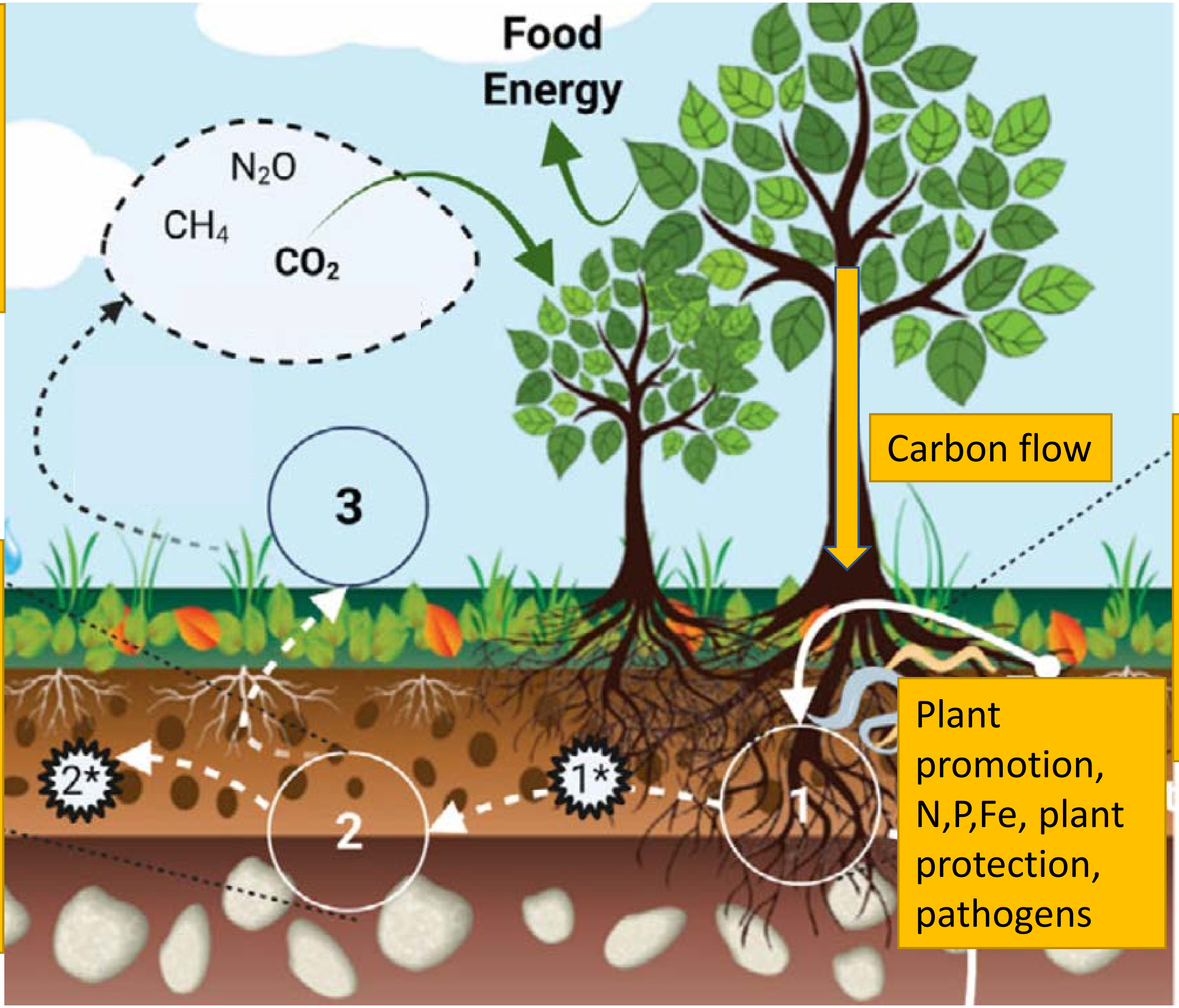
Uncovering rhizosphere microbial resilience and potential to support plant growth

Mika Tarkka

Helmholtz Centre for Environmental Research

18th Congress of the European Society for Agronomy in Rennes, France

What are the services and disservices provided by microbiomes?



3

Gas production:
Nitrous oxide,
methane, CO_2,
other volatiles

Carbon flow

Rhizosphere

2

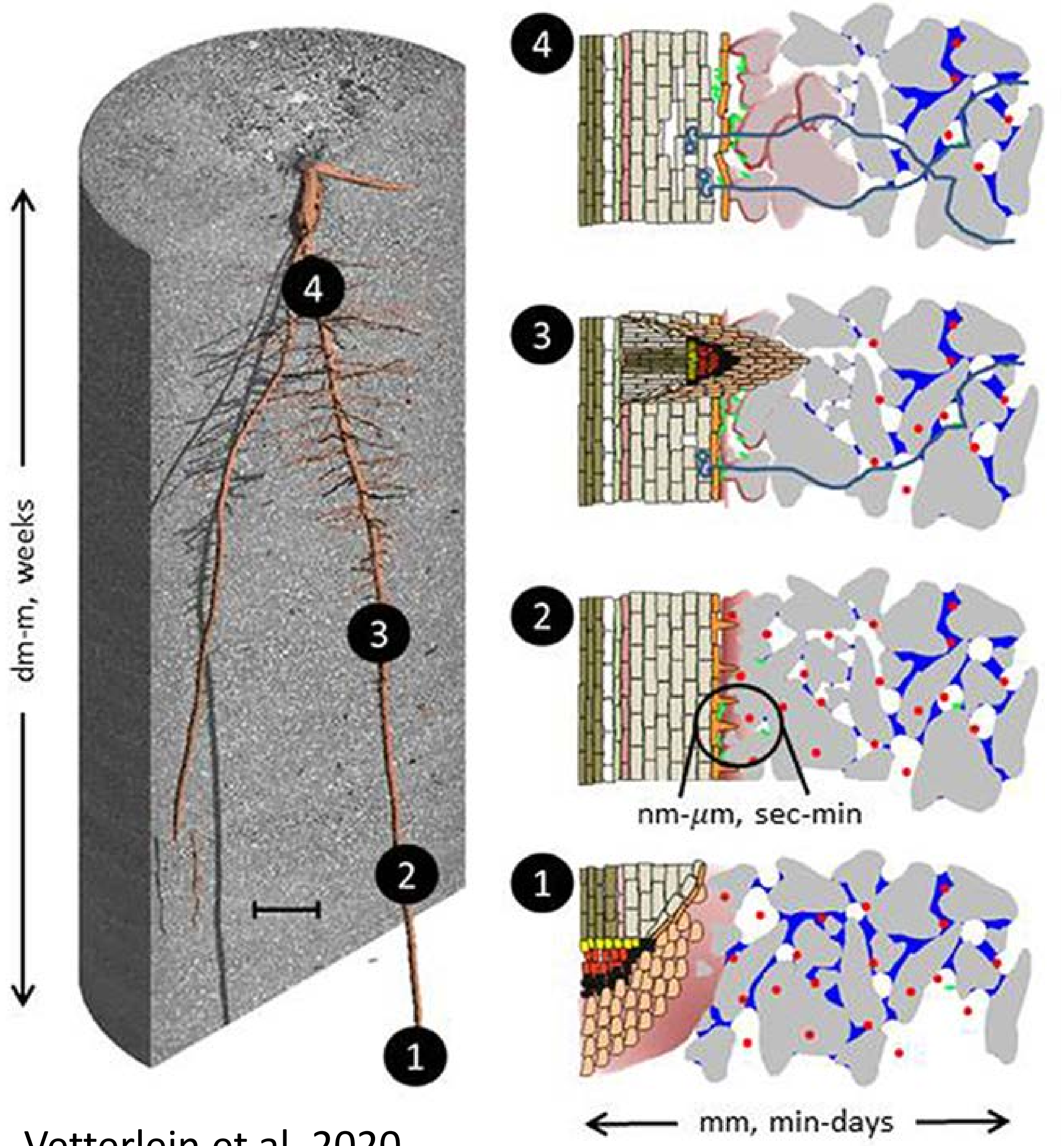
Soil structure +
Biological
processes,
Nutrients,
carbon,
"Hotspots„
of activity

