francisco Dini-Andreote[4,5], Yangchun Xu[1], Qirong Shen[1], Alexandre Jousset[1] and Zhong Wei[1]✉

Early life interventions may have significant effects on later microbiome states

→ highlights exciting opportunities for microbiome diagnostics and plant disease prevention


Soil health
Agriculture of holobionts
Plant neo-domestication
Holobiont farming practices



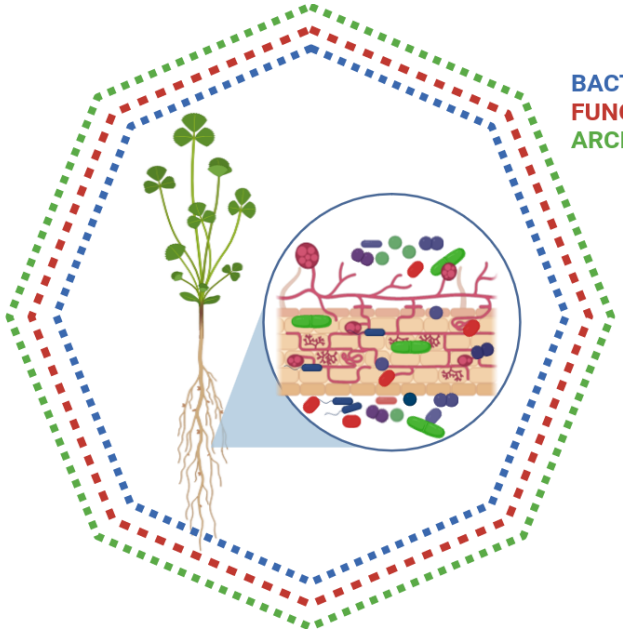
Holobiont-selected seeds

Coated holobiont-selected seed with microbial-based formulation
→ toward 'enhanced' holobiont-selected seed' ?

Université de Rennes

Many thanks

-to the Académie and to Mylène for organizing the today's scientific event
-to all the peoples that have been involved in this work in the group
-Funding bodies for past and present grants for research



Neodarwinism dogma of evolution by selection (Lewontin 1970) :

-phenotypic variation

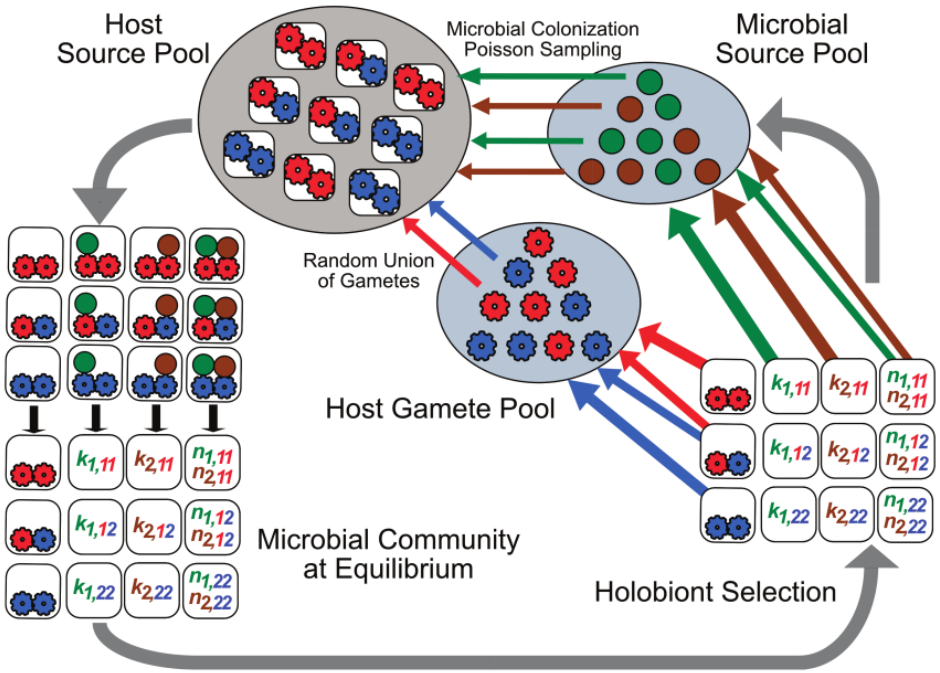
-differential fitness

-**heritable fitness**

A glimpse in genetical inheritance (population theory for the hologenome)

