Breeding for within-field diversity
to promote agroecological transitions

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Wheatamix

MOBiDiv

MoBiDiv

https://mobidiv.hub.inrae.fr/

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MoBiDiv – Mobilising and Breeding intra- and inter-specific diversity for a systemic change toward a pesticide-free agriculture

Coordination Aline Fugeray-Scarbel and Jérôme Enjalbert

Financed by : CULTIVER PROTÉGER autrement

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A zero-pesticide agriculture, you said?

EU's von der Leyen backtracks on cutting pesticide use

European Commission President Ursula von der Leyen said the proposal to halve chemical pesticide use in the EU by the end of the decade had 'become a symbol of polarization.'

Le Monde with AFP

https://www.lemonde.fr/

Reporterre

Faire un don au jo

Agriculture

Réduction des pesticides : le recul du gouvernement

Le plan de réduction des pesticides Écophyto a un nouvel indicateur, a annoncé le Premier ministre le 21 février. Pour les associations écologistes, il s'agit d'un « retour en arrière ».

https://reporterre.net/Reduction-des-pesticides-le-recul-du-gouvernement

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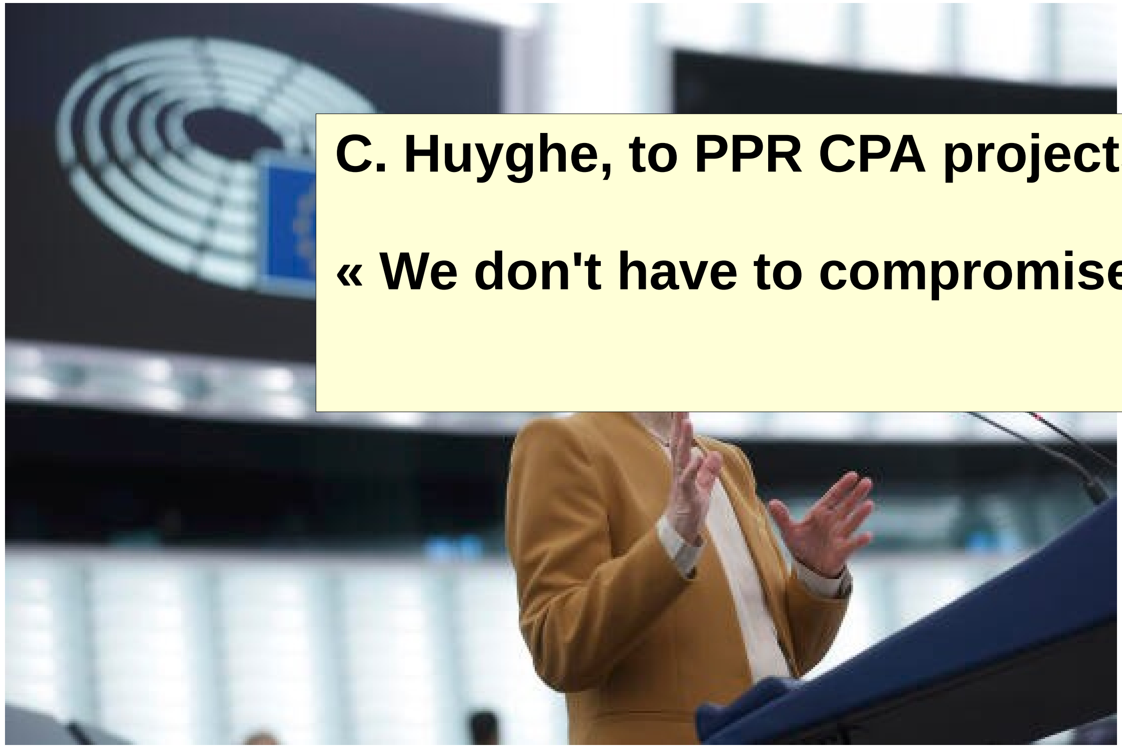

C. Huyghe, to PPR CPA projects:

« We don't have to compromise on our ambition to think ahead. »

https://www.lemonde.fr/

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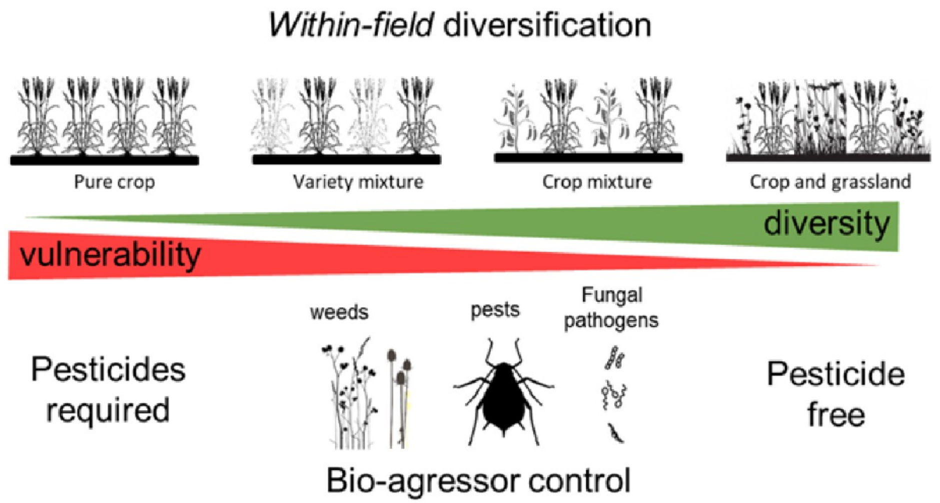
MoBiDiv – Mobilising and Breeding intra- and inter-specific diversity for a systemic change toward a pesticide-free agriculture

Coordination Aline Fugeray-Scarbel and Jérôme Enjalbert

- Central principle in agroecology: mobilizing **crop diversity within fields** boosts the natural regulations and allows avoiding the use of pesticides

- Objective : create methods and tools to breed, mix, register and evaluate varieties for a pesticide-free agriculture

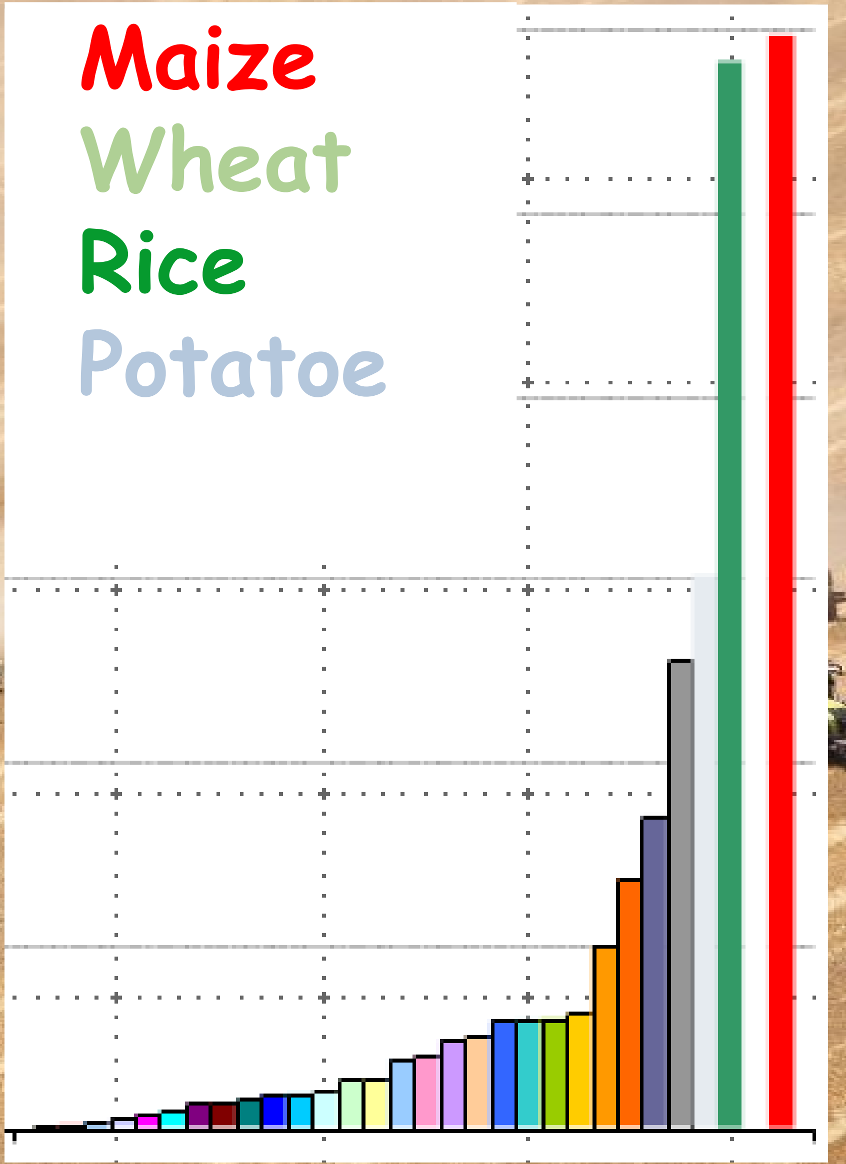


Evolution of crop diversity

Agriculture in industrialized countries

- Simplification / Uniformization
- Mecanization – Intensification

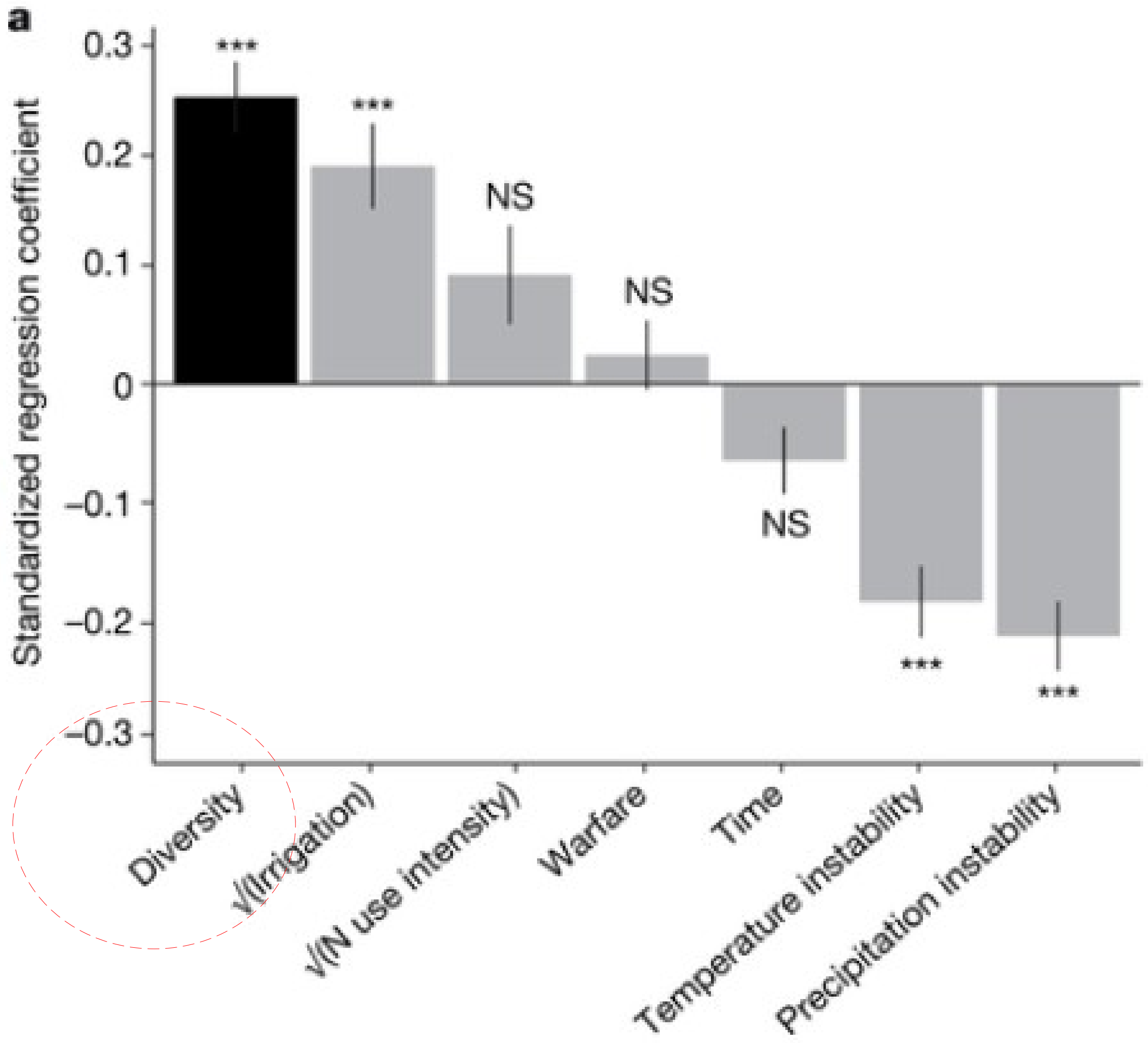
Evolution of crop diversity



→ Few crops feed the world
→ Crop biodiversity is decreasing...


MATTHEW McCONAUGHEY
ANNE HATHAWAY
JESSICA CHASTAIN
MICHAEL AND CAINE
MANKIND WAS BORN ON EARTH. IT WAS NEVER MEANT TO DIE HERE.
FROM THE DIRECTOR OF THE DARK KNIGHT TRILOGY AND INCEPTION
INTERSTELLAR
IN THEATRES AND IMAX
EVERYWHERE
NOVEMBER 7
LEGENDARY
interstellarmovie.com
#interstellar

Crop diversity is a critical leverage toward resilience and sustainability



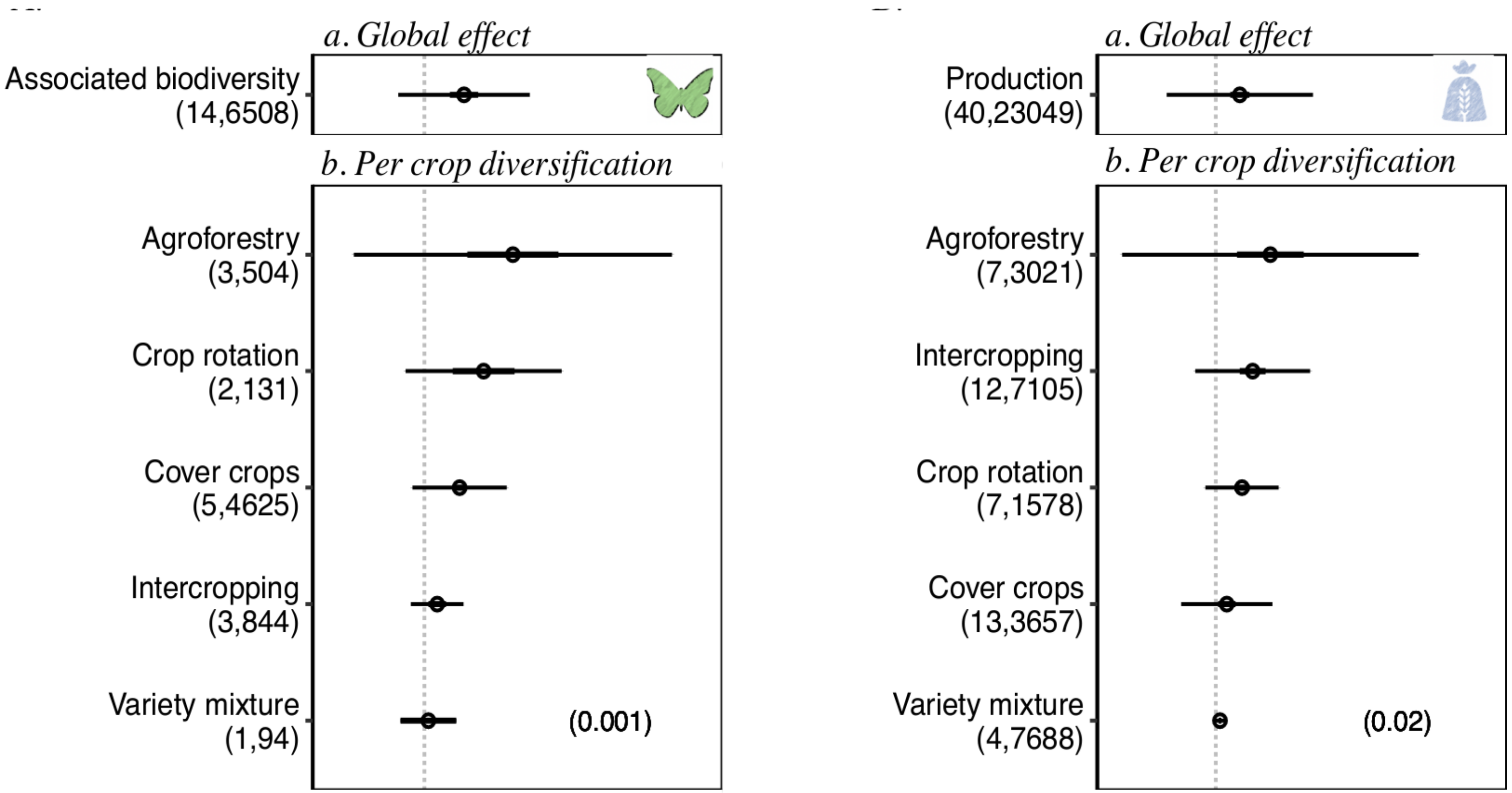
- Annual yields - FAO
- 50 years
- 176 crop species
- 91 nations

Renard and Tilman 2019

→ National food production is stabilized by crop diversity

Leverages for the agroecological transition

→ **Substitute pesticides by natural regulations**



Beillouin et al. 2021

- Diversification as a critical leverage for agroecological plant protection

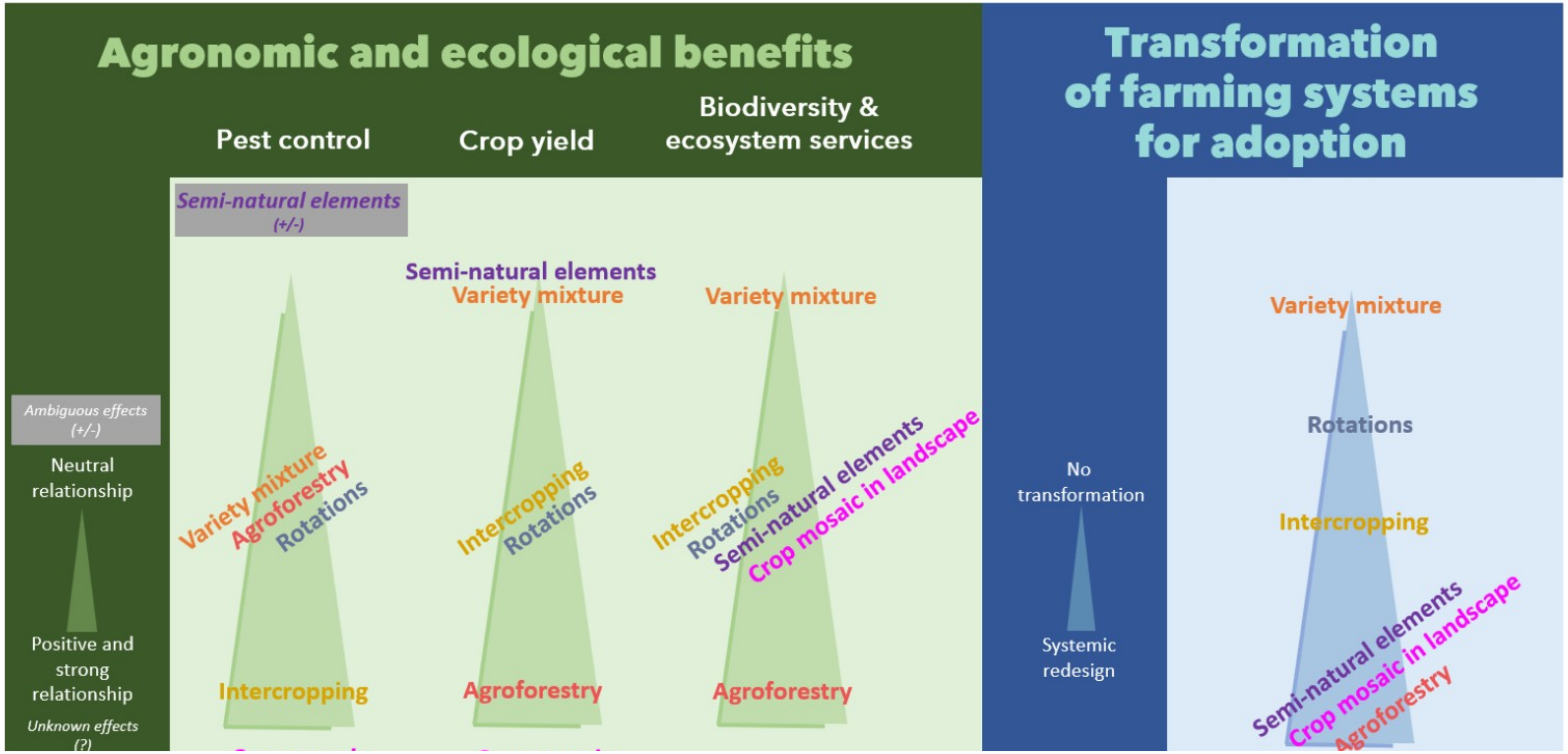
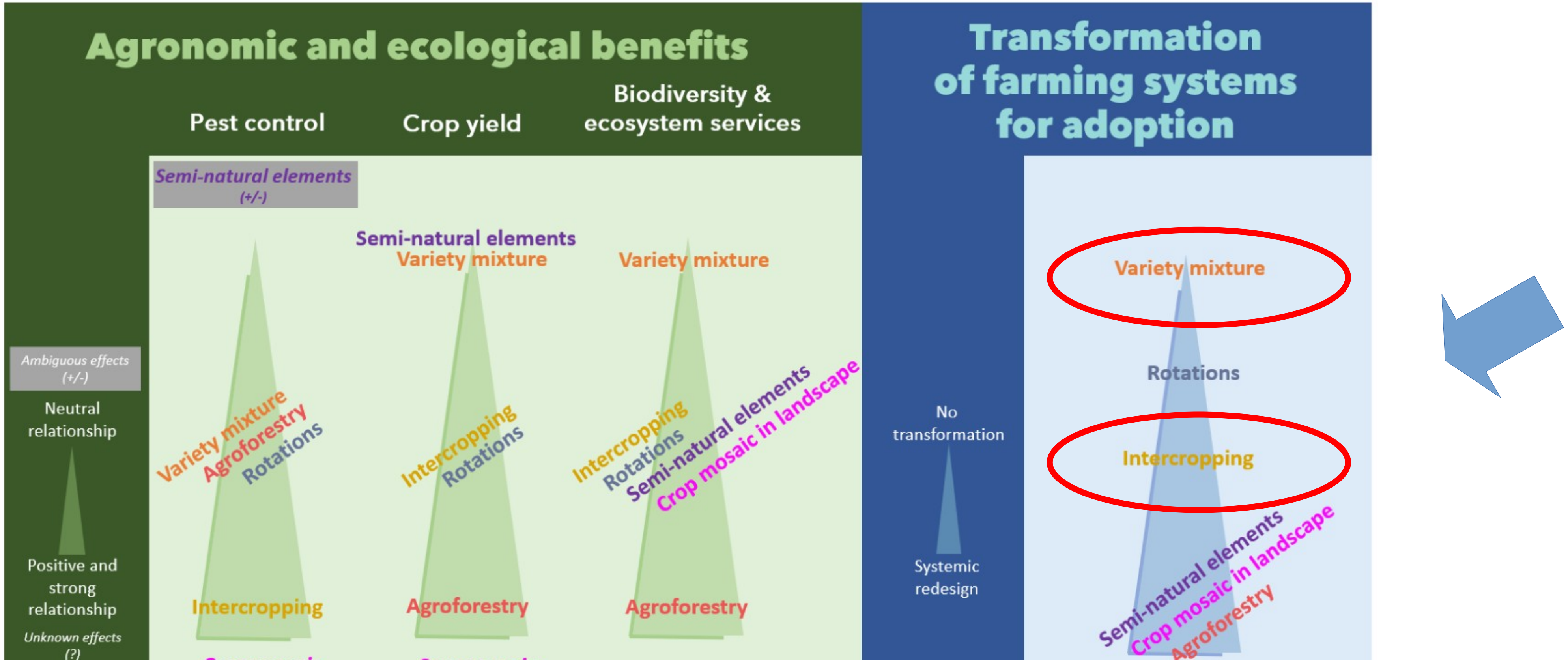