Plant
promotion,
N,P,Fe, plant
protection,
pathogens

1

Abb.: Verstraete u.a. 2021

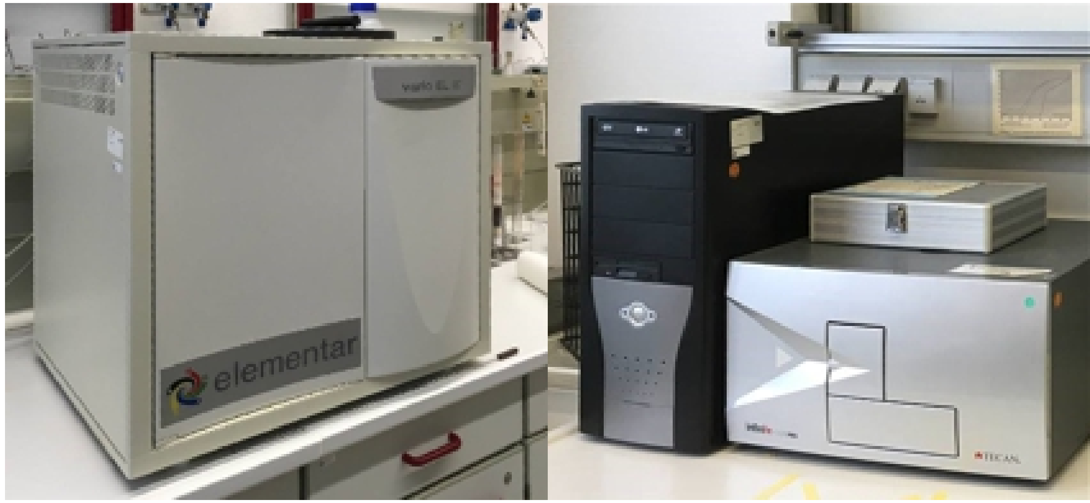
Rhizosphere research to support plant growth and health



Vetterlein et al. 2020

- Rhizosphere: the soil influenced by living roots
- Rhizosphere forms as the root grows
- Rhizodeposits select for certain microorganisms
- Dynamic and stress-affected compartment of the soil

How can we record diversity and functions of rhizosphere microbiomes?



Parameters for the whole community

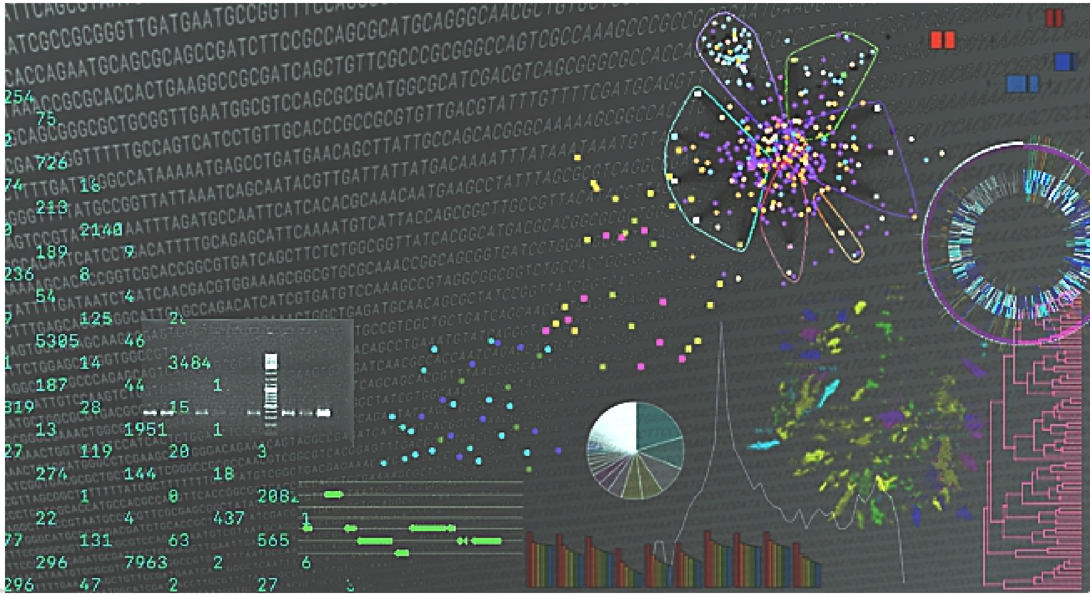
Analytic Pipeline of Soil Eco-indicators (APPLE)

Biomass, respiration, growth, enzyme activities, biomolecules, isotopic composition

Parameters for the whole community with species composition

Meta Omics Pipeline

Diversity and functions by high-throughput molecular-analyses at gene and gene product levels