lineal inheritance = vertical transmission

+ 'collective inheritance' (pseudo-vertical)



e.g. Vandenkoornhuyse et al., 2015 ; Vannier *et al., Frontiers in Microb* 2015
Roughgarden *Am Nat* 2023 ; Lewontin *Ann Rev Ecol Syst* 1970

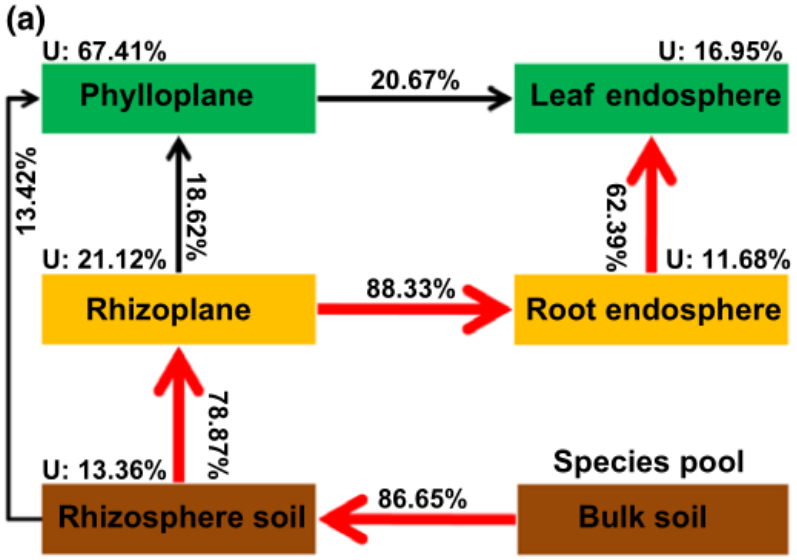
Université de Rennes

The plant microbiota : keystone for survival

Microorganisms recruitment from the soil reservoir :

=> the most important mechanism for plant survival = to buffer environmental constraints

→ Recruitment from the microbial reservoir of a single microorganism
= mobilization of a number of new genes associated to this microorganism



Vannier et al. *Frontiers in Plant Sci* 2015
Vandenkoornhuyse et al. *New Phytol* 2015; Xiong et al New Phytol 2021

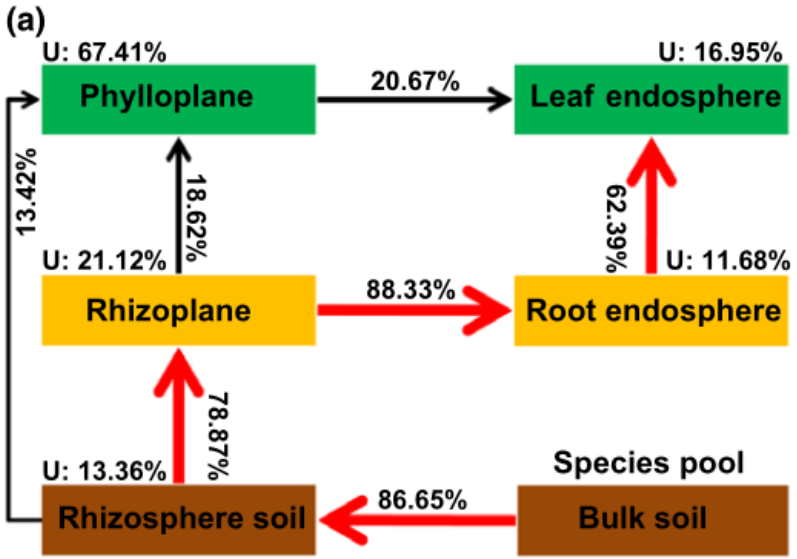
The plant microbiota : keystone for survival