Figure 2: Classification of the different diversification options according to (i) the agronomic and ecological benefits (pest control, crop yield, biodiversity and ecosystem services), and (ii) the level of transformation of farming system required for their adoption (the lower in the Figure, the higher the benefits or the required transformations)

INRAE collective scientific assessment, Vialatte et al. (2023)

- Diversification as a critical leverage for agroecological plant protection



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1) Mixing to control of pest and diseases: the mecanisms

2) Why and how to breed for performance in mixture

3) Participatory Breeding, a critical asset to face diversification

4) Conclusion

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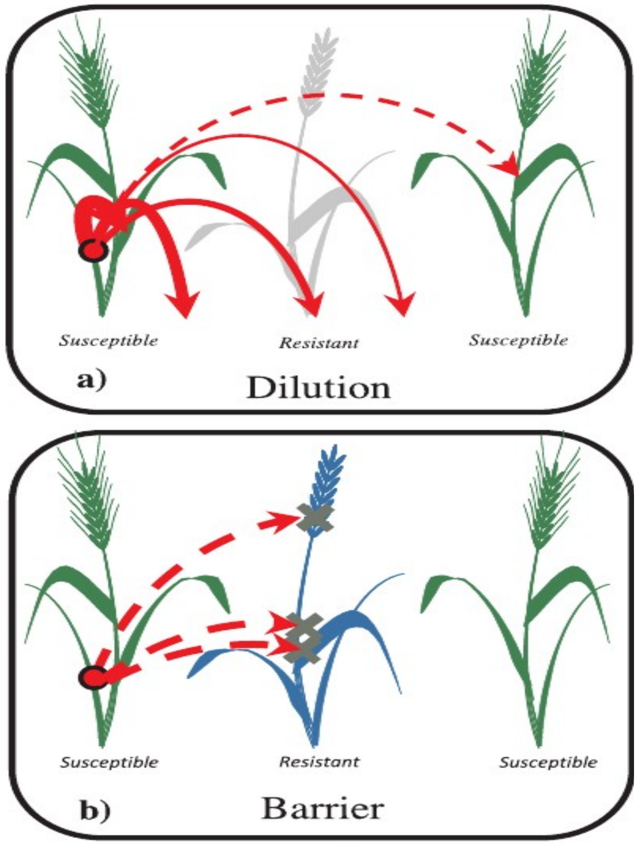
The paradigm of (genetic) homogeneity

A typical field in conventional agriculture:
1 species, 1 genotype → no diversity → **higher pest/disease**

Variety mixtures and disease control: The mechanisms

- **Well known effect on diseases** (Wolfe 1985)

- **Mechanisms :**
  - Dilution / Barrier



Borg et al. (2018)

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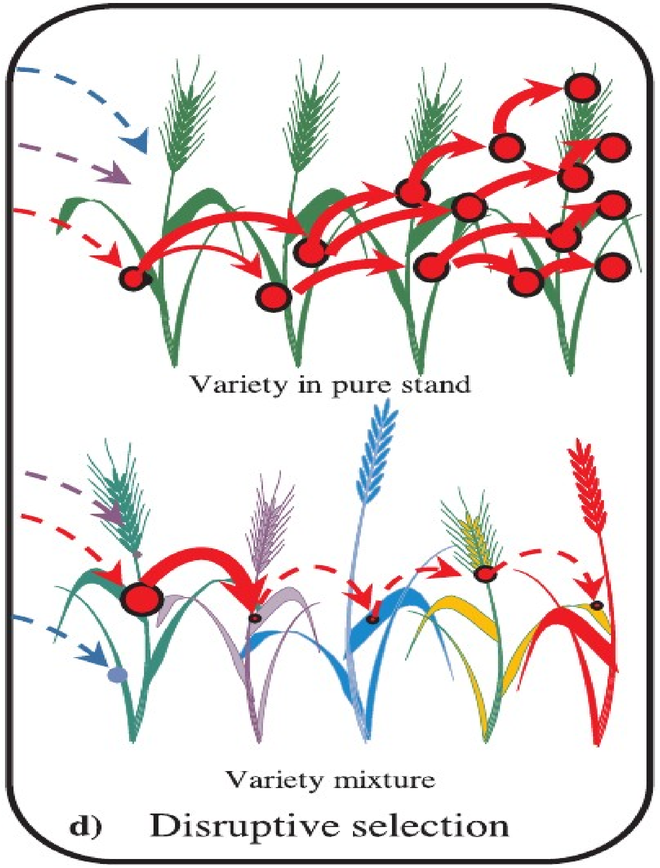

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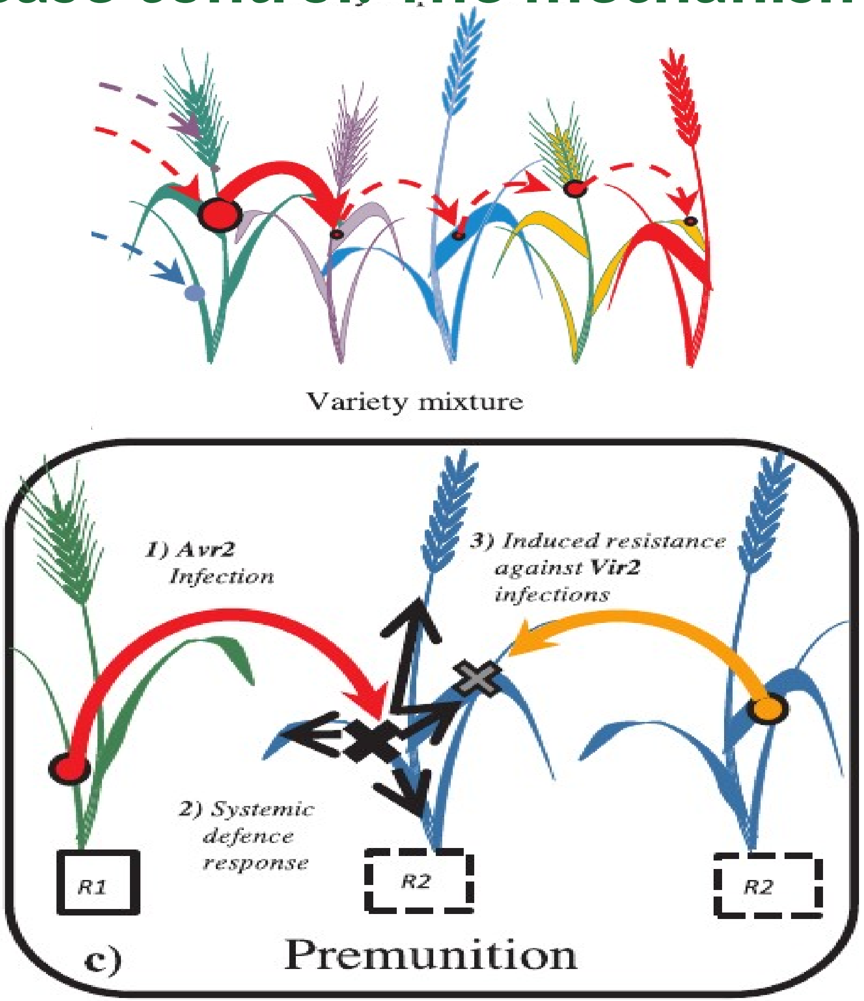

Borg et al. (2018)

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  - Premunition
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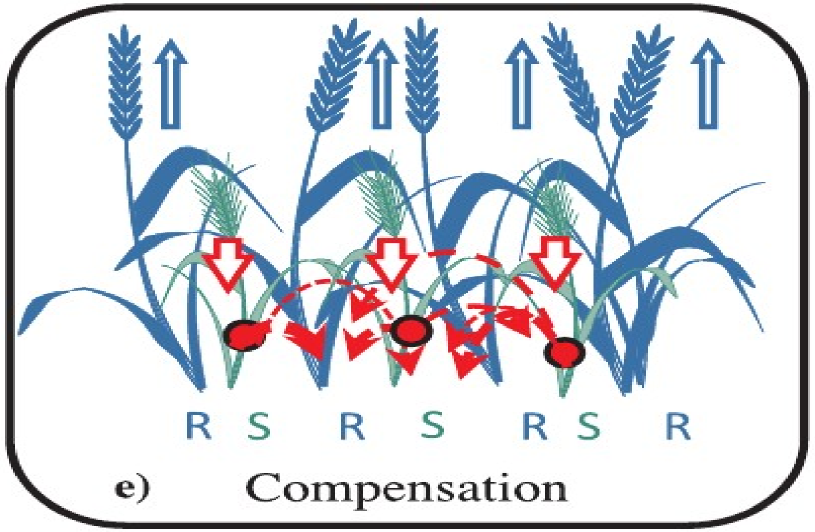

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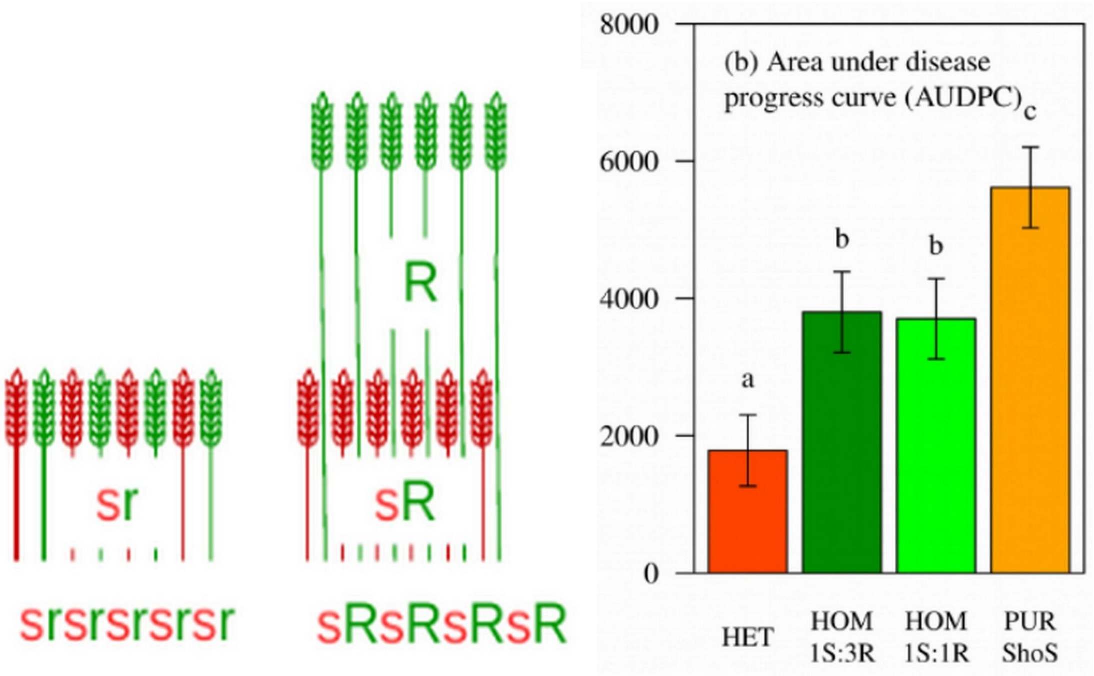
  - Combining Resistance / Architecture traits



Vidal et al. (2019)

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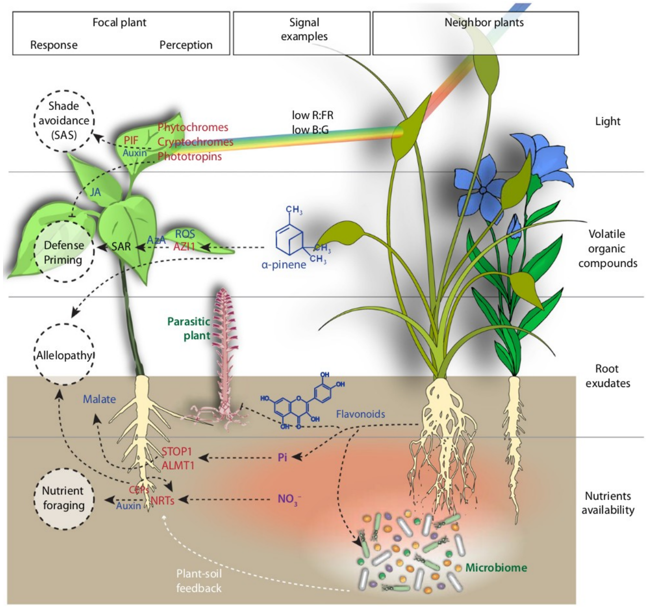
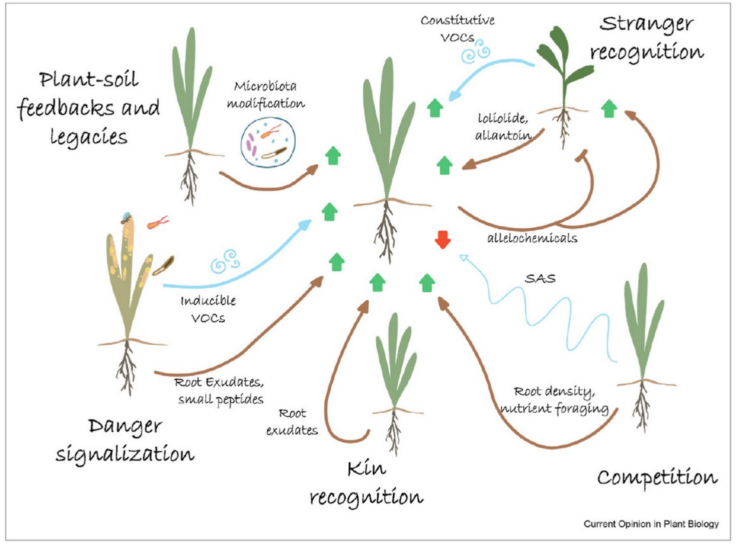


Subrahmaniam et al (2018)



Pelissier et al. (2021)

Variety mixtures and disease control: The mechanisms

- **Well known effect on diseases** (Wolfe 1985)

- **Mechanisms well studied :**
  - Dilution / Barrier
  - Disruptive selection
  - Premunition
  - Compensation
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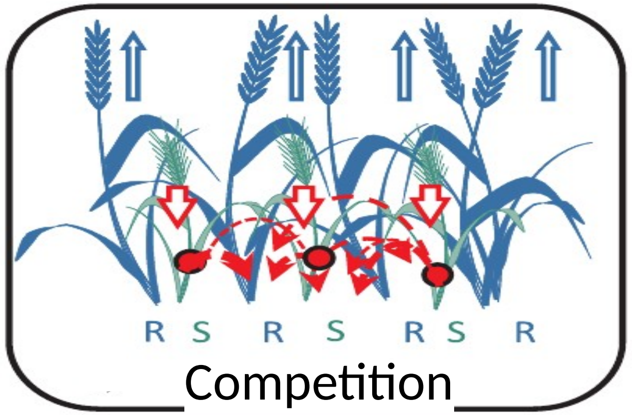
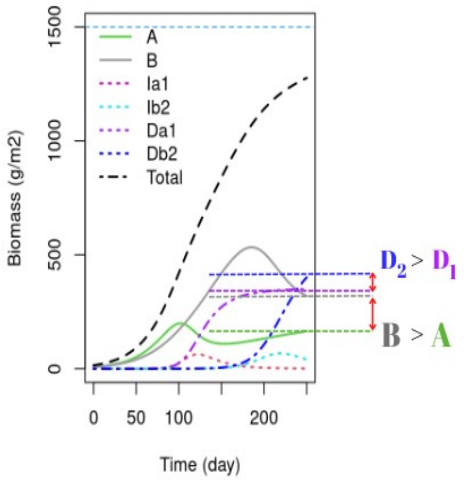
  - Neighbor-Mediated Susceptibility
  - Host competition and pathogen virulence evolution





A. Fesquet et al., in prep / Project COMBINE

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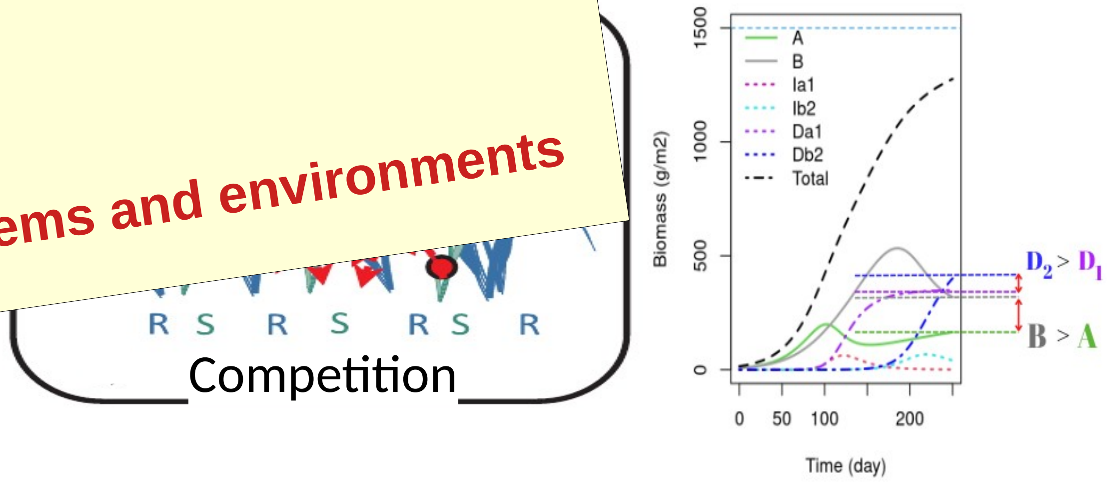
CAUTION !