Rhizosphere formation

Minh Ganther

Lioba Rüger

Bunlong Yim

18th Congress of the European Society for Agronomy in Rennes, France

Rhizosphere Priority Program 2019-2025

**RHIZOSPHERE
SPATIOTEMPORAL
ORGANISATION**
SPP 2089

Plant-microbe interplay

Water acquisition

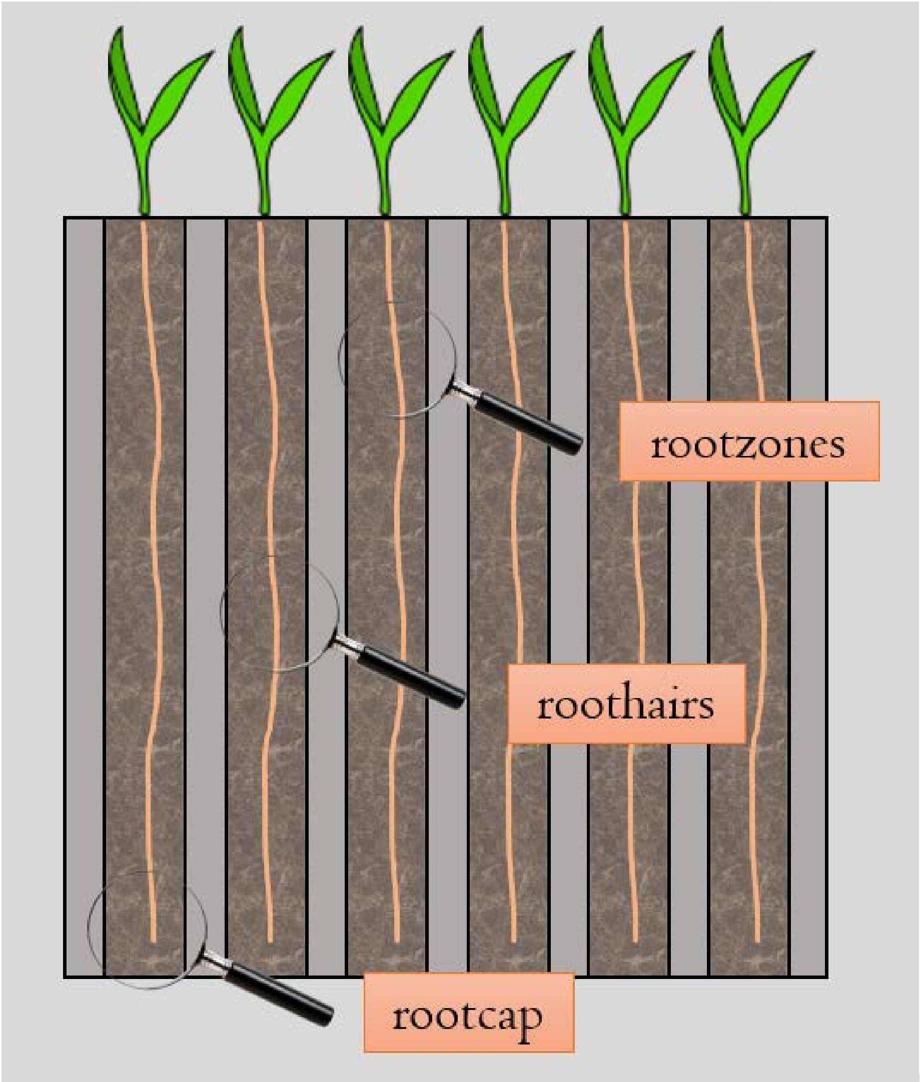
Nutrient acquisition

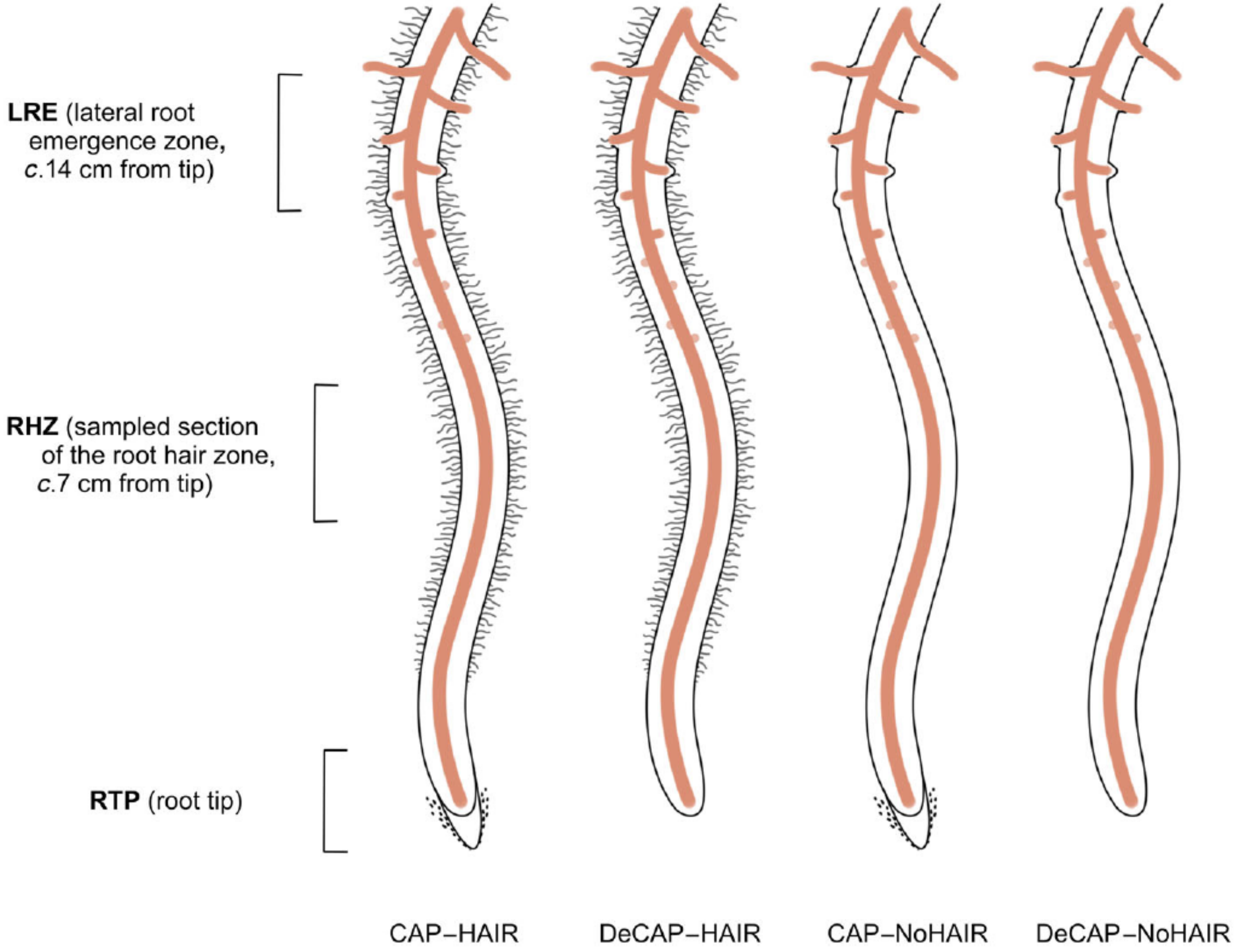
Soil structure
Carbon flux

Vetterlein et al. 2020 *Front Agron*
Vetterlein et al. 2021 *J Plant Nutr Soil Sci*