Microorganisms recruitment from the soil reservoir :

=> the most important mechanism for plant survival = to buffer environmental constraints

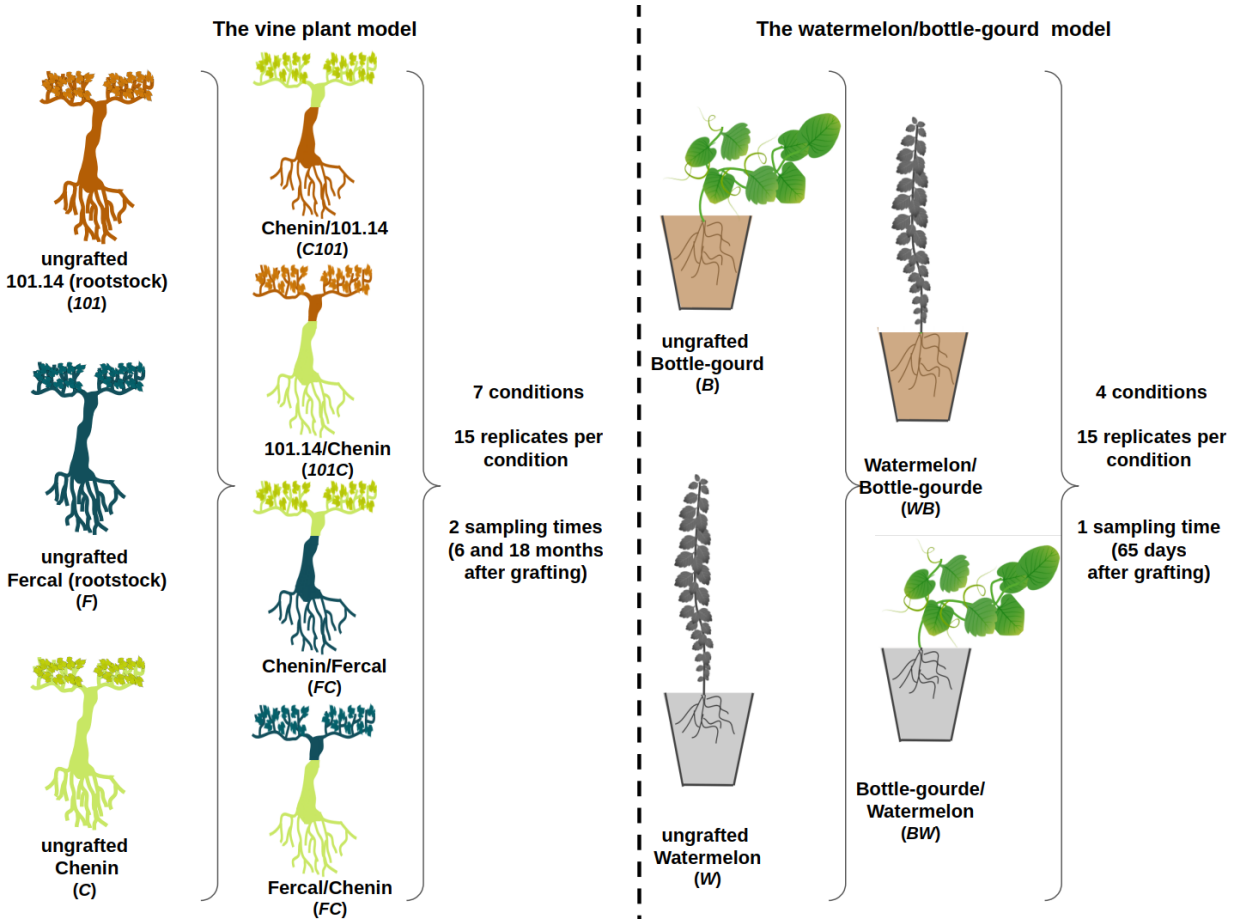
→ Recruitment from the microbial reservoir of a single microorganism
= mobilization of a number of new genes associated to this microorganism