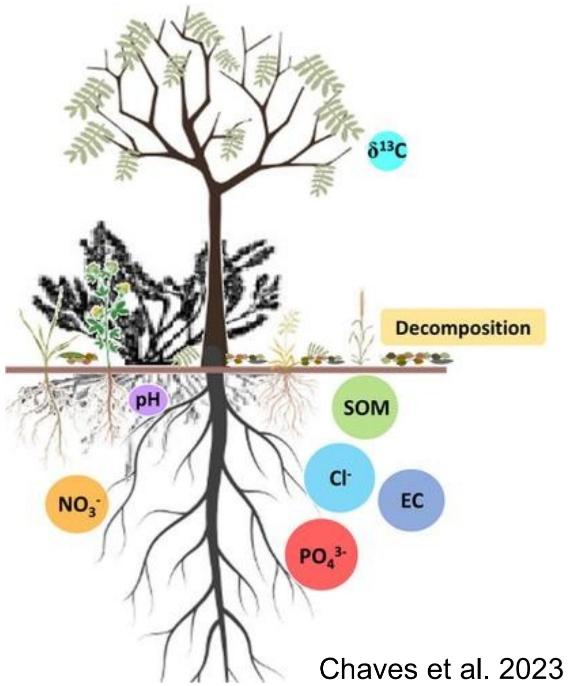
Mechanisms depending on pathosystems and environments



A. Fesquet et al., in prep / Project COMBINE

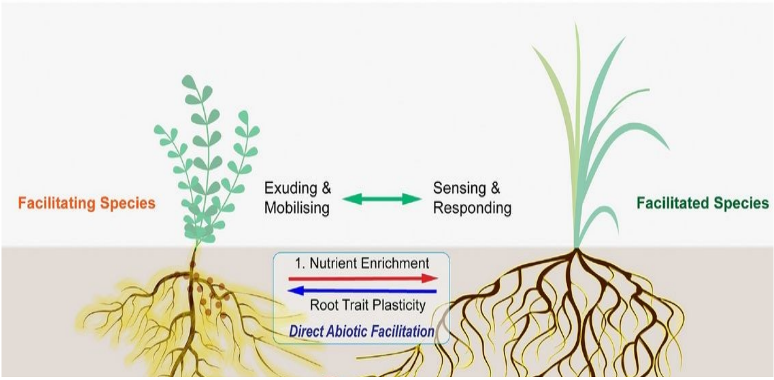
Biodiversity-Ecosystem Functions: the ecological mechanisms

- Niche complementarity



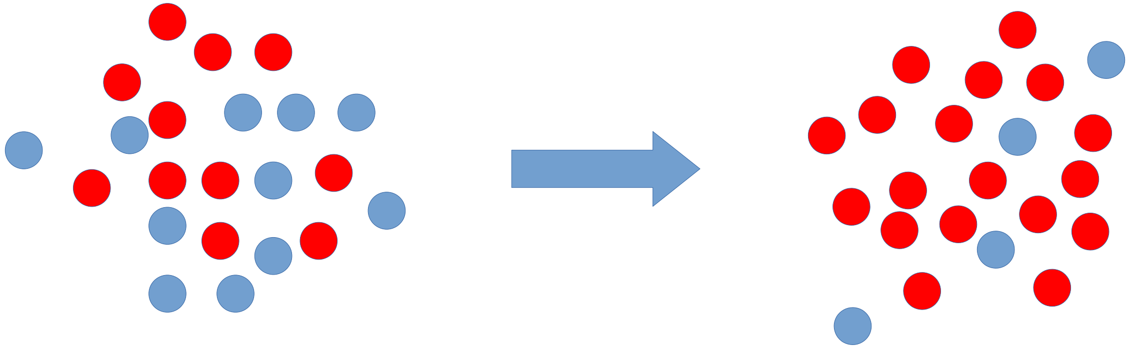
Chaves et al. 2023

- Facilitation



Yu et al. 2021

- Selection



Barot et al. *(2017)*

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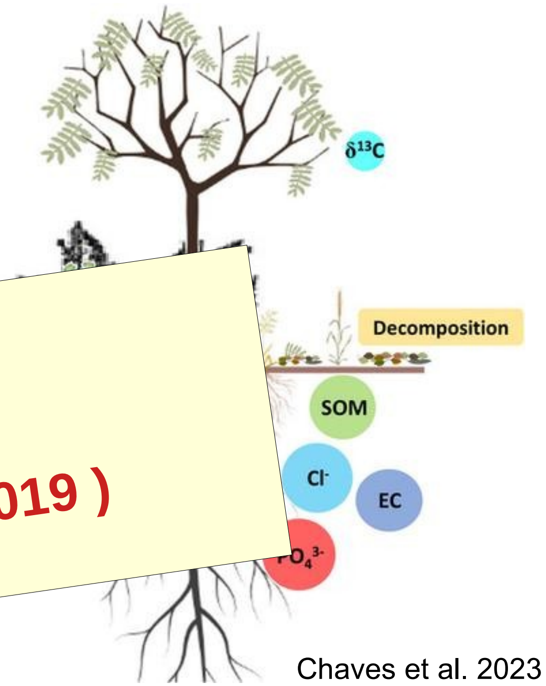

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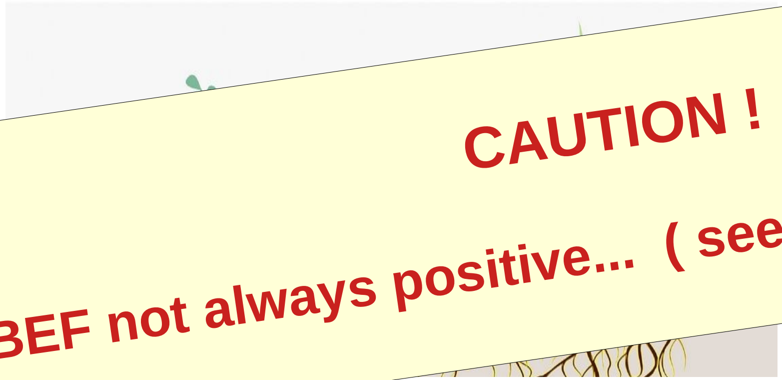
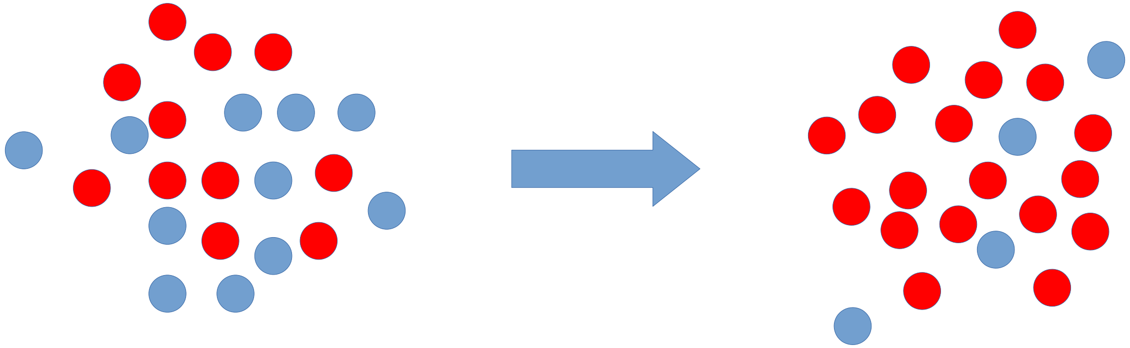


Yu et al. 2021

CAUTION !

BEF not always positive... (see van der Plas 2019)

- Selection



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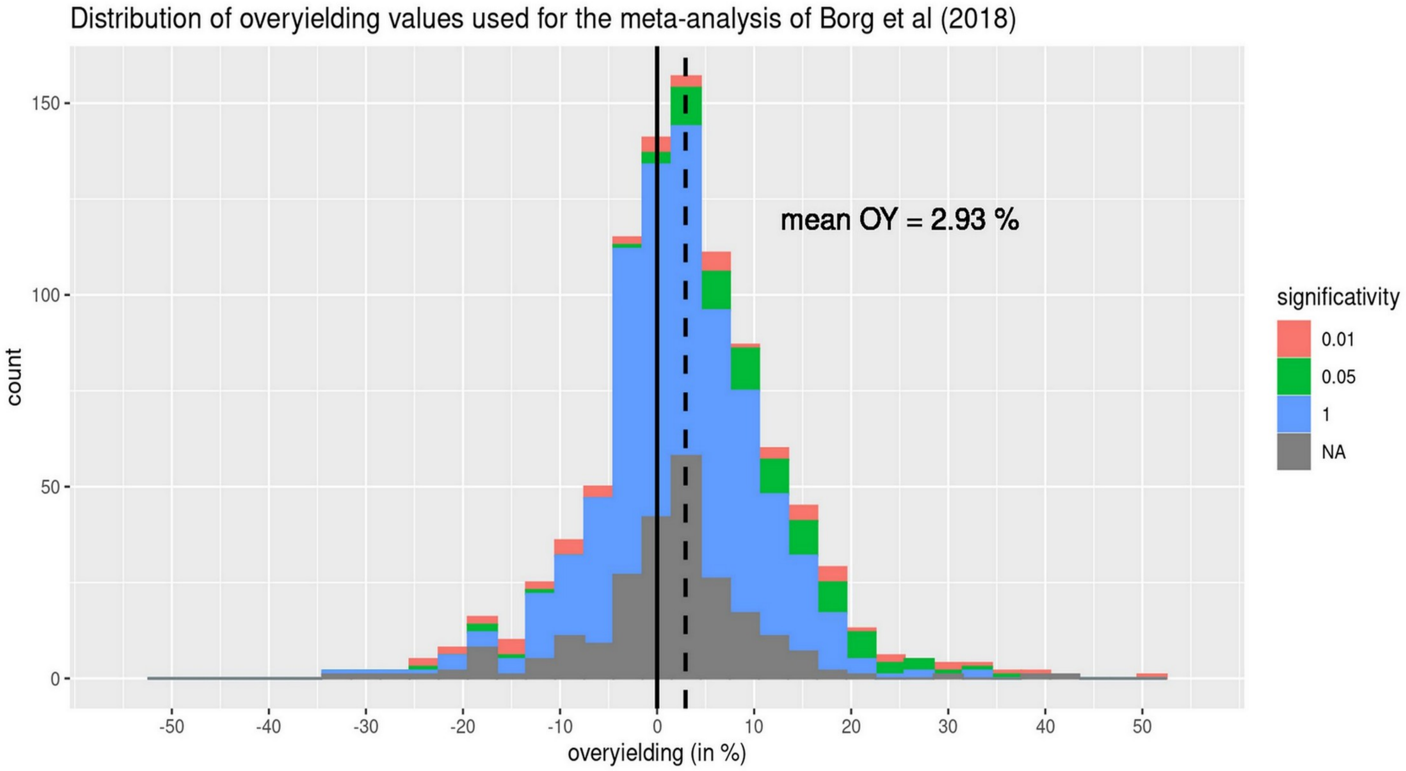
Mixtures' performances

- **Wheat variety mixtures**
  - **Stabilize yield** (Reiss & Drinkwater 2019)
  - **Overyielding in 70% of the trials**
    - but modest mean increase : 3%
    - Higher if disease impact (6%)
  - **But strong variations**
    +/- 40% of overyielding!

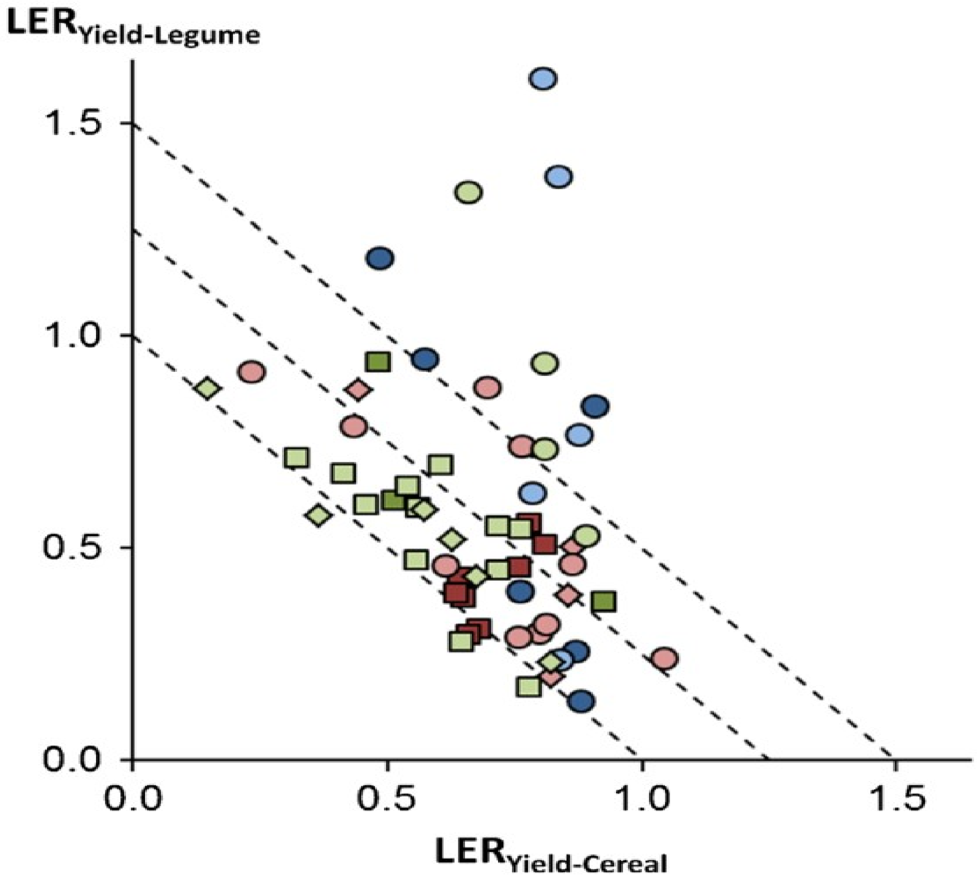


Borg et al. 2018

Mixtures' performances

- **Cereal-Legume Intercropping**
  - **Strong overyielding (20% LER)**
  - **Almost as productive as the best component, and under low-input**

Li et al. (PNAS 2022)



Bedoussac and Justes (2015)

Potential of crop mixtures to reduce pesticide use in France. A data analysis.

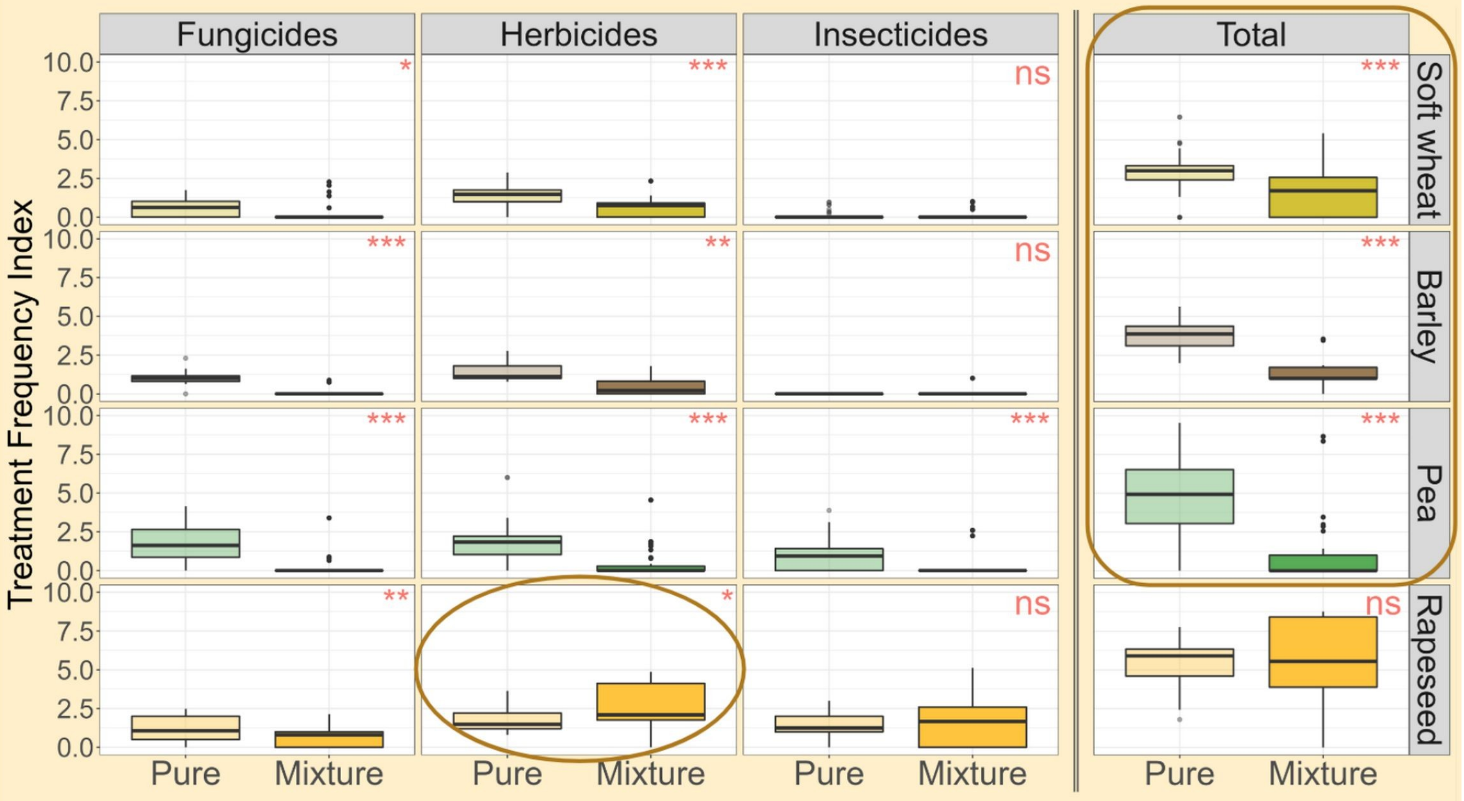
Elodie Yan[1], Marco Carozzi[1], Nicolas Munier-Jolain[2], Philippe Martin[1]

[1] Université Paris-Saclay, INRAE, AgroParisTech, UMR SADAPT, F-91120, Palaiseau, France. Contact : elodie.yan@inrae.fr

[2] Université Bourgogne-Franche-Comté, INRAE, Institut Agro Dijon, UMR Agroécologie, F-21000, Dijon, France

Mixtures' performances

- **Cereal-Legume Intercropping**
  - **Strong overyielding (20% LER)**
  - **Almost as productive as the best component, and under low-input**
  - **Positive impact on quality**
  - **Strong decrease in pesticide use**



TFI comparison for fungicides, herbicides, insecticides and all pesticides on soft wheat (44 pairs), barley (16), pea (84) and rapeseed (45) when in pure crop or in mixtures

MOBIDIV

Yan et al. (2023)

Mixtures' performances : varietal choice matters !

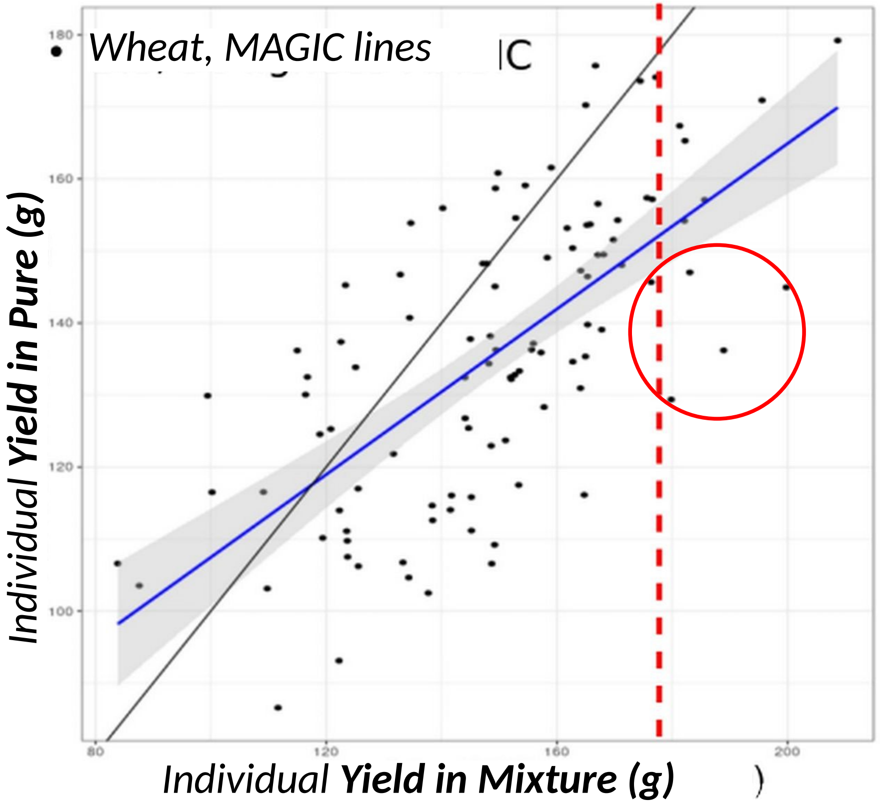
- **Varieties impact mixture preformance** *Demie et al. (2022)*

  → Loose correlation between performance in pure vs. mix

-

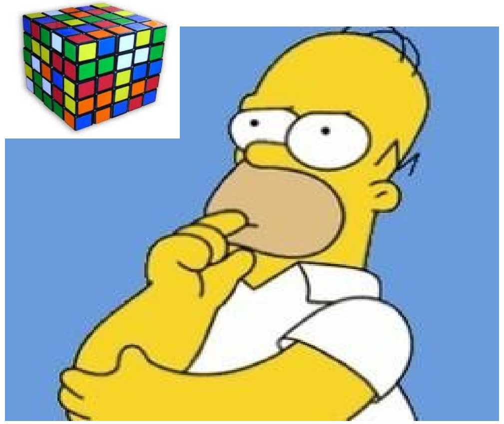
→ Breeding for mixing ability is promising

(don't rely on varieties bred for pure stand performance !)