Formation of the rhizosphere: from the root cap to lateral root zone

The effects of root zones and root cap removal on maize gene expression and prokaryote and protist community composition





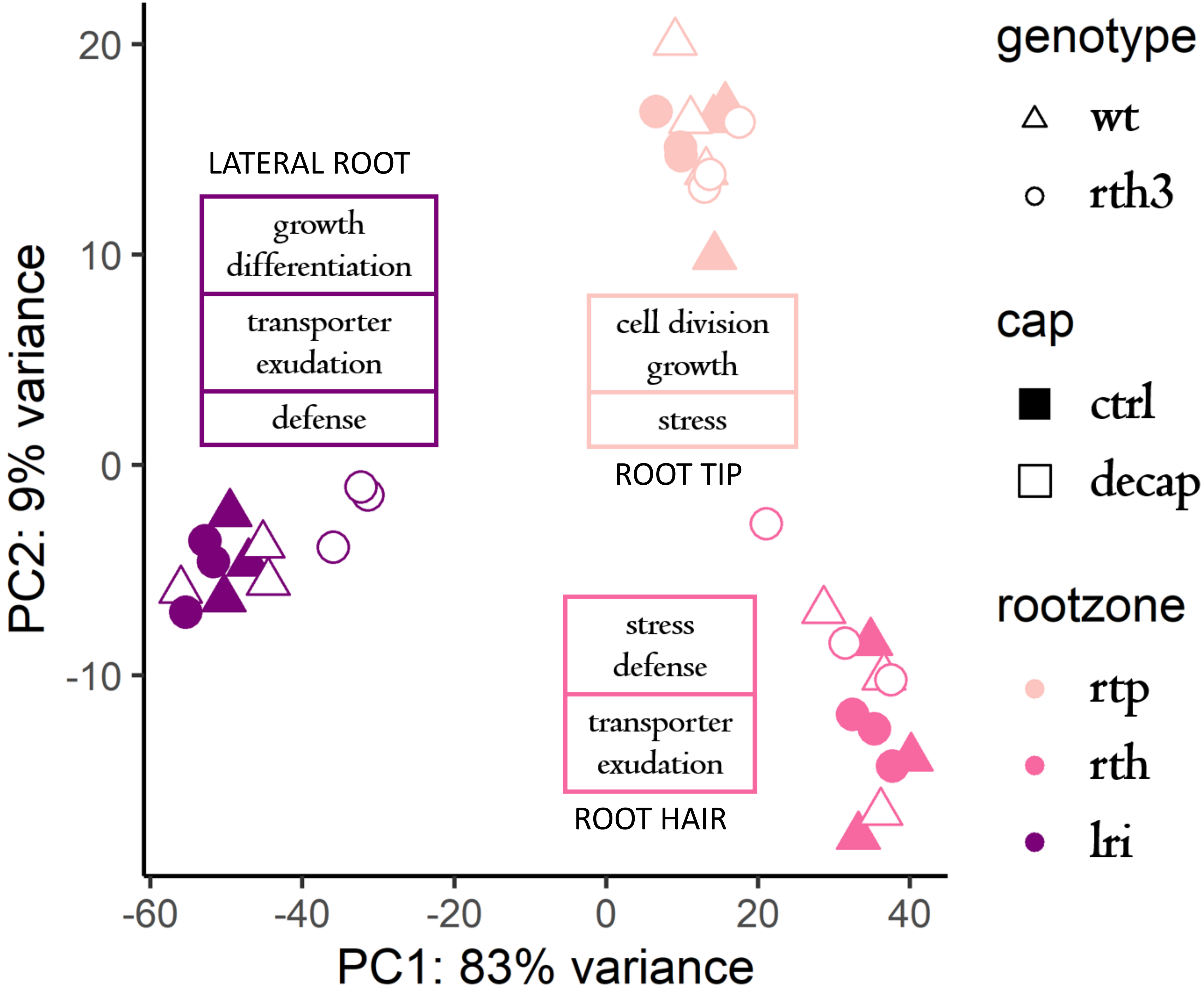
Maize root gene expression

Root parts are different, but root cap removal or absence of root hairs (rth3) have a low effect

RNA sequencing of maize roots

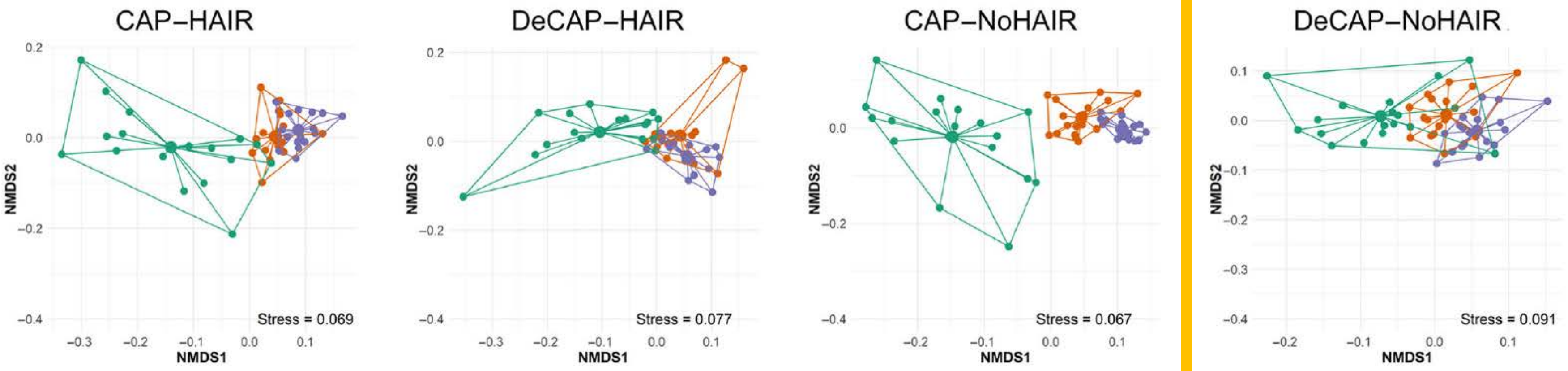
Functions: enriched gene ontology terms (functions based on gene expression)