→ Much more efficient and dynamic process than plant-genome changes with a direct effect on plant performance (fitness)



Vannier et al. *Frontiers in Plant Sci* 2015
Vandenkoornhuyse et al. *New Phytol* 2015; Xiong et al New Phytol 2021

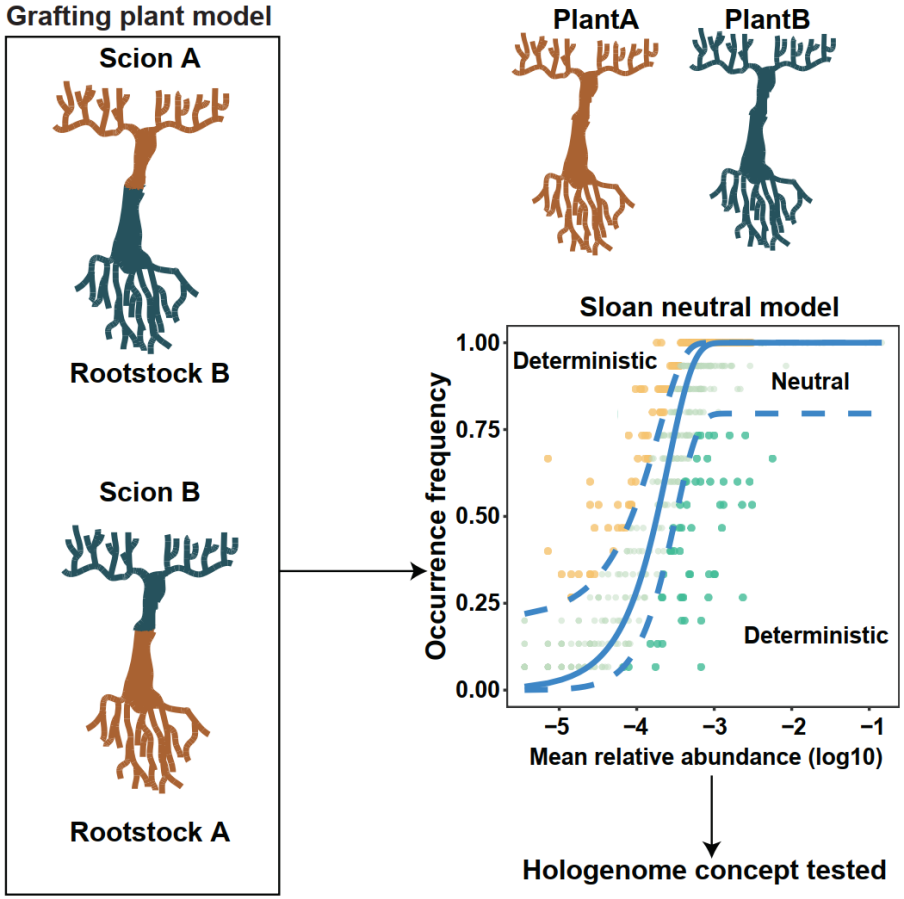
Testing the validity of the hologenome concept



- Rootstock and scion exerted a significant influence on bacterial community composition
- Rootstock exhibited the largest significant impact

Biget, Wang et al. iScience 2023

Testing the validity of the hologenome concept



The yellow bacterial taxa were more frequent than expected, and were interpreted as being actively maintained and selected by the host plant

Biget, Wang et al. iScience 2023