Rémerand et al. in prep

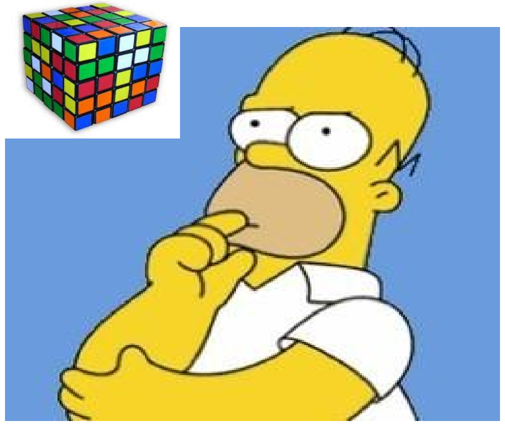
Breeding for mixing ability



- **But breeding for mixtures is a nightmare…**
  → curse of combinatorics

→ more 5-way wheat mixtures than stars in our Galaxy

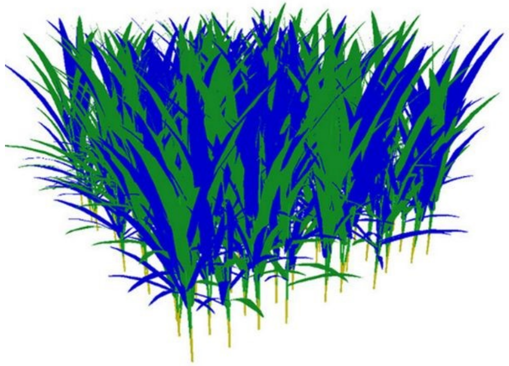
Breeding for mixing ability



Two strategies :

- ***Trait-blind approaches: Mixing Ability***
  - Non sorted components: GMA & SMA (ex. var. mixtures)
  - Sorted components : Pr & As (ex. species mixtures)

- ***Trait-based approaches: ecophysiological modeling***
  - Modeling of plant-plant interactions (ex. var. mixtures)



I/ Breeding for mixing ability

A/ Group Performance (yield in mixture)

<u>Estimate Mixing Ability of varieties</u> : GMA/SMA Model (Variety Mixtures)

Evaluation of a panel of genotypes in binary mixtures

	G1	G2	G3	G4	G5
G1	Y_{11}	Y_{12}	Y_{13}	Y_{14}	Y_{15}
G2		Y_{22}	Y_{23}	Y_{24}	Y_{25}
G3			Y_{33}	Y_{34}	Y_{35}
G4				Y_{44}	Y_{45}
G5					Y_{55}

SMA_{12}

→ GMA_1

GMA_1 : General Mixing Ability
Mean performance in mixture

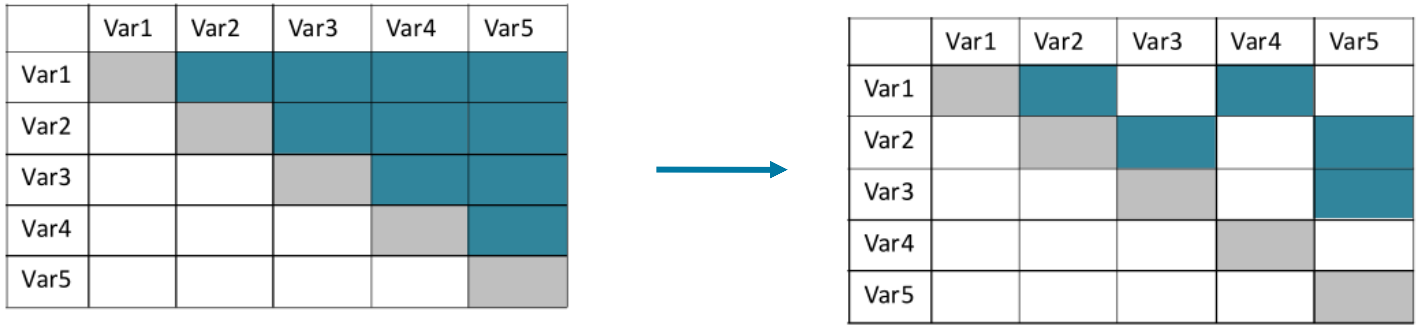
SMA_{12} : Specific Mixing Ability
Interaction term

$$Y_{12} = \mu + \tfrac{1}{2}(GMA_1 + GMA_2) + SMA_{12}$$

Broadening the GMA-SMA models

Emma Forst,
I. Goldringer
T. Mary-Huard
C. Ambroise,
S. Robin

<u>The trick: Use of incomplete designs</u> *!*



Complete design   Incomplete design

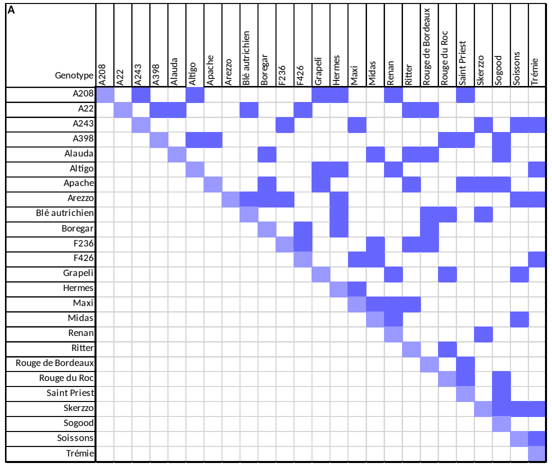
→ **Development of <u>mixed models</u>, variance components framework :**

- ✓ Estimation of variances: σ_{GMA}^2 and σ_{SMA}^2 **(REML procedure)**
- ✓ Prediction of the GMA and SMA values (**BLUP**)

→ Generalization of quantitative genetics of hybrid breeding

* More than 2 components   * any proportion allowed

Application on binary mixtures



Emma Forst,
I. Goldringer
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C. Ambroise,
S. Robin

- Use of a diversified panel: ***25 genotypes***

  Elites varieties, organic varieties, landraces, INRA lines
- Mixtures design: ***75 binary mixtures***

→ Correlation between mixtures / pure stand components yield: **0.51**

→ Correlation between observed *vs* predicted (based on GMA-SMA) mixture yield: **0.88**

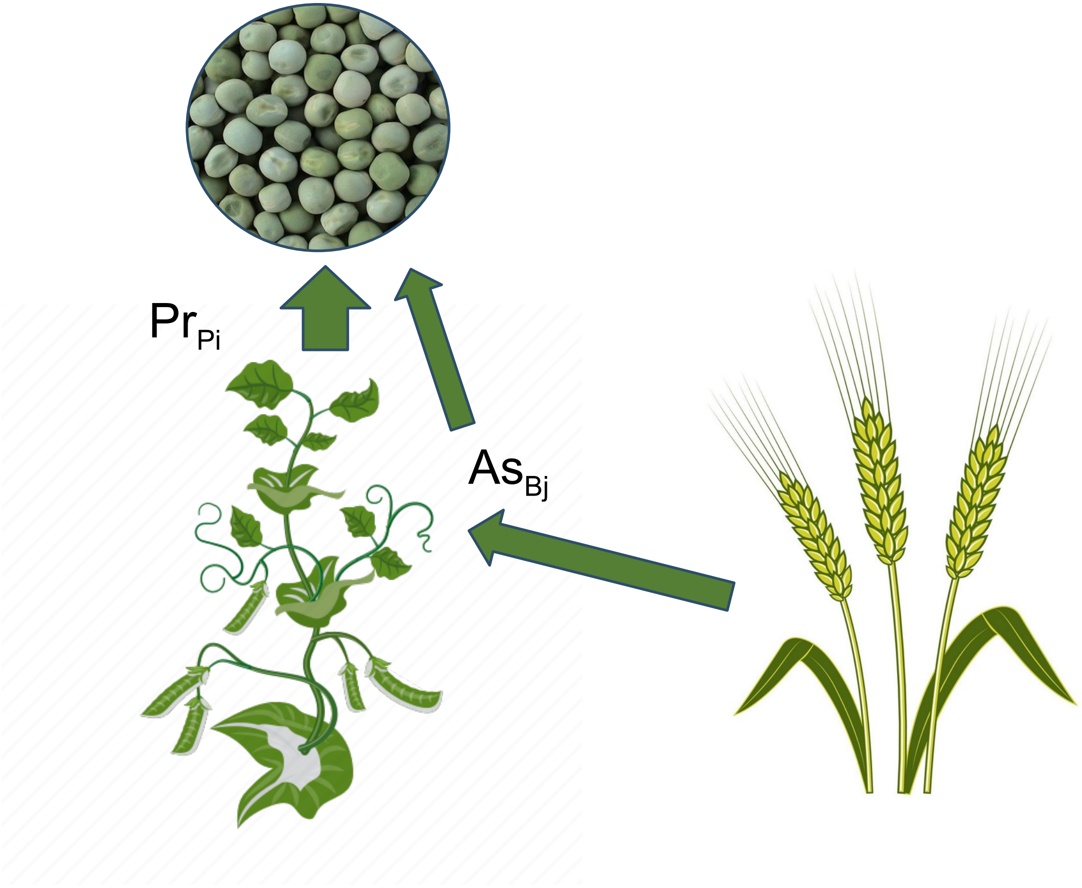
→ A useful model to breed for mixing ability

I/ Breeding for mixing ability

B/ Access to individual performance in mix

Pea production in Pea/Barley mixture:

$$E[x_{Pi/Bj}] = \mu_P + Pr_{Pi} + As_{Bj} + Pr{*}As_{Pi/Bj}$$



- Pr_{Pi}: **<u>produceur</u>** effect
- As_{Bj}: **<u>associate</u>** effect
- $Pr{*}As_{Pi/Bj}$: specific pea/barley interaction

Haug et al. (2021)

FiBL

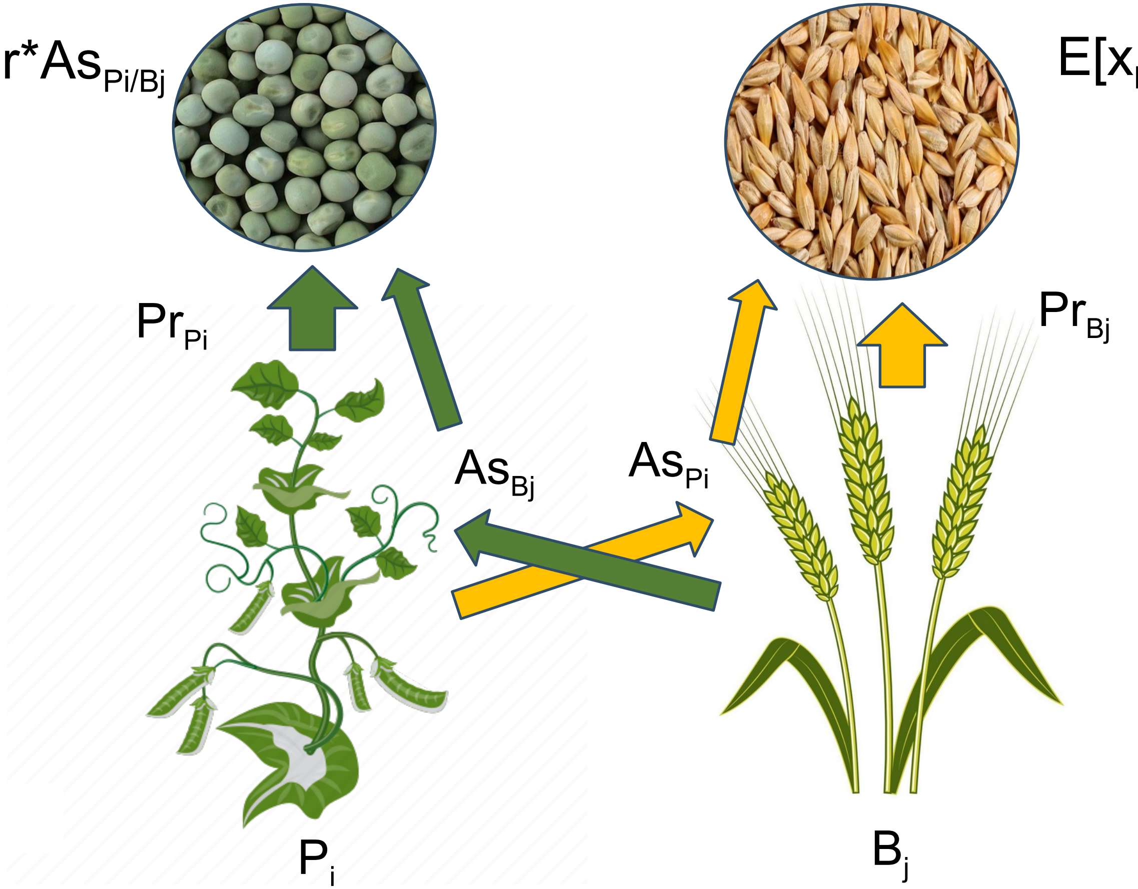
B ; Haug

I/ Breeding for mixing ability

B/ Access to individual performance in mix

$E[x_{Pi/Bj}] = \mu_P + Pr_{Pi} + As_{Bj} + Pr{*}As_{Pi/Bj}$

$E[x_{Bi/Pi}] = \mu_B + Pr_{Bj} + As_{Pi} + Pr{*}As_{Bj/Pi}$



Haug et al. (2021)

FiBL

B ; Haug

Experimental design

- 32 pea genotypes and 8 barley genotypes
- 2 sites and 2 seasons

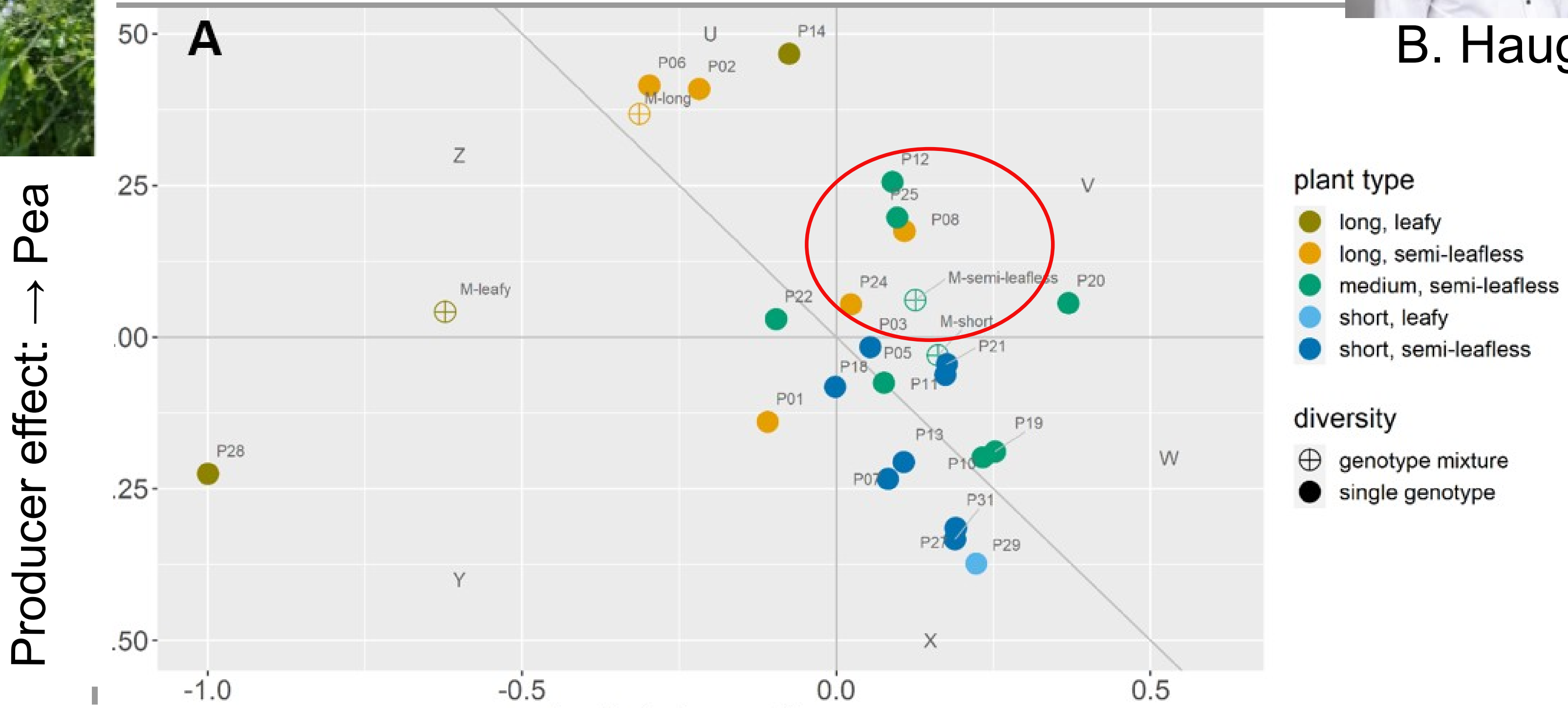
	peas	P01	P02	P03	P04	P05	P06	P07	P08	P09	P10	P11	P12	P13	P14	P15	P16	P17	P18	P19	P20	P21	P22	P23	P24	P25	P26	P27	P28	P29	P30	P31	P32
barleys	No barley (pure stand pea) / No pea (pure stand barley)	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
B1	1	1				1					1				1					1			1				1			1			
B2	1	1					1			1						1		1					1						1		1		
B3	1				1	1				1					1						1	1				1						1	
B4	1			1					1				1				1	1						1					1			1	
B5	1				1			1				1		1					1					1				1					1
B6	1		1				1					1		1							1	1				1					1		
B7	1		1					1			1						1		1						1		1						1
B8	1			1					1				1			1				1					1			1		1			

FiBL

Haug et al. 2023

Barley-pea mixture: measuring Prod/Asso effects

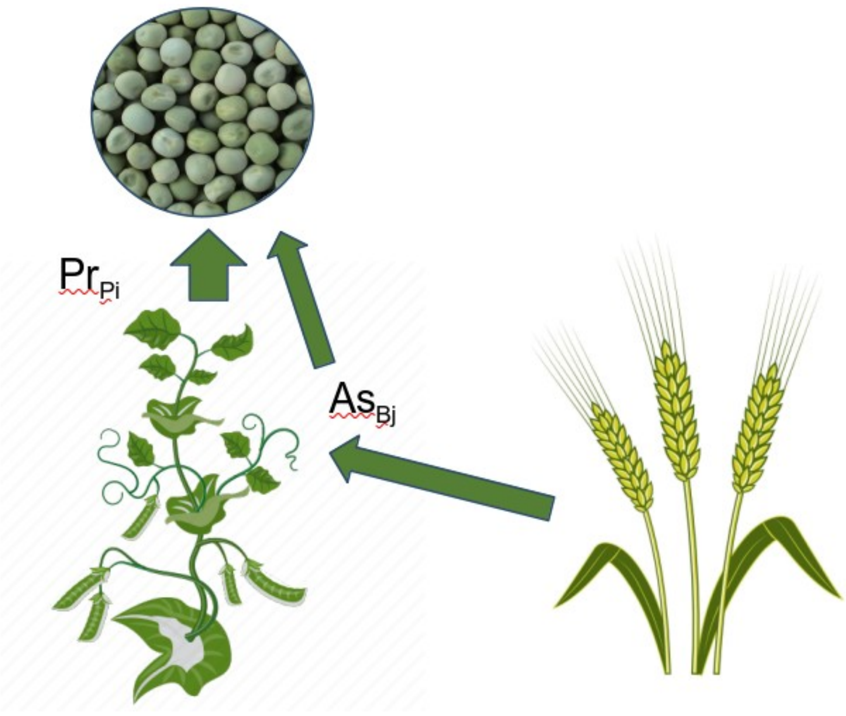
B. Haug



- Negative correlation Pr/As
- But some Pr+/As+

→ Breeding for Producer AND Associate effects seems promising

New breeding methods for intercropping

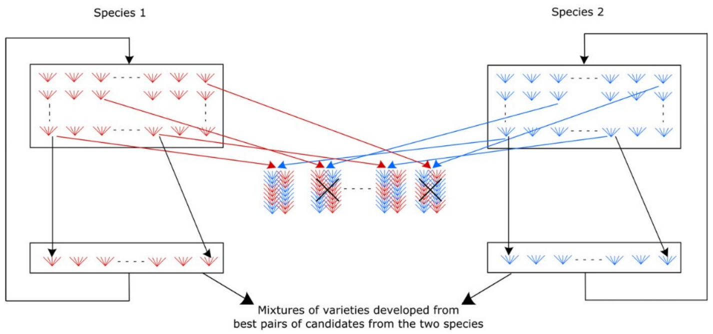


→ Strong effect of Associate (IGE) effects on heritability and breeding

→ Design of new breeding schemes : reciprocal / genomic selection

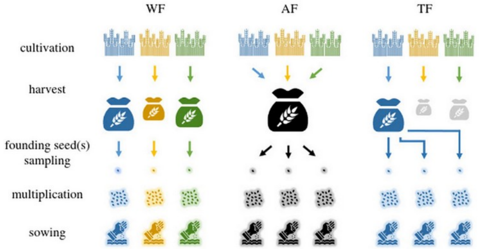
Sampoux et al. (2019)