Principal components analysis

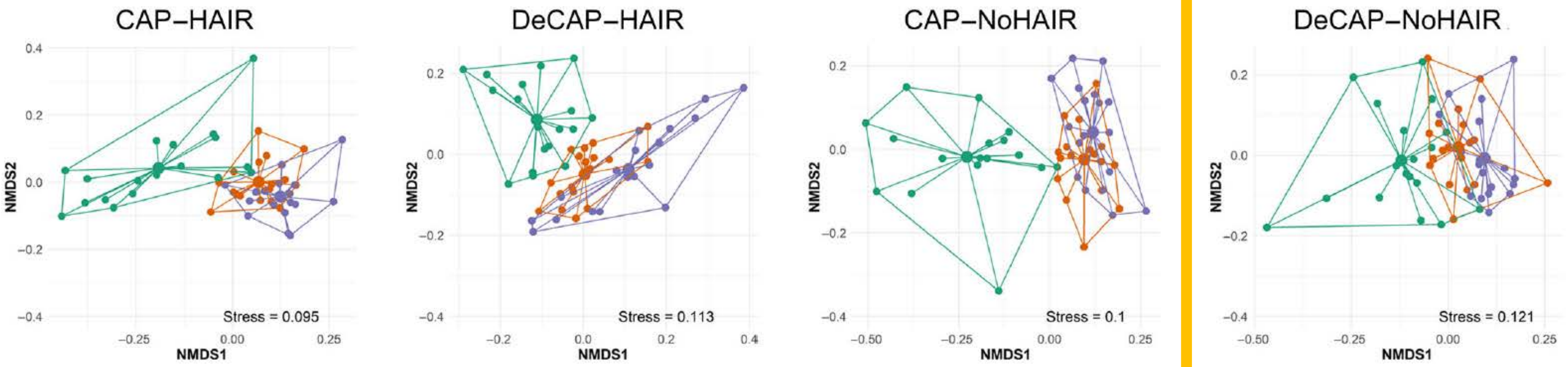


DeCapping (no root cap) leads to reduced differentiation of the rhizosphere microbiome

PROKARYOTES: bacteria and archaebacteria



PROTISTS: unicellular eukaryotes that feed on bacteria



Root zones

🟩 TIP 🟧 HAIR 🟪 LAT R

Community compositions of the microorganisms

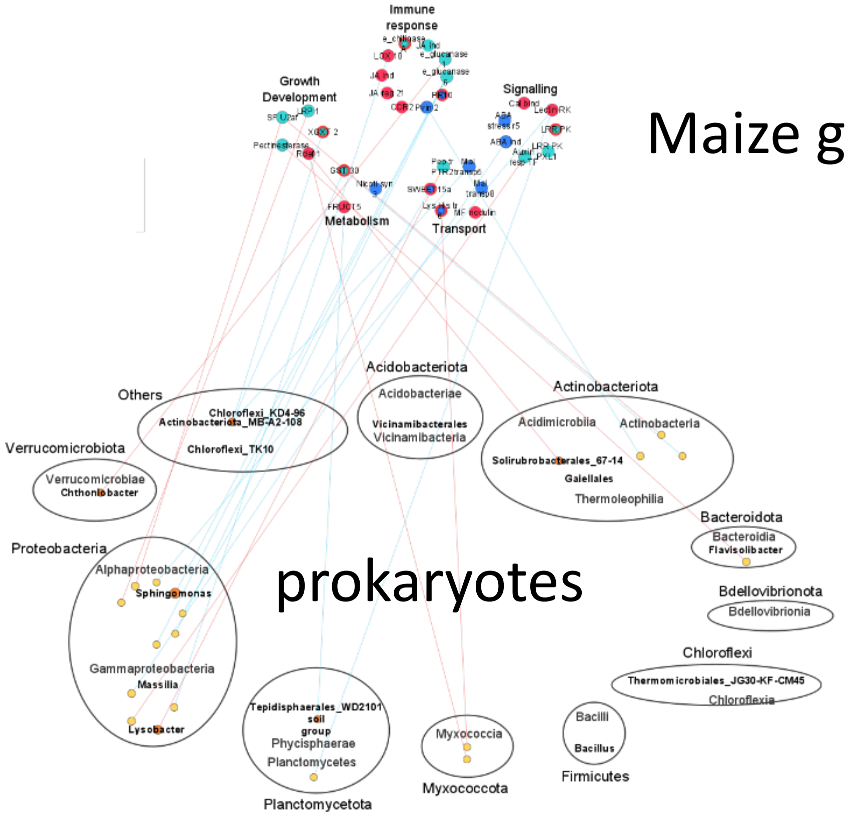
The root tip community composition is similar to those in the root hair zone and lateral root forming zone!

Maize gene categories

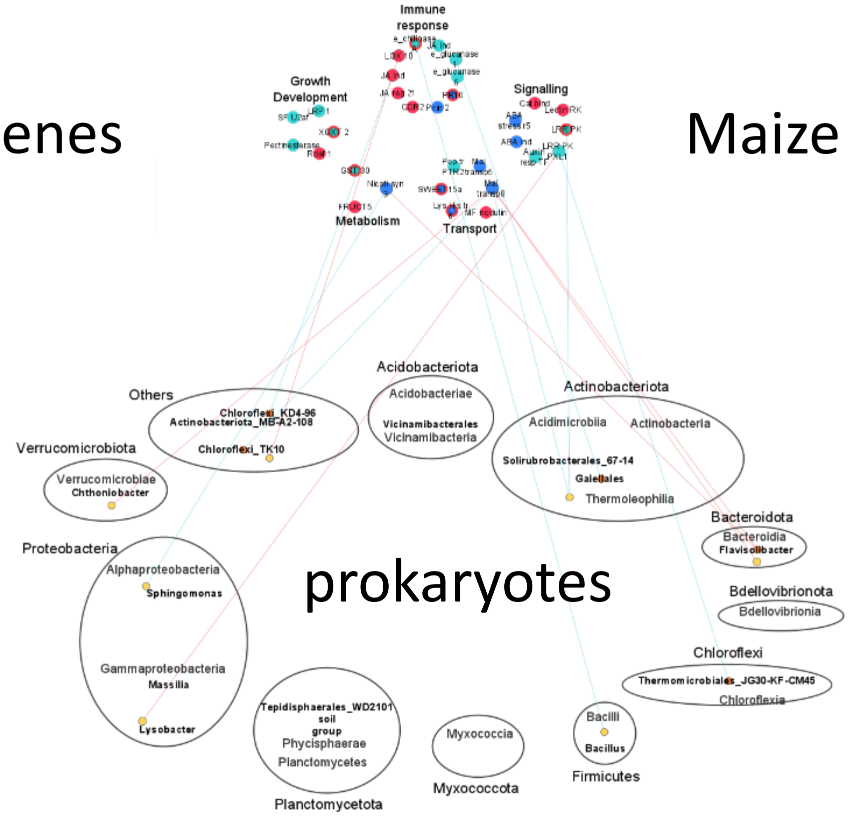
- ● transport
- ● growth
- ● immunity

Correlations between maize root gene expression and prokaryote abundance levels are related to the zone of the root

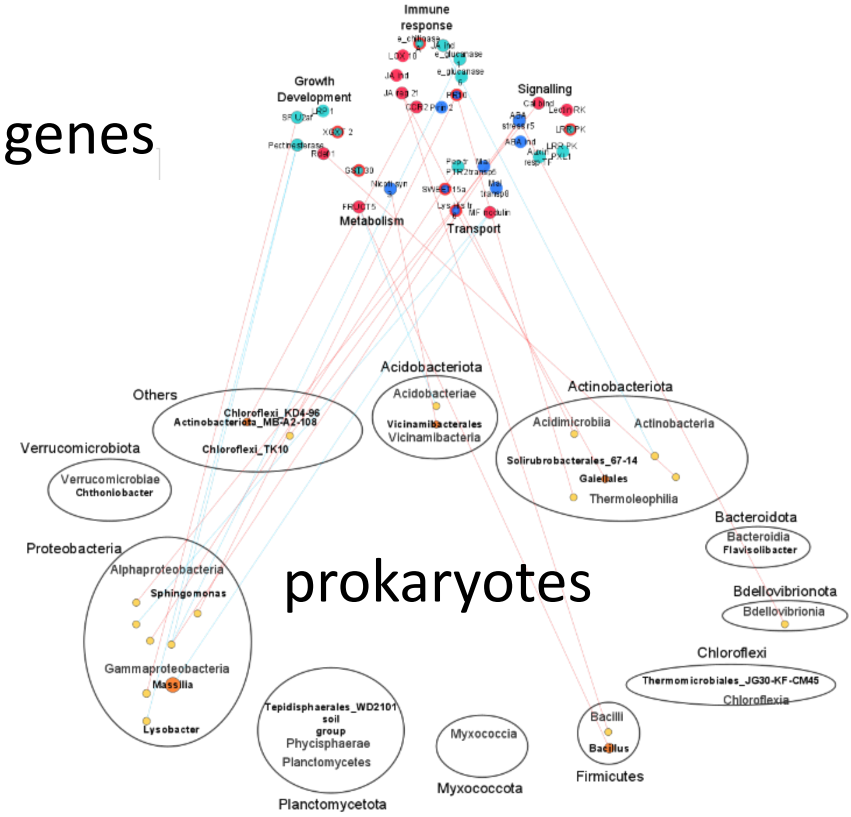
Root tip



Root hair forming zone

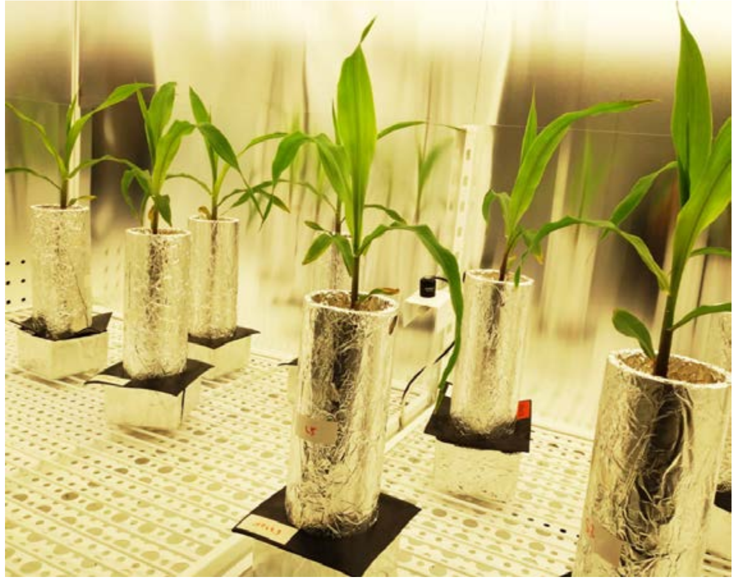


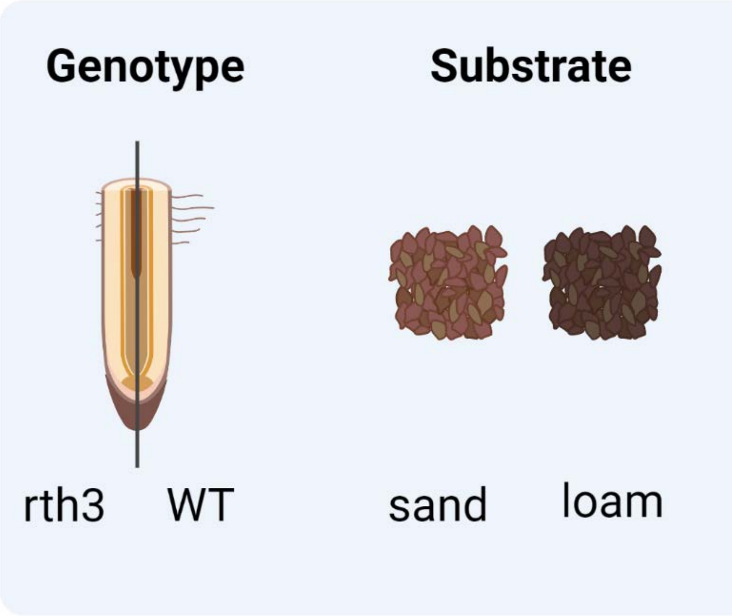
Lateral root forming zone



Formation of the rhizosphere: soil properties and depth

The effects of soil type and column depth on maize gene expression, prokaryote community composition, and plant beneficial acdS carrying prokaryote community composition

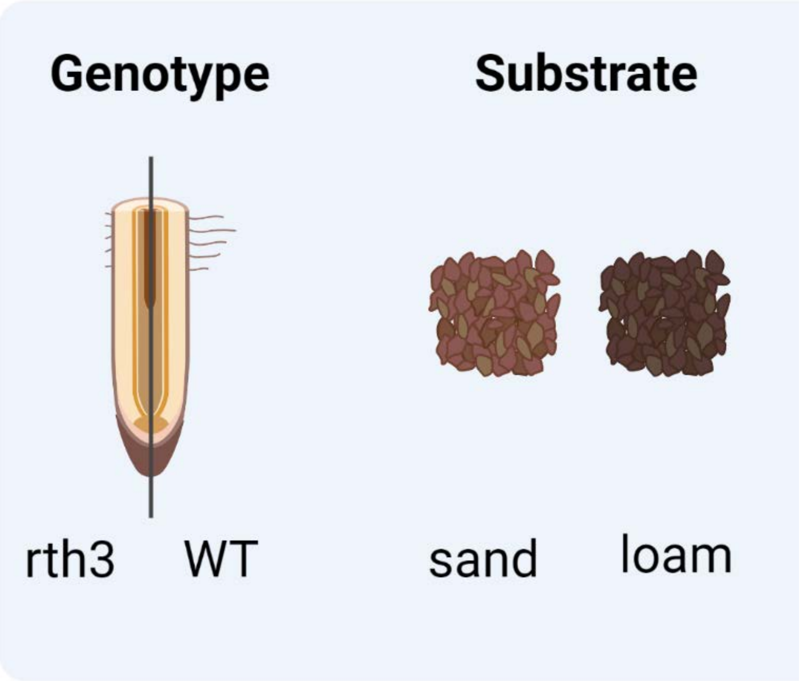


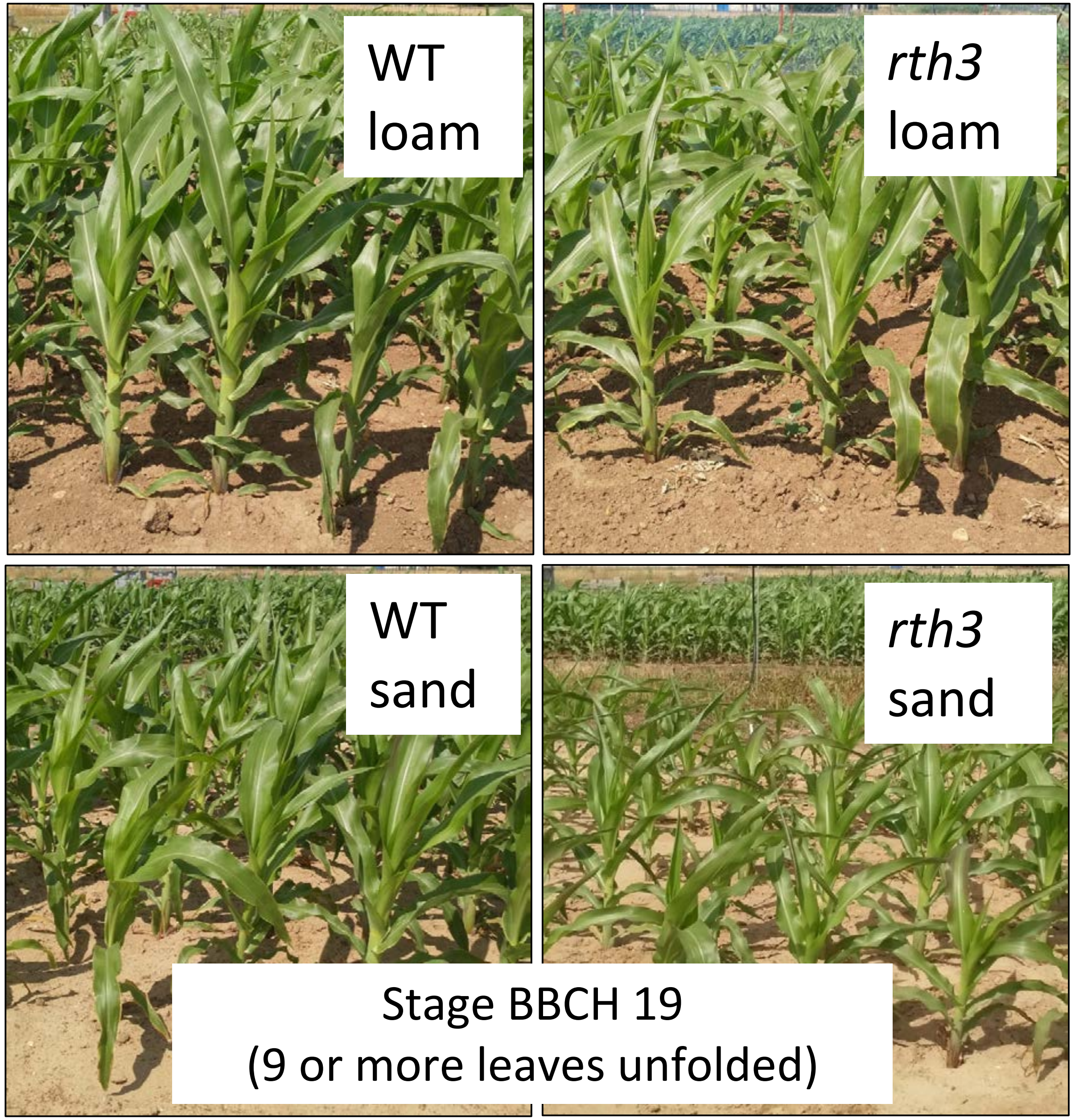


- Soil type greatest effect
- Depth of the columns a strong effect
- Presence of root hairs had minimal effect

Ganther et al. 2021 *Plant Soil,* Gebauer et al. 2021 *Frontiers Microbiol,* Yim et al. 2021 *Plant Soil*

Maize field experiment





Stage BBCH 19
(9 or more leaves unfolded)

Rhizosphere microbiomes

- arise from soil microbiomes that are diverse

-soil type is the reservoir for microorganisms, soil depth modifies the community, and plant developmental stage has a strong impact on them