Bančič et al. (2021)



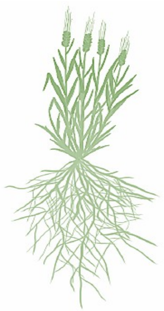
→ Group selection and composite populations

Montazeaud et al. (2020)

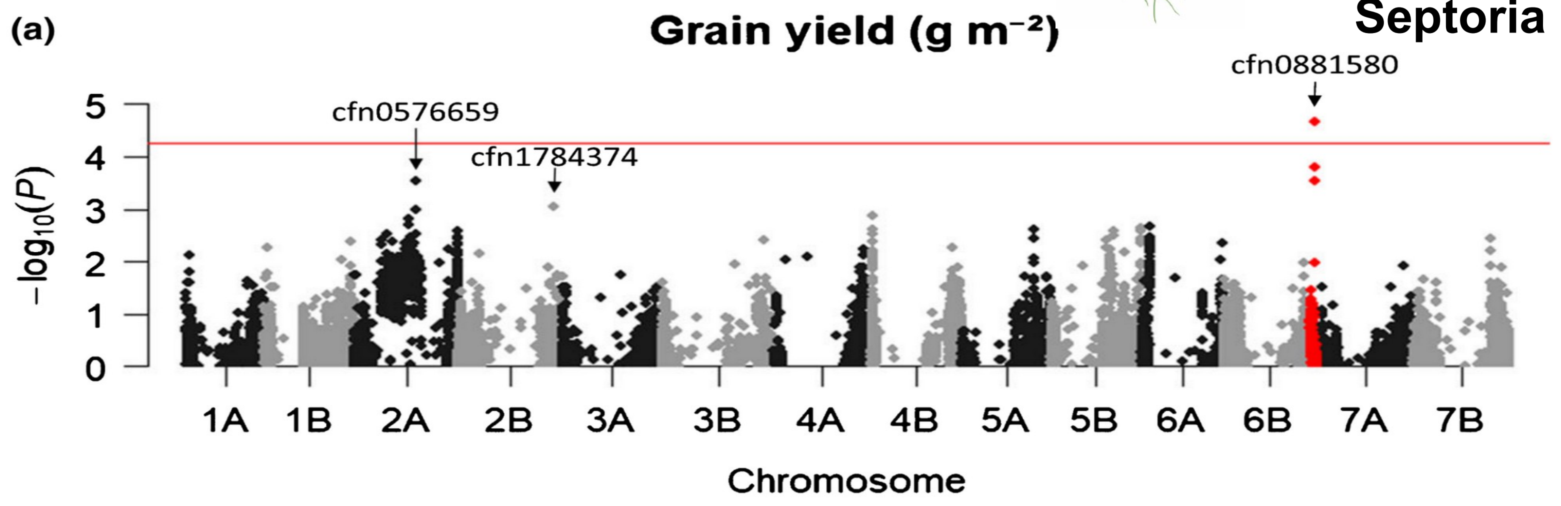


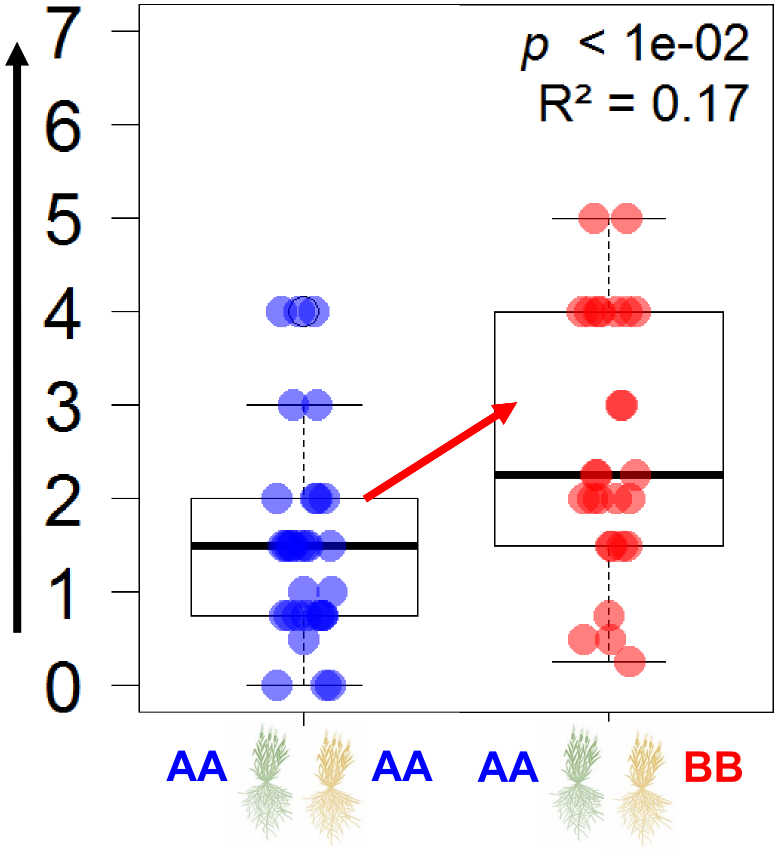
Decifering genes behind plant-plant interactions

GWAS approach used on mixtures in few species so far (teams of S. Wuest, F. Roux,…)
Experiment : ~350 pairs of lines (Durum Wheat - AGAP)



Septoria





Montazeaud et al, 2022

When neighbors do not share the same allele, the disease increases

II/ Traits based : Trait → Function → Service

→ **Ideotyping: designing varieties by trait assembly** (Donald 1968)

- **Ecophysiology: strong knowledge on plant interactions with the environment**
- **Increasing work on plant-plant interactions**

II/ Traits based : ideotyping varieties

- **Ex. 1: Wheat Mixtures**

→ **Tillering: a critical process for plant-plant interactions**

II/ Traits based : ideotyping varieties

- **Ex. 1: Wheat Mixtures**
  - 3D FSPM model of bread wheat
  - Centred on tillering dynamics & competition for light
  - Individual Based Model

WALTer: a three-dimensional wheat model to study competition for light through the prediction of tillering dynamics FREE

Christophe Lecarpentier, Romain Barillot, Emmanuelle Blanc, Mariem Abichou, Isabelle Goldringer, Pierre Barbillon, Jérôme Enjalbert, Bruno Andrieu

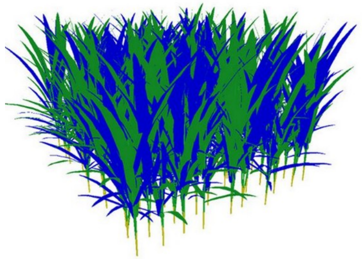
Annals of Botany, Volume 123, Issue 6, 8 May 2019, Pages 961–975, https://doi.org/10.1093

C. Lecarpentier

E. Blanc

Col. P. Barbillon, T. Flutre, C. Pradal, C. Fournier

II/ Traits based : ideotyping varieties



- **Ex. 1: Wheat Mixtures**
  - Identification of trait combinations by simulation and optimization

WALTer: a three-dimensional wheat model to study competition for light through the prediction of tillering dynamics

Christophe Lecarpentier, Romain Barillot, Emmanuelle Blanc, Mariem Abichou, Isabelle Goldringer, Pierre Barbillon, Jérôme Enjalbert, Bruno Andrieu

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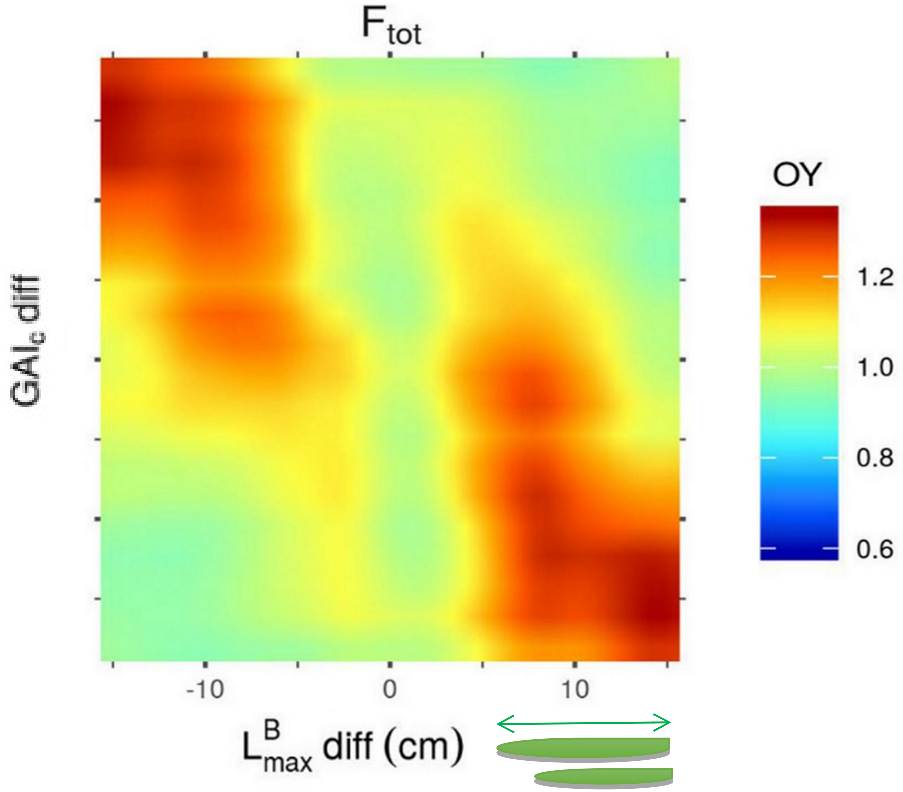


C. Lecarpentier

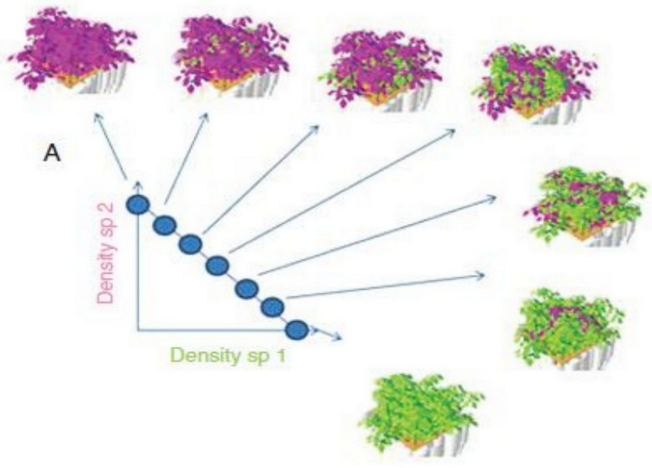
E. Blanc

Col. P. Barbillon, T. Flutre, C. Pradal, C. Fournier

II/ Traits based : ideotyping varieties

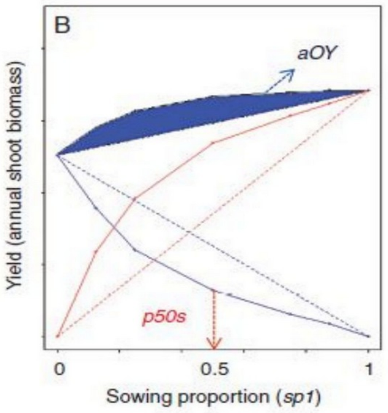
- **<u>Ex. 2: Crop Mixtures</u>**

In silico Mixture Experiment

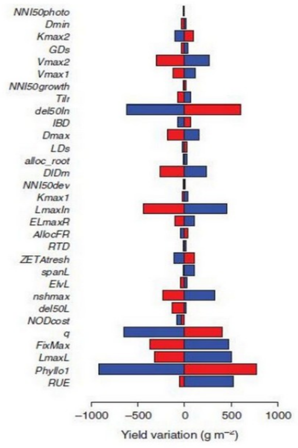


Louarn et al. (2020)

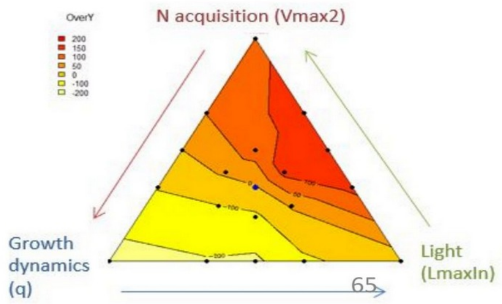
Impact on agronomic performance (Overyielding = aOY)



Analysing trait contribution (ranking – selection criteria)



Identifying compatible combination of traits between species (Ideomix)



Breeding => Combining Trait-Based + Trait-Blind

Breeding for within-field diversity
to promote agroecological transitions

1) Mixing to control of pest and diseases: the mecanisms

2) Why and how to breed for performance in mixture

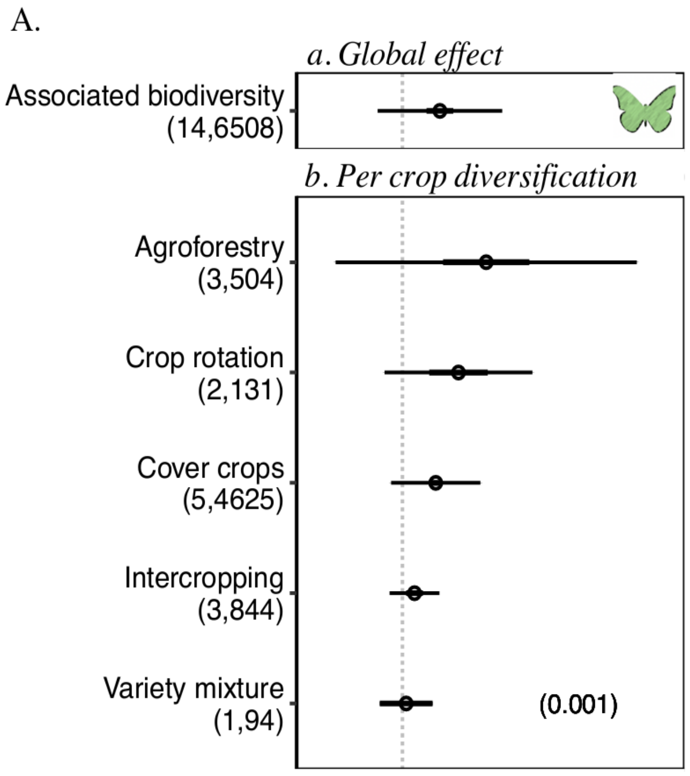
3) Participatory Breeding, a critical asset to face diversification

4) Conclusion

Diversification

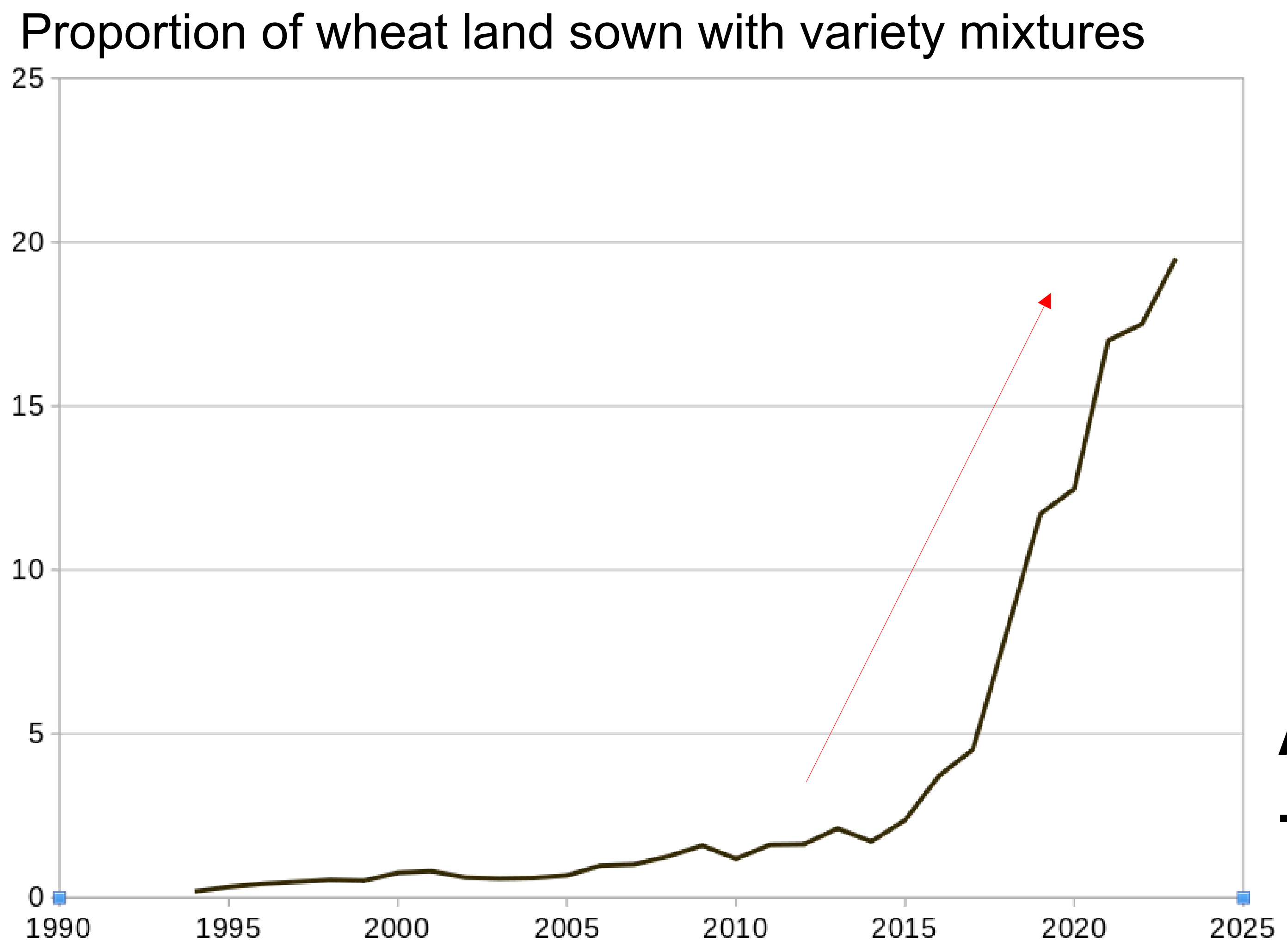
- More species to crop,
- More varieties to breed,
- More mixtures to observe,
- More cropping systems...

→ **Need to make it participatory !**



Beillouin et al. 2021

A recent increase : wheat variety mixtures



Data : France-Agrimer / Arvalis

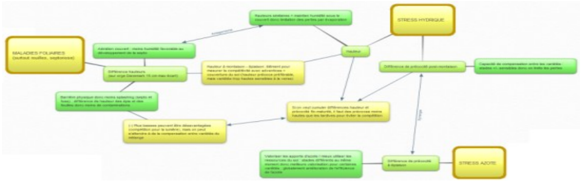
Almost 20%
-> higher than the first variety!

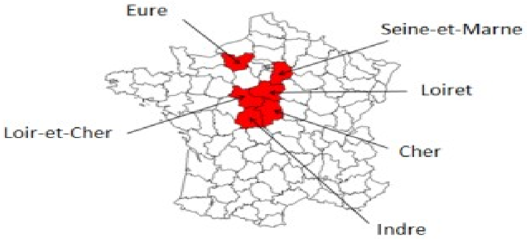
Participatory ideotyping


A. Gauffreteau & J. Borg
INRAE

Collaboration with 6 departmental agriculture services (24 farmers):

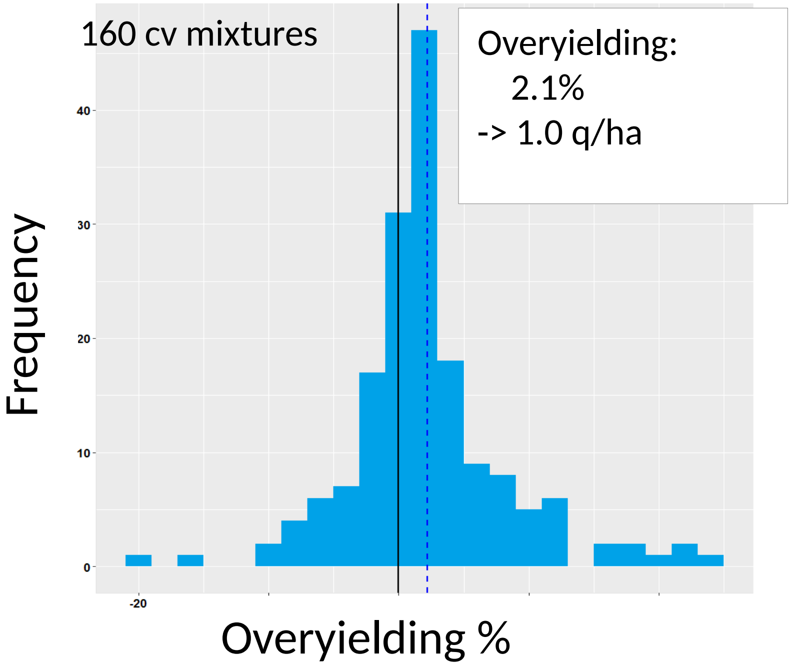
1) Ideotyping workshops
2) Agronomic evaluations





<u>Overyielding statistics, 2015-2016-2017 harvests:</u>

In 68% of the trials, mixtures performed better than the mean of the pure cultivars



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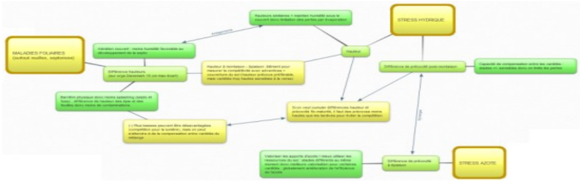
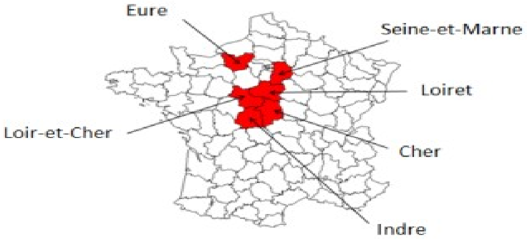
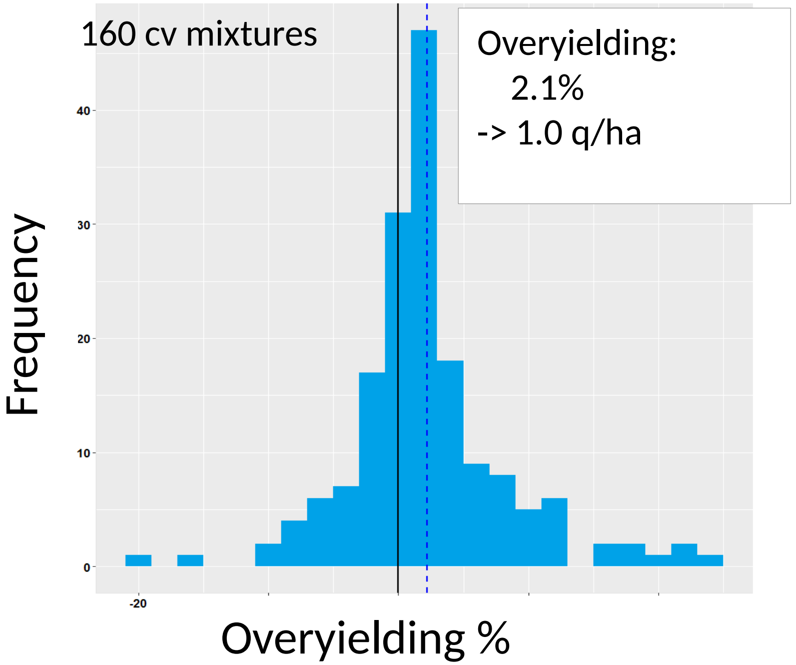




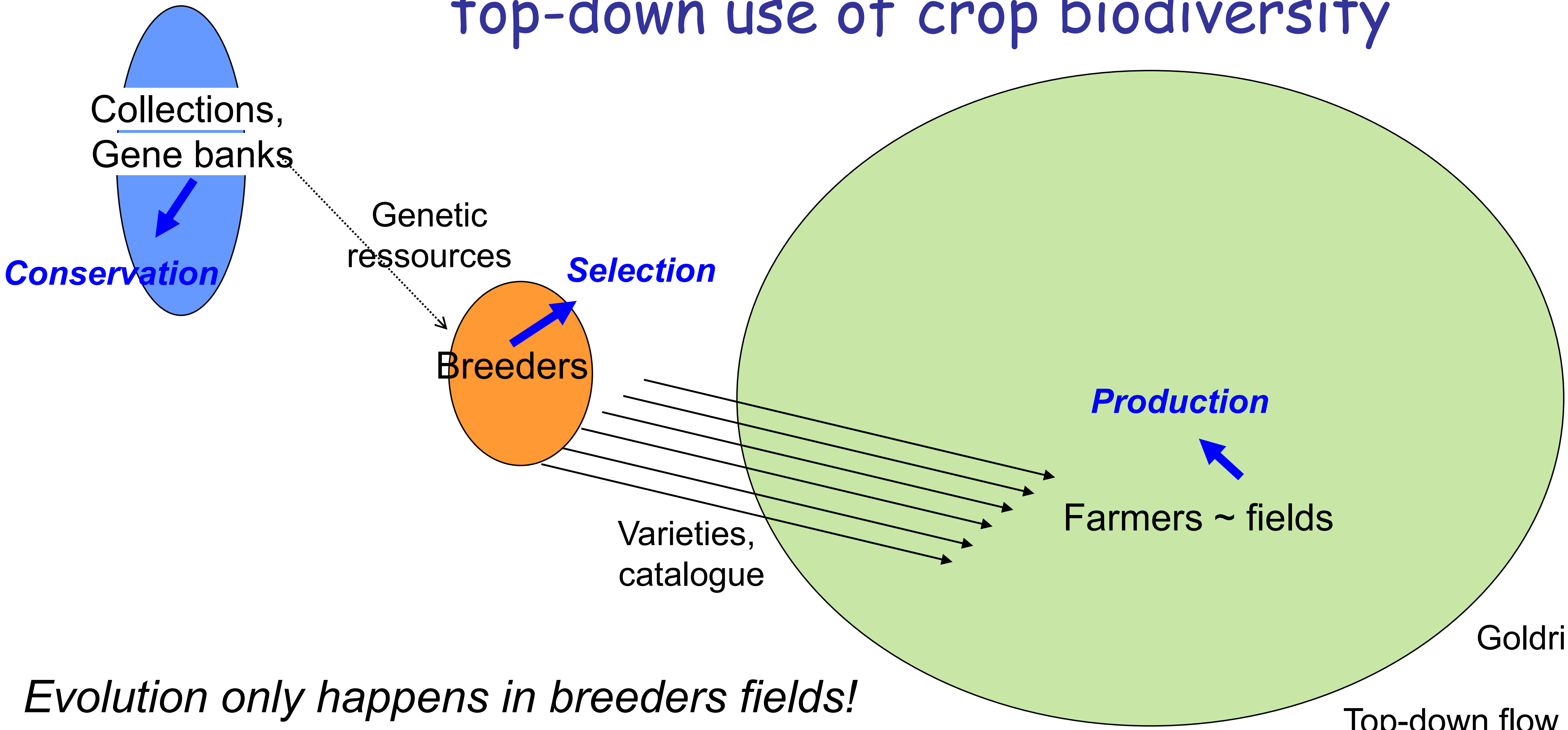
<u>Overyielding statistics, 2015-2016-2017 harvests:</u>

In 68% of the trials, mixtures performed better than the mean of the pure cultivars

BUT: Farmers are not looking for overyielding!
They look for lower risks, as **they usually handle a little number of pure varieties:**
Mixtures = more varieties grown at the farm scale
(and they can save time in crop management)



Modern plant breeding, a centralized, top-down use of crop biodiversity

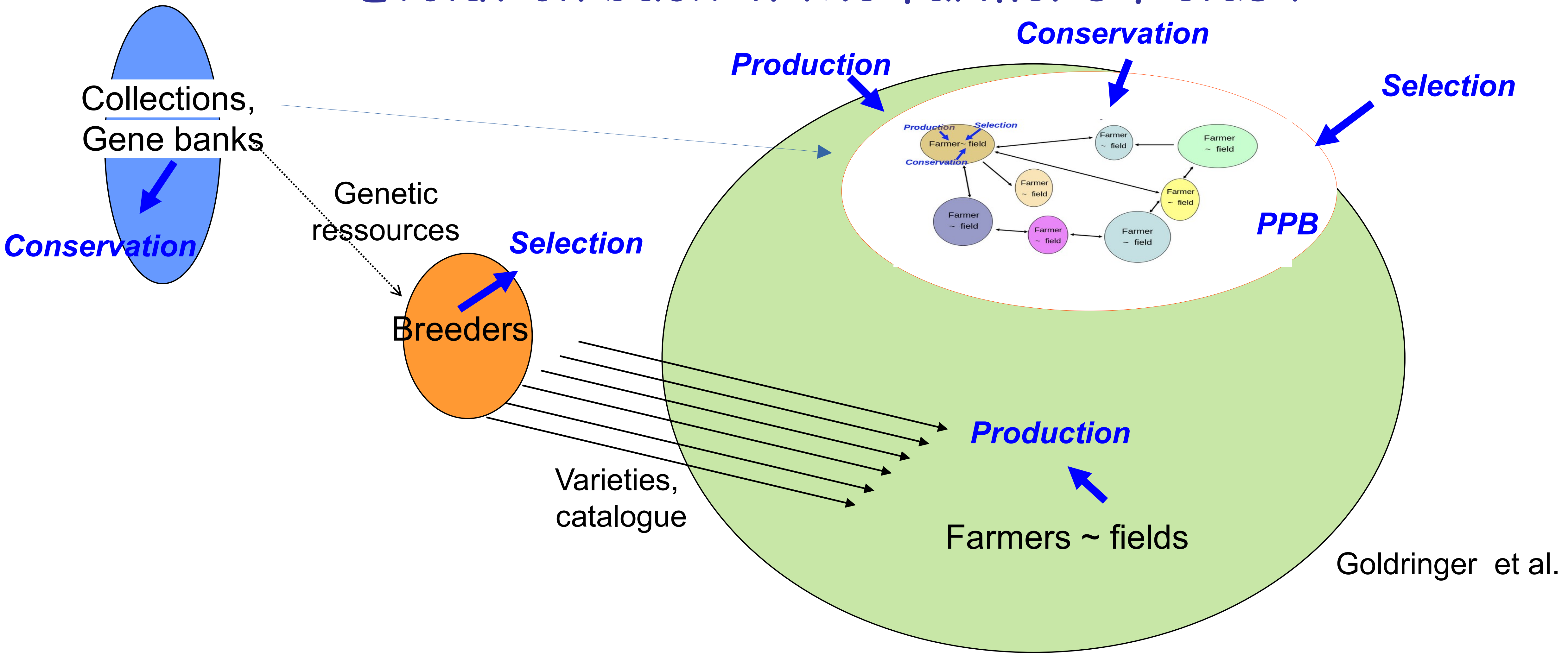


Goldringer et al.

Evolution only happens in breeders fields!

Top-down flow of information (Bonneuil & Thomas 2009)

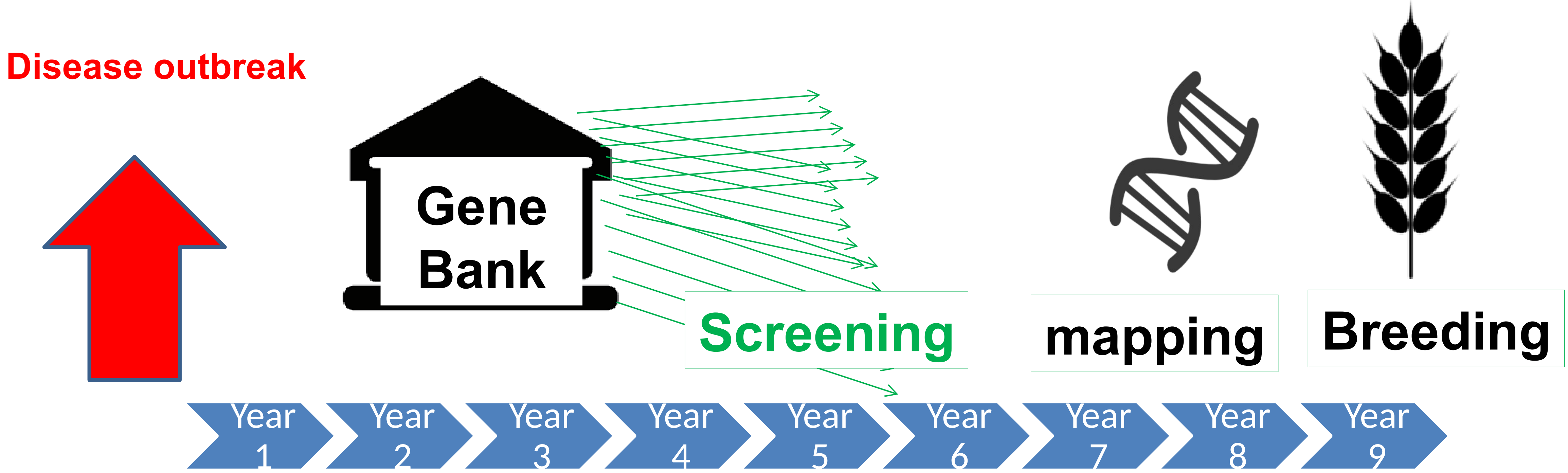
Participatory Plant Breeding… Evolution back in the farmer's fields !



→ METAPOPULATION dynamics, a known way to preserve both neutral and adaptive diversity

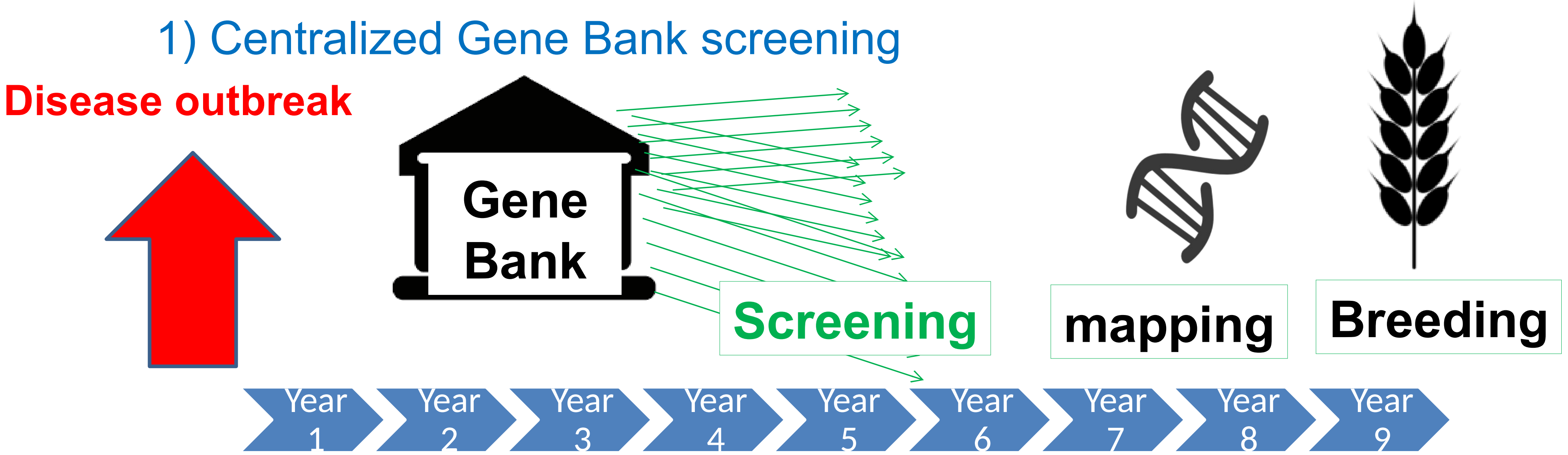
In situ / on farm participatory breeding as a source of resilience

1) Centralized gene bank screening for new resistances

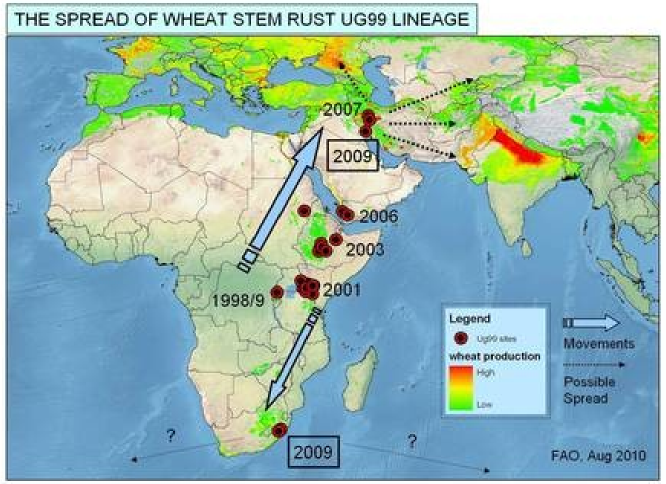


In situ / on farm participatory breeding may speed up screening

1) Centralized Gene Bank screening

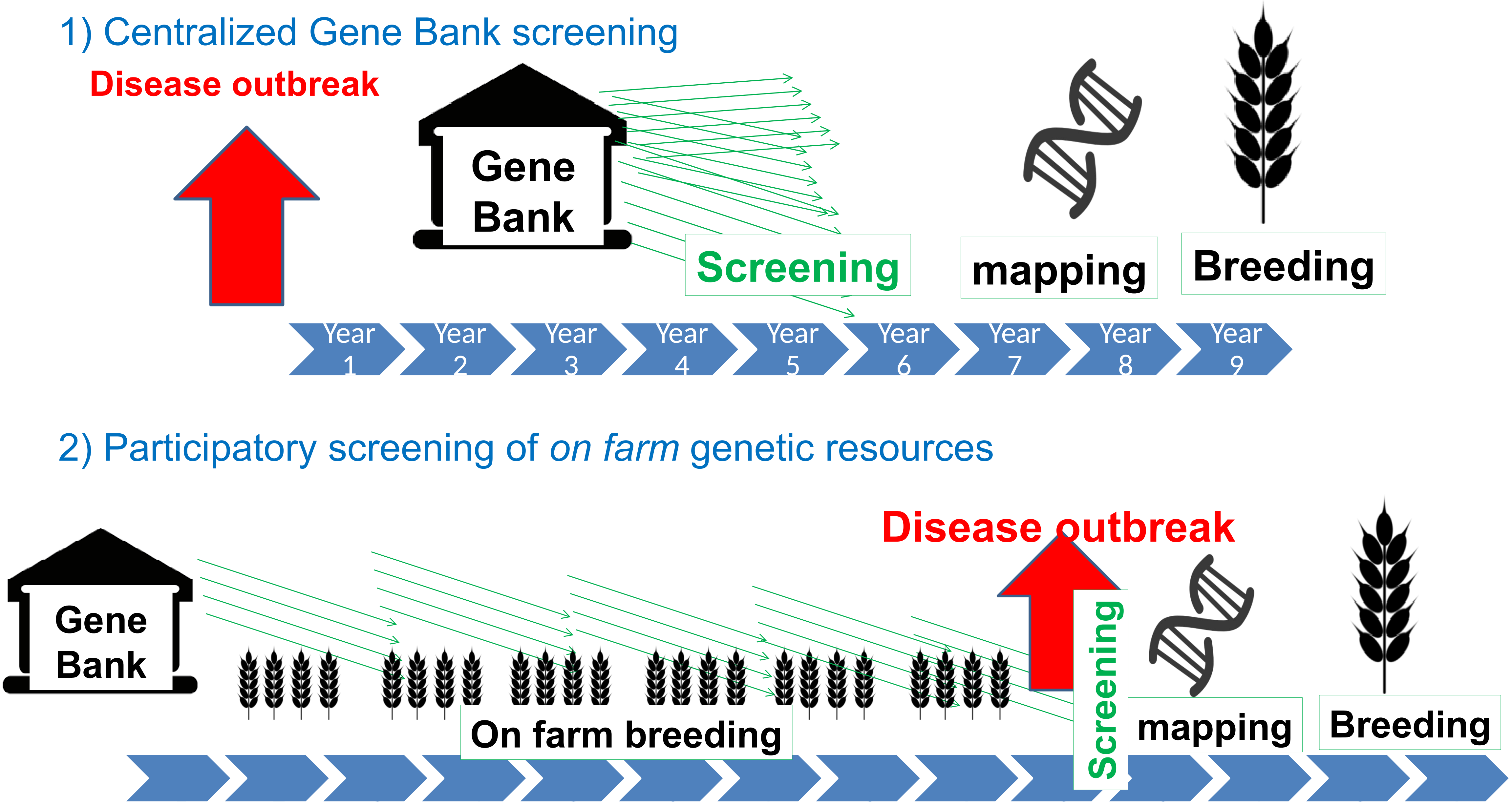


→ *Wheat Stem Rust Ug99 case*



https://www.fao.org/

In situ / on farm participatory breeding may speed up screening



Conclusion

- No simple solutions to expect : we are facing wicked problems
- We should target resilience/stability, not optimality
- Diversification of crops and cropping systems is necessary
- Research stance: please study mixtures and their complexity!