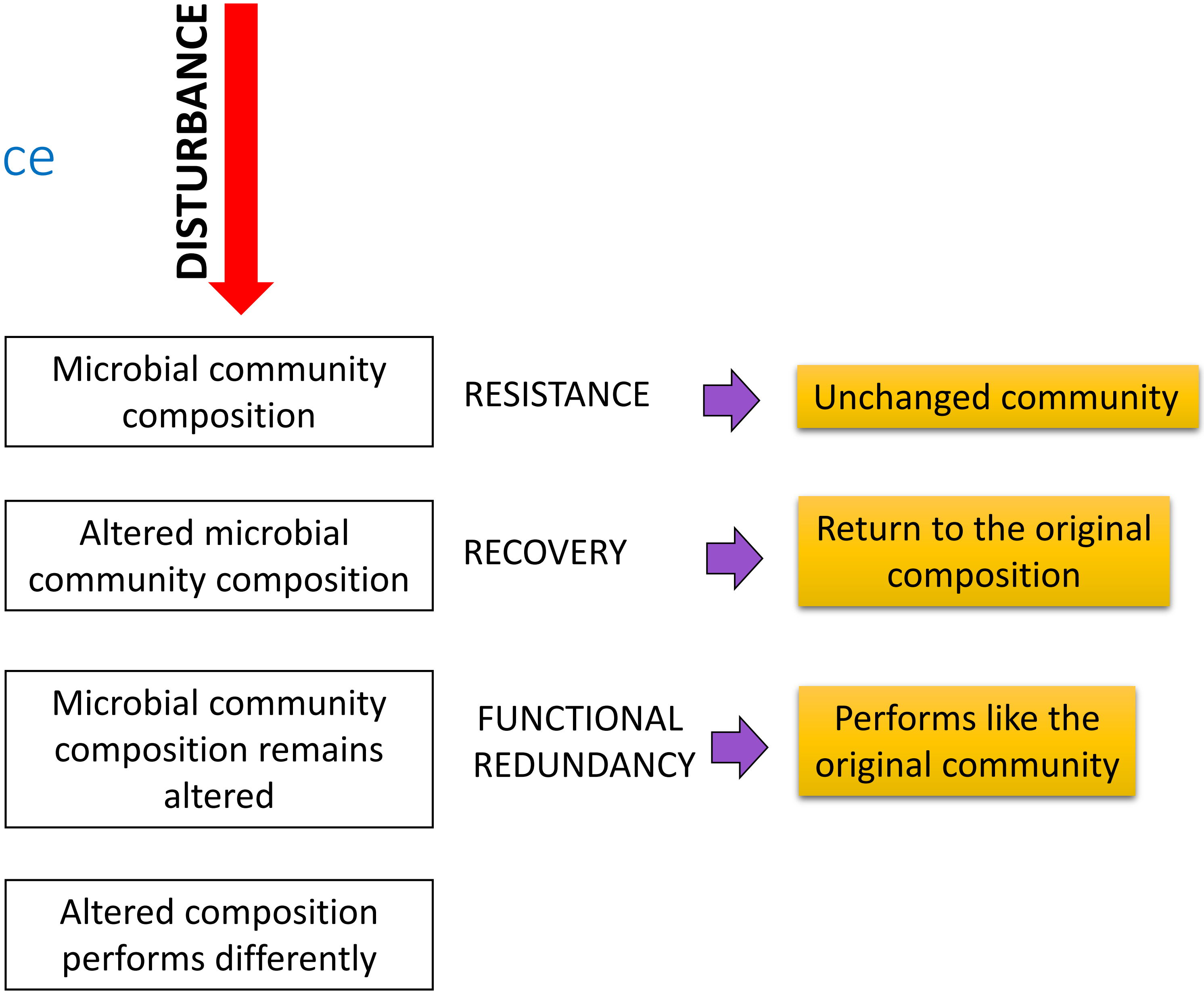
- rhizosphere formation is a well organized process

-root cap-derived cells and secreted mucilage offer first control

-secondary controls occur at older root parts by root exudates and plant defense

Resilience

How disturbance changes the structure and performance of microbial communities



DISTURBANCE

Microbial community composition

RESISTANCE

Unchanged community

Altered microbial community composition

RECOVERY

Return to the original composition

Microbial community composition remains altered

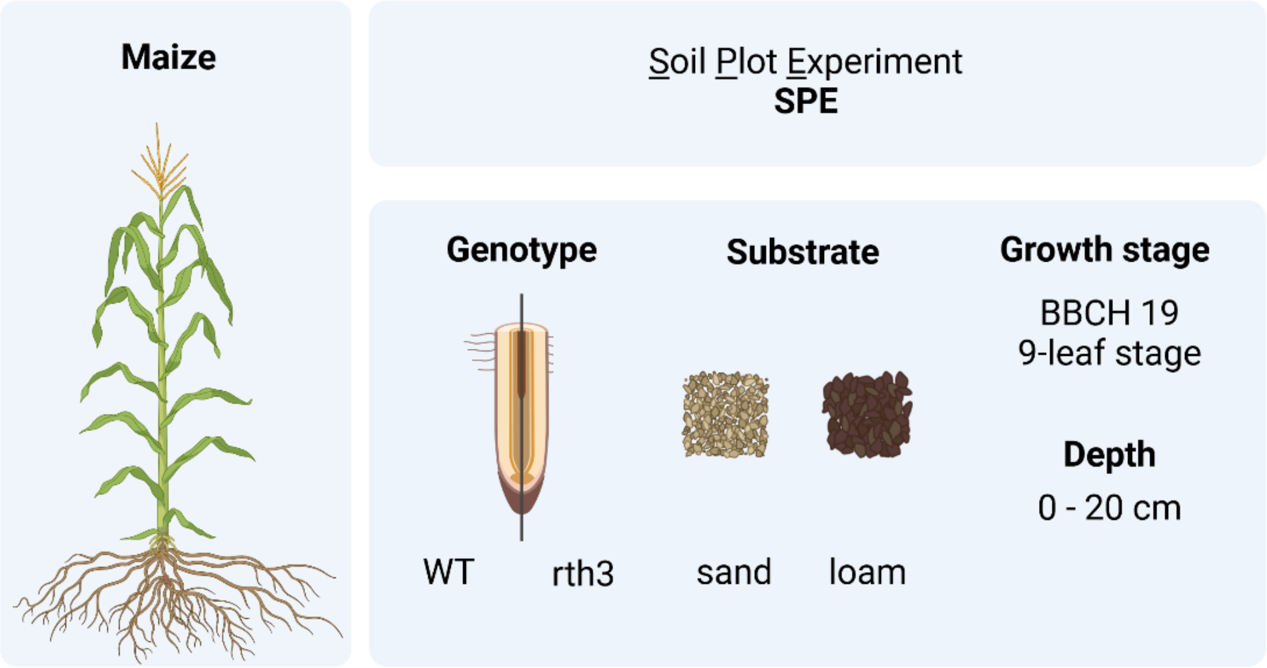
FUNCTIONAL REDUNDANCY

Performs like the original community

Altered composition performs differently

Griffiths et al. 2000 Oikos, Allison & Martiny PNAS 2008, Abdul Rahman et al. 2021 IJMS

Maize field experiment