Acknowledgments

Wheatamix

Timothée Flutre
Isabelle Goldringer
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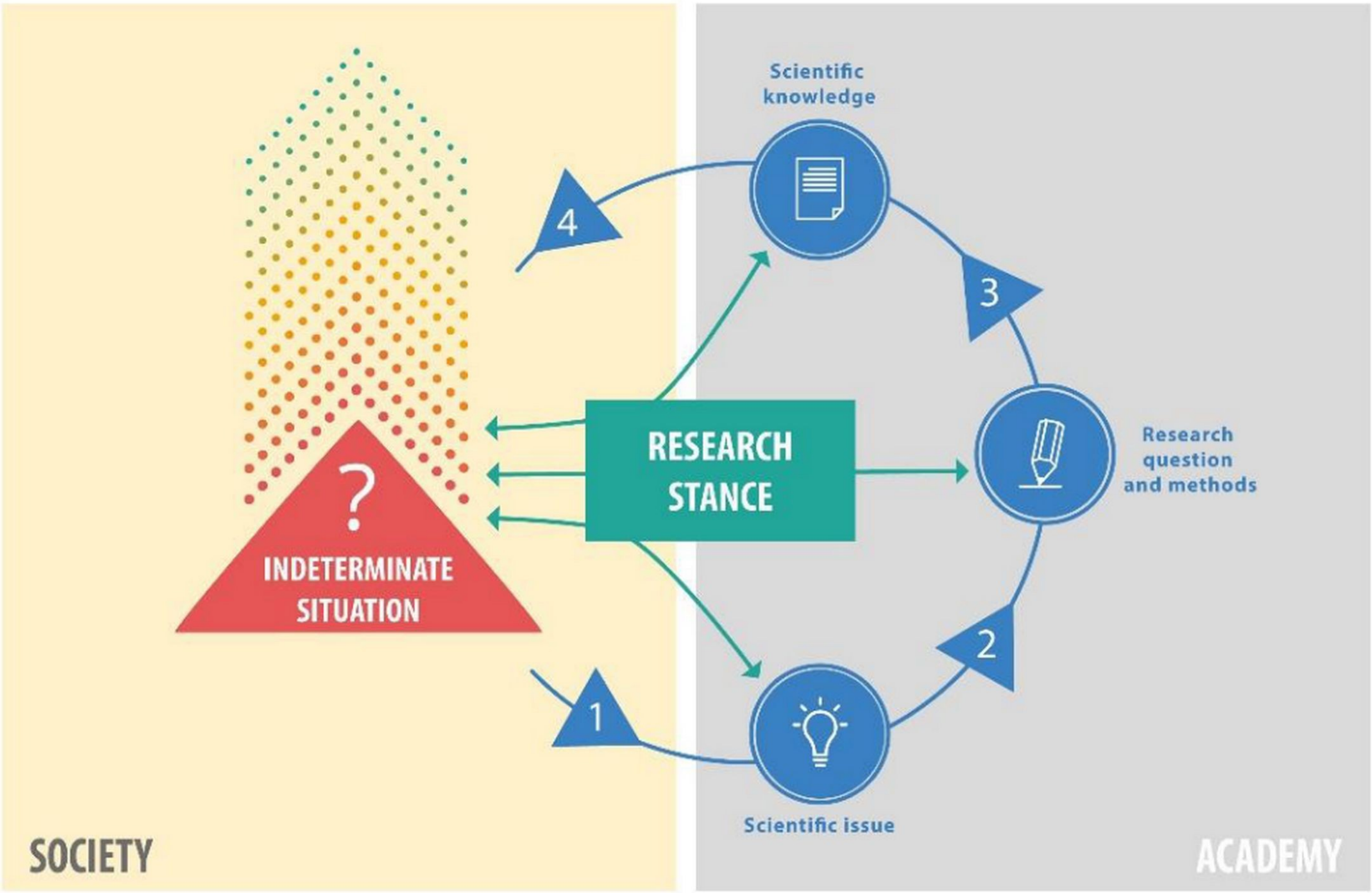
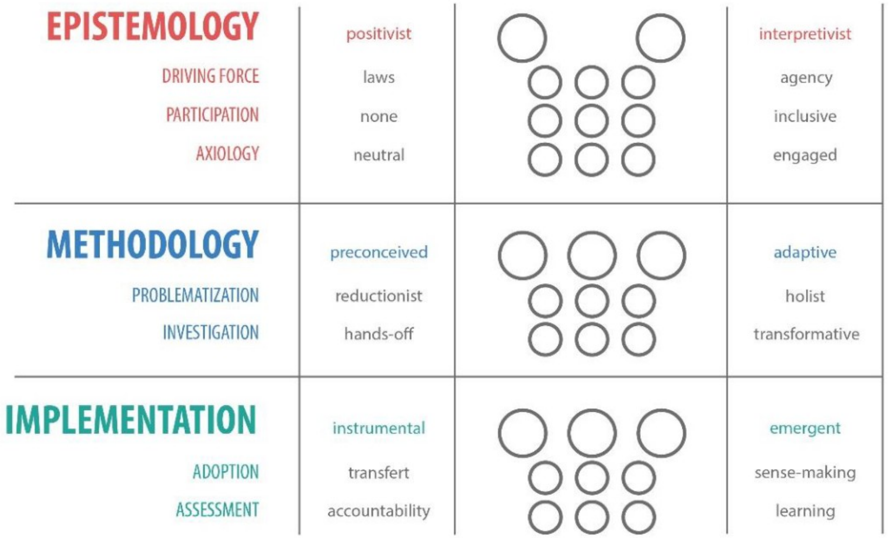
Arnaud Gauffreteau
Philippe Martin
Elodie Yann
Jean-Benoît Morel
Stéphane Lemarié
Jacques David
Philippe Hinsinger…

Emma Forst
Emmanuelle Blanc
Christophe Lecarpentier
Xavier Leroux

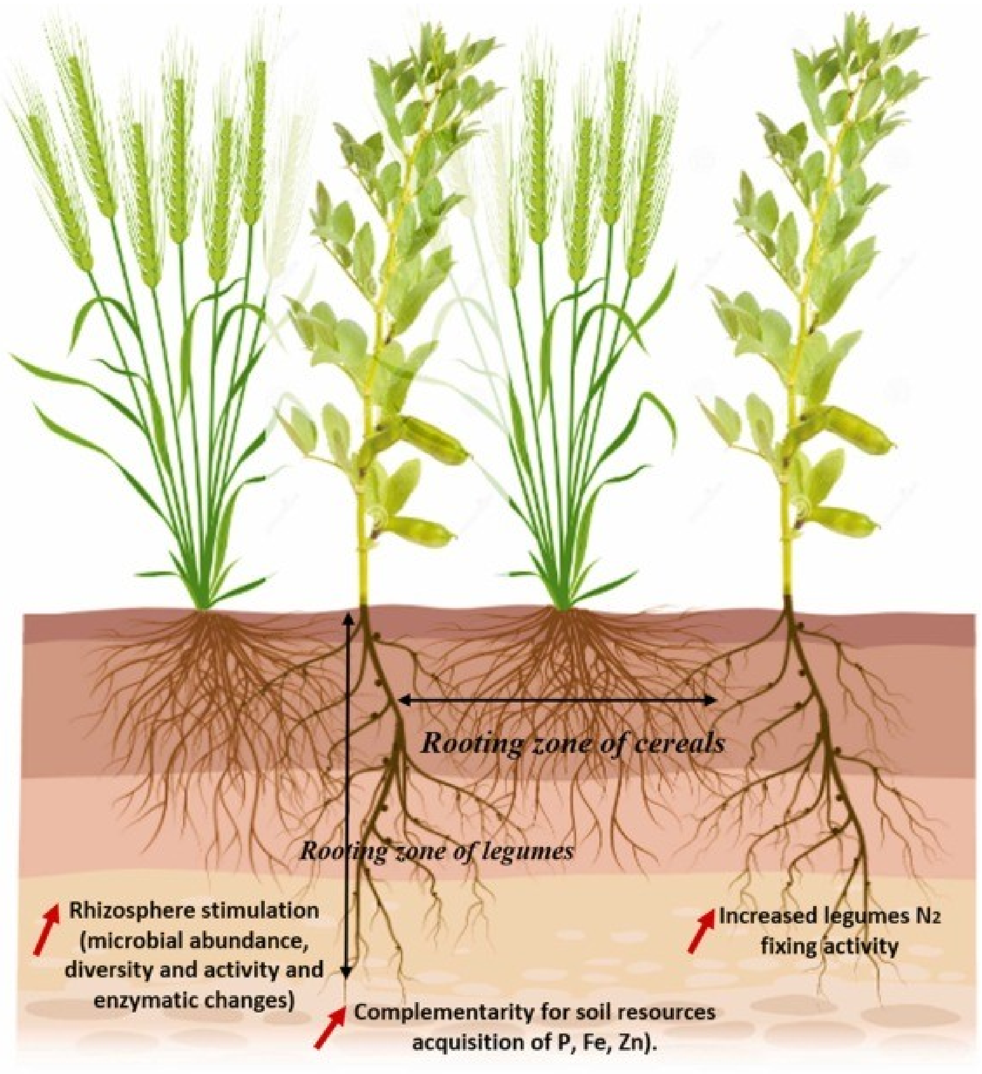
Research stance towards action





Sustainability transitions = indeterminate situations
= wicked problems

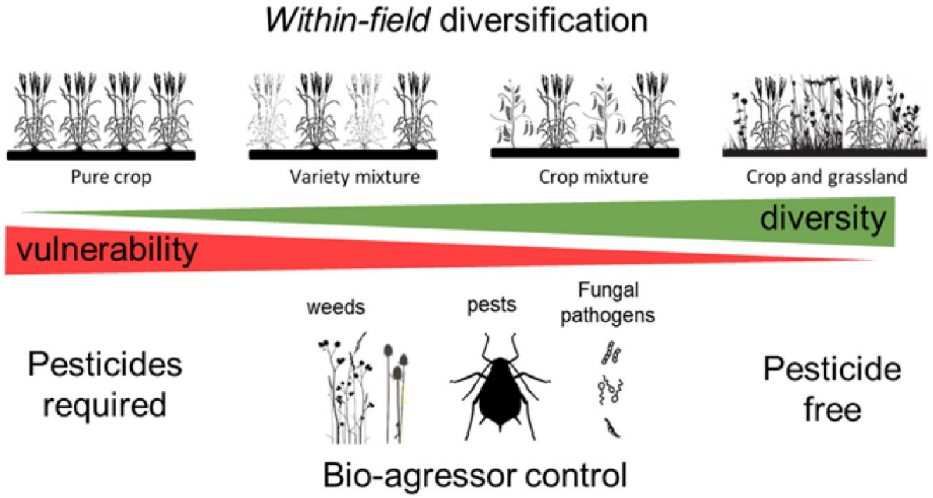
Hazard et al. 2019



Chamkhi 2023

MoBiDiv: Mobilizing the within-field diversity all along the seed system

- Central principle in agroecology: mobilizing crop diversity within fields boosts the natural regulations and allows avoiding the use of pesticides



- Objective of the project: create methods and tools to breed, mix, register and evaluate varieties for a pesticide-free agriculture
- Focussing on key model crops:
  - Wheat, main player in pesticide use in France
  - Pea, a good legume partner
  - Forage crops, emblematic for biodiversity and ecosystem s



MoBiDiv key objectives

Analyse the diversification dynamics in France

- socio-economic drivers of diversification and impact on biodiversity and pesticide-use

Understand plant-plant interactions to control weed, pest and disease

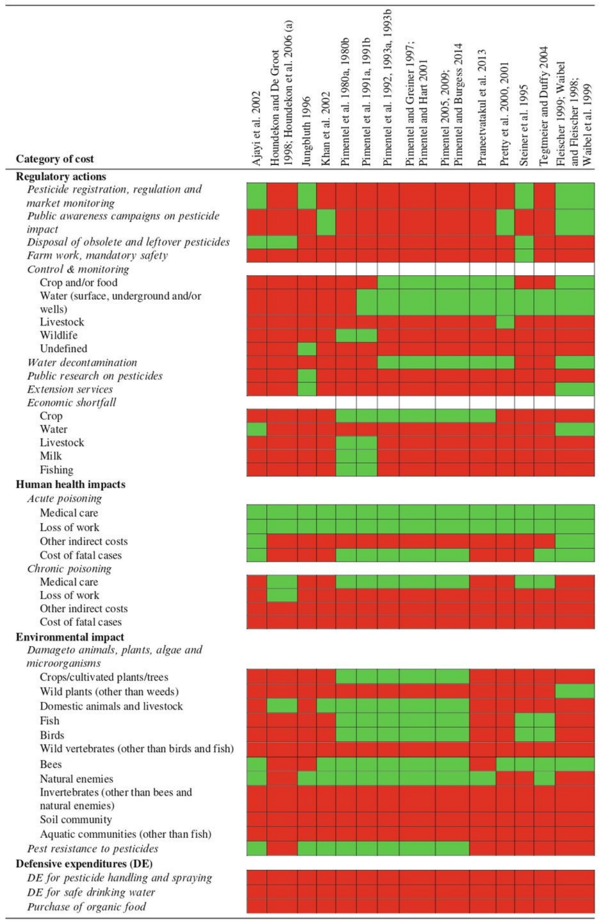
- models & experiments to produce new data and knowledge
- integrating nature-based regulations relying on cultivated and wild biodiversity

Manage mixtures complexity in breeding, assembly and evaluation

- developing participatory approaches & adapted statistical models

Explore scenarios for new market standards, funding sources and organization

- Mobilize actors of the seed sector to promote within-field crop diversification



- **Strong use of pesticides**
  - The Hidden and External Costs of Pesticide Use
- **Strong contribution of agriculture to climatic change**

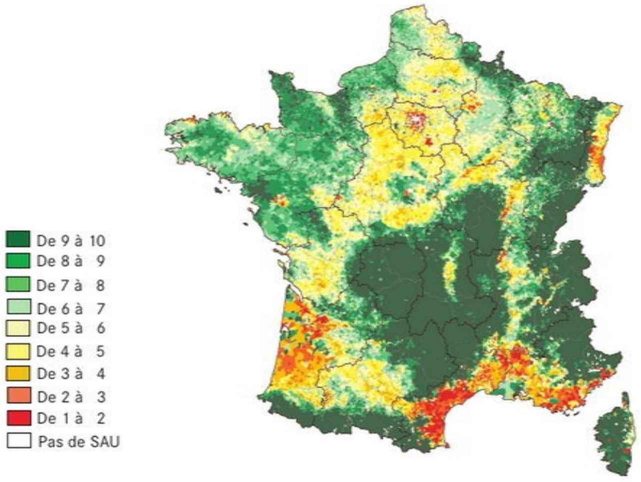
Bourget & Guillemaud 2016

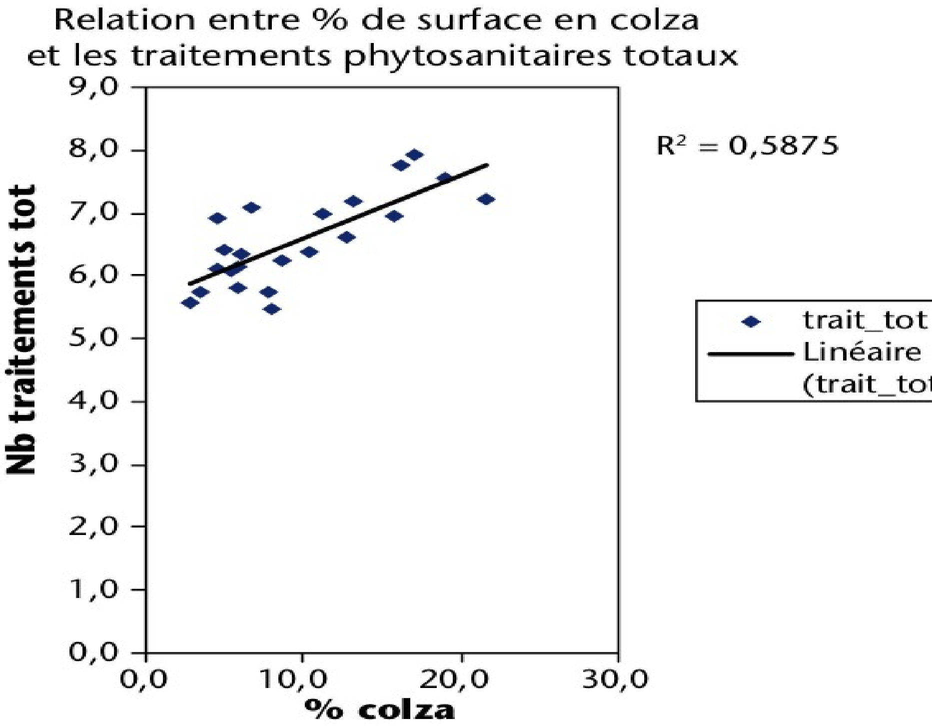
→ We need an agroecological transition!

Homogeneity and dis-services

- **Side effects of intensification :**
  - GHG and Climate Change
  - Soil and Water pollution / Nurient Cycling ...

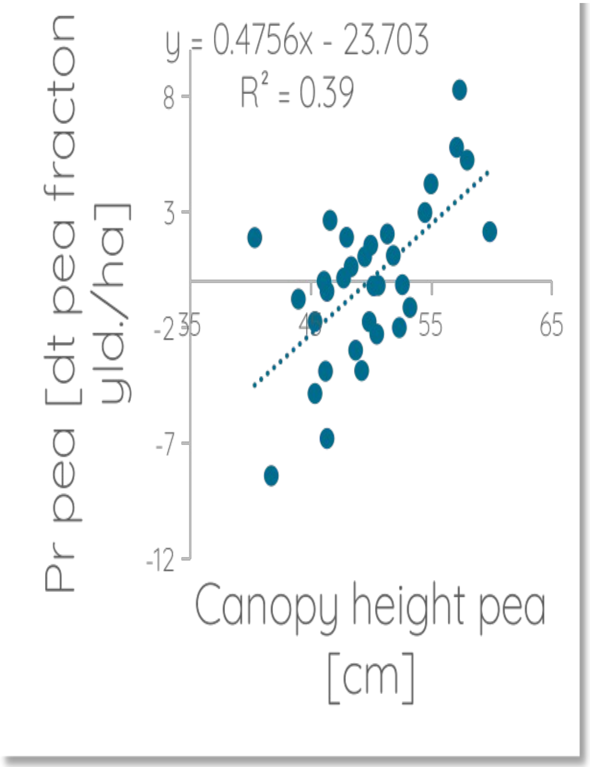
- **Side effects of field/region/country specialization :**
  - Higher pathogen, weeds and pest pressures
  - Higher yield instability (Renard & Tilman 2019)

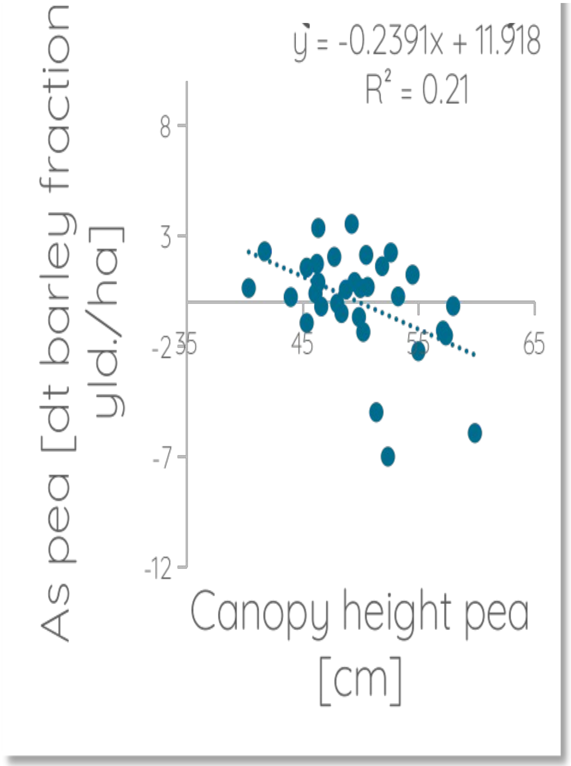




→ Example of rapeseed in the Seine basin in France (Schott et al, 2010)

Interpret the interactions in terms of relationships between Pr-As and traits





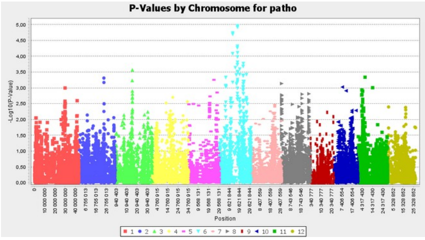
GMA_{pea}	Pr_{pea}	As_{pea}	Biological interaction-function (BIF) of pea trait	pattern
			Commensalism	+/0
			Commensalism	0/+
			Mutualism	+/+
			Antagonism	+/-
			Antagonism	-/+
			Neutralism	0/0
			Amensalism	0/-
			Amensalism	-/0
			Competition	-/-

Trait value axis →

Haug et al. (2021)

- Different traits can correspond to different interactions.

Ongoing experiment: Wheat-Pea GWAS

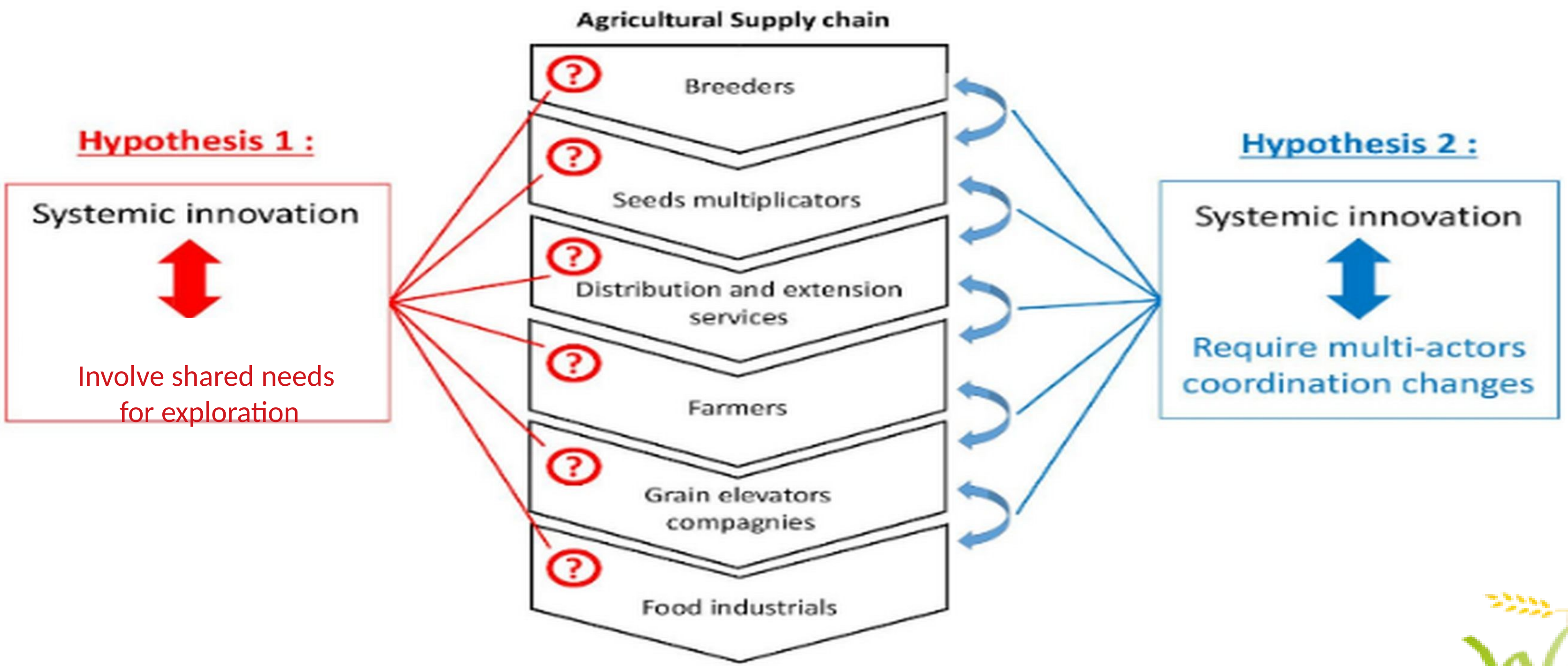


- Panel of 200 wheat lines studied in combination with 2 pea cultivars
- 2 years (2023-2025), 2 sites (Saclay & Rennes)
- Phenotyping: Yield, quality, disease resistances
- **Scientific questions :**
  - Neighbour Mediated Immunity
  - Nitrogen use synergy
  - Mixing ability for yield and disease control

- **Collaborations**:
  - **IGEPP** – Rennes (N. Moutier, A. Baranger) - **BIOGER** (T. Vidal) – **ECOSYS** (JM Gilliot) + **GS Biosphera** project (**IPS2**: ML. Martin-Magniette, E. Delannoy) + **GQE GeVAD** (M.Tenaillon team)

MOBiDiv

Wheat cultivar mixtures, a case of systemic innovation



Results of the global survey:

⇒ Lack of references on mixtures limits their development (Denmark survey)

⇒ Example of systemic innovation that both requires i) shared needs for exploration, and ii) concerted changes of various actors of the supply chain

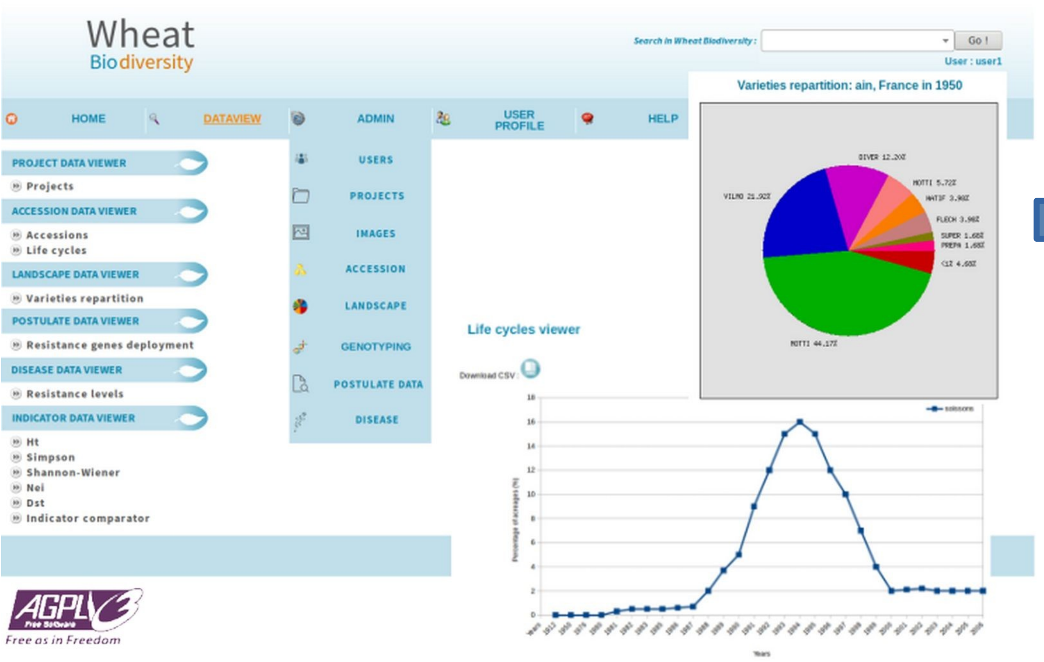
Labarthe et al. (TFSC 2021)

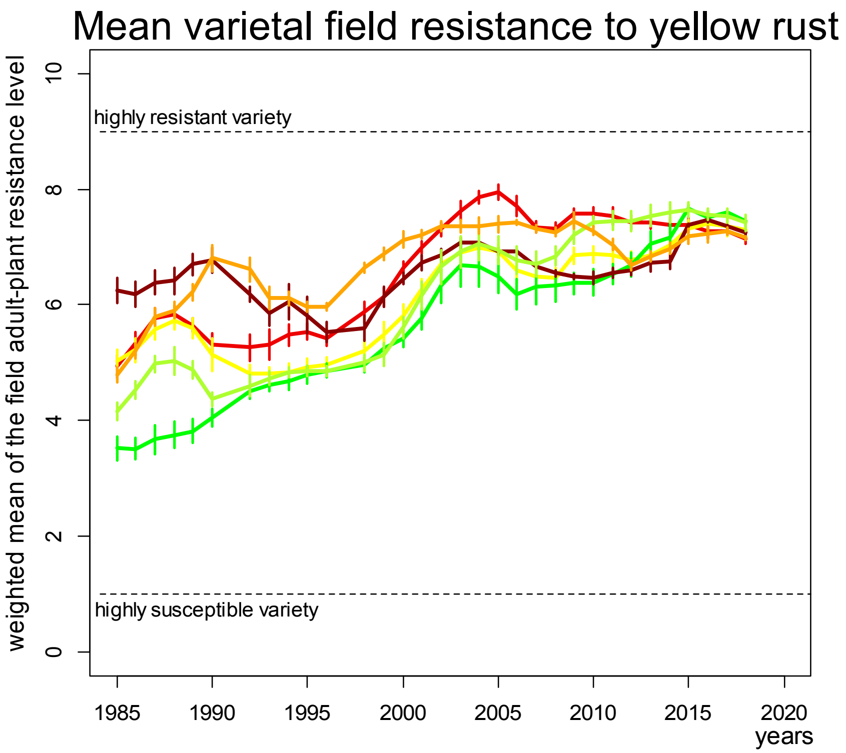
Better monitoring cultivar resistance evolution

<u>DiverCiLand : A database dedicated to crop diversity monitoring</u>

→ Manage accessions, traits (resistance), Molecular markers

→ Data visualization



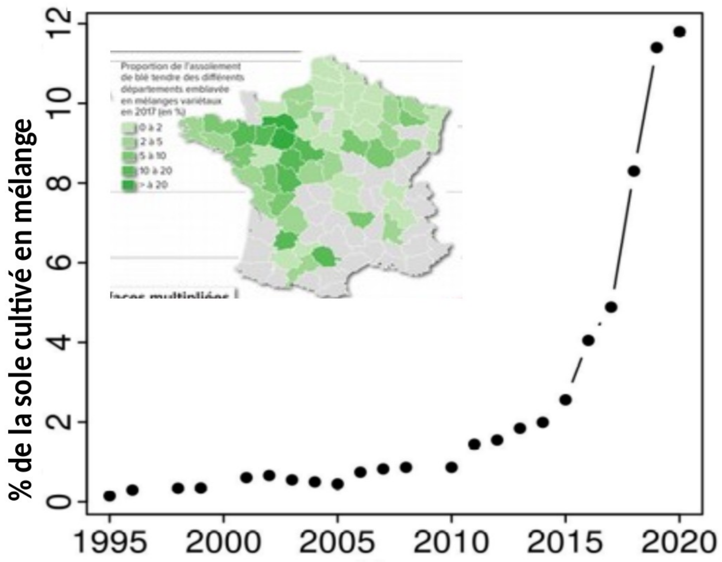


F. Dubs, R. Perronne, T. Vidal, M. Polart, Y. de Oliveira, J. Enjalbert

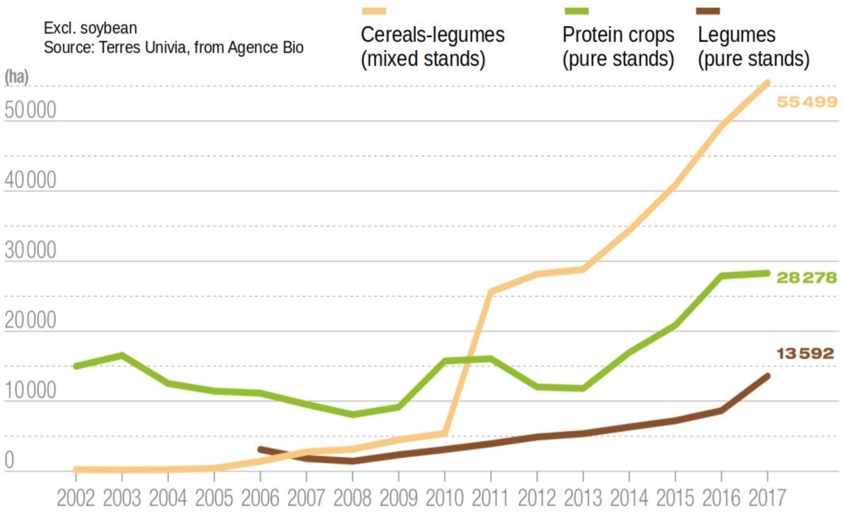
RUSTWATCH
WHEAT RUST EARLY WARNING

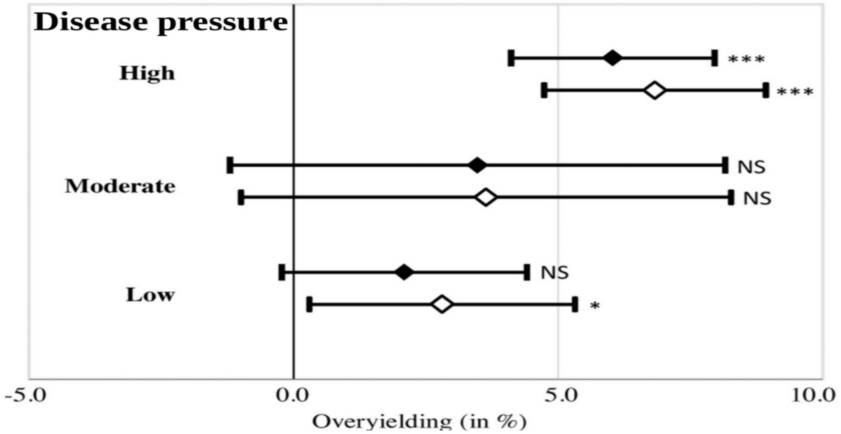
Links between intra-field diversification and total crop yield

Bread wheat varietal mixtures in France

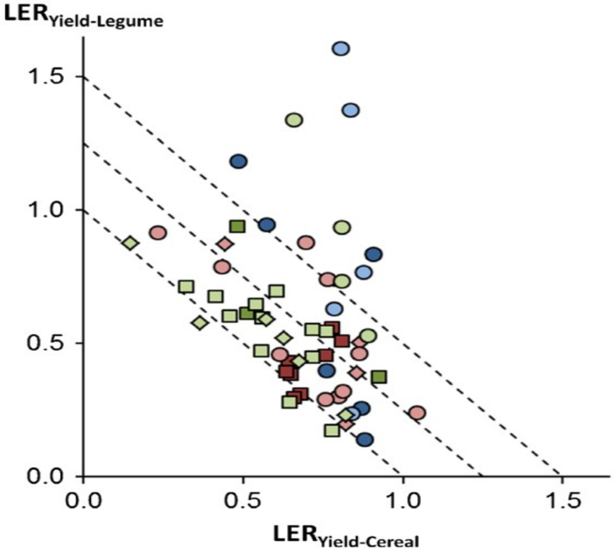


Surfaces with organic legumes in France: mixed stands vs. pure stands





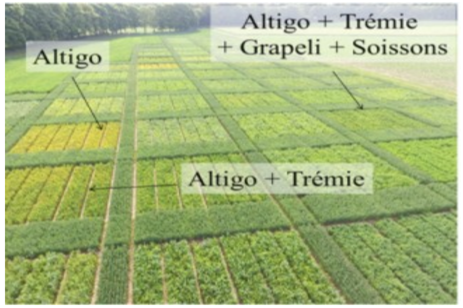
Borg et al (2017)



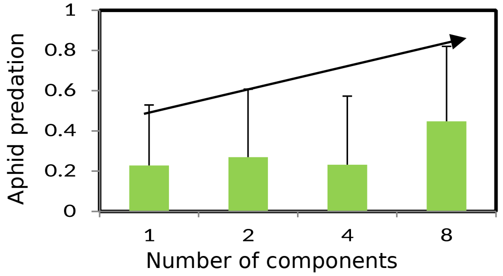
Bedoussac and Justes (2015)

Some weak but significant effects on services detected !

- Effective control of pathogens

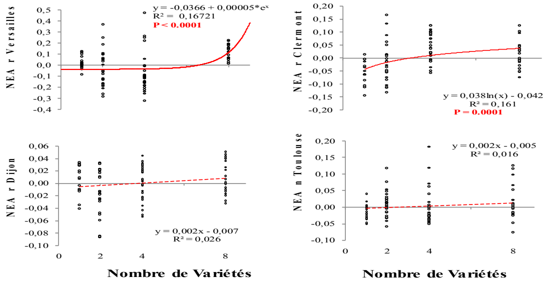


- Positive impact of aphid predation



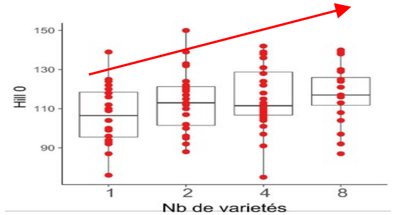
Dubs et al. 2018, Porcher et al.

- Improved nitrogen cycle through modification of soil bacterial communities



Hugoni et al., in prep

- Improved recruitment of mycorrhizae



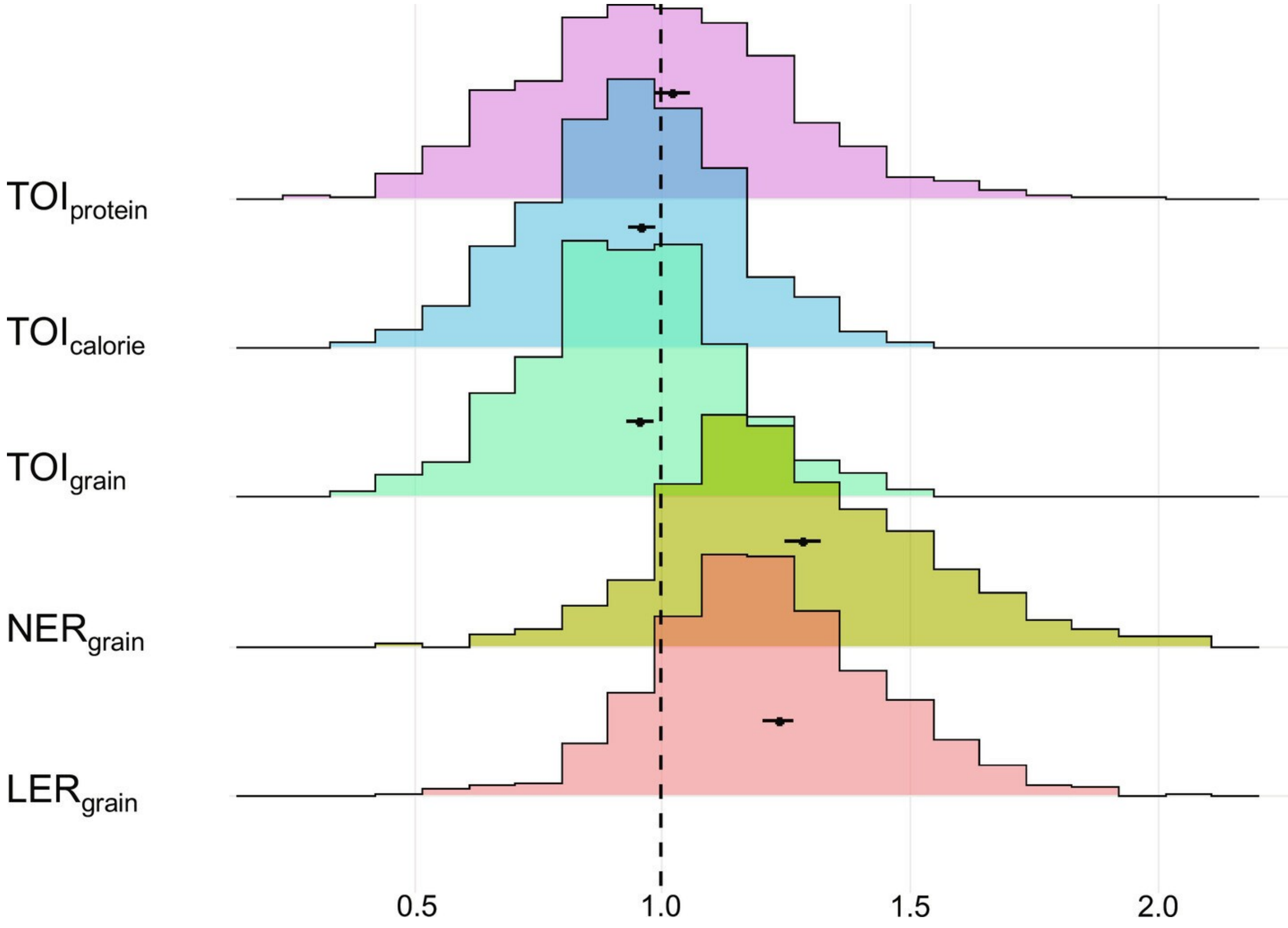
Taschen et al., in prep

- Improved worm health if fed with mixtures

Chassé *et al.* 2019

Mixtures' performances

- **Cereal-Legume Intercropping**
  - **Strong overyielding (20% LER)**
  - **Almost as productive as the best component, and under low-input**
  - **Positive impact on quality**



Li et al. (PNAS 2022)

Participatory ideotyping

- **OPTIMIX: a Multicriteria Evaluation tool to help the design of wheat cultivar mixtures**

  - Works with cultivar VCU characteristics
  - Users propose a mixture of varieties
  - Optimix evaluates the efficiciency of disease control, and provides a full explanation of pros and cons of the mixture
  - Refutability of criteria and rules

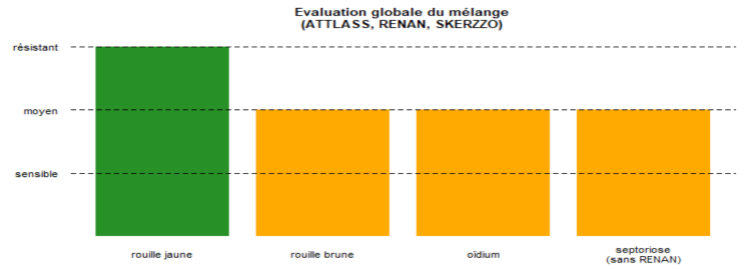
(Still under development → http://moulon.inra.fr/optimix/)

Caractéristiques des variétés :

Variété	Rouille jaune	Rouille brune	Oïdium	Septoriose (tritici)	Hauteur	Précocité montaison	Précocité épiaison	Classe qualité
ATTLASS	9	6	6	7.00	4.00	4.00	6.00	BP
RENAN	6	8	6	NA	4.00	1.00	6.00	BAF
SKERZZO	7	6	7	7.00	4.00	4.00	6.00	BPS

Source : Arvalis (2017)

Evaluation globale du mélange :



Explications :

- rouille jaune : au moins 50% de résistantes et moins de 40% de sensibles; avec un bonus dû à la hauteur (effet parapluie : au moins une variété résistante plus haute qui protège les autres)
- rouille brune : moins de 50% de résistantes et moins de 40% de sensibles; avec un bonus dû à la hauteur (effet parapluie : au moins une variété résistante plus haute qui protège les autres)
- oïdium : moins de 50% de résistantes et moins de 40% de sensibles; avec un bonus dû à la hauteur (effet parapluie : au moins une variété résistante plus haute qui protège les autres)
- septoriose : maximum de 30% de sensibles et 0% de résistantes, ou moins de 3 variétés en mélange; pas de malus dû à la hauteur (infection verticale : au moins une variété sensible plus haute qui infecte les autres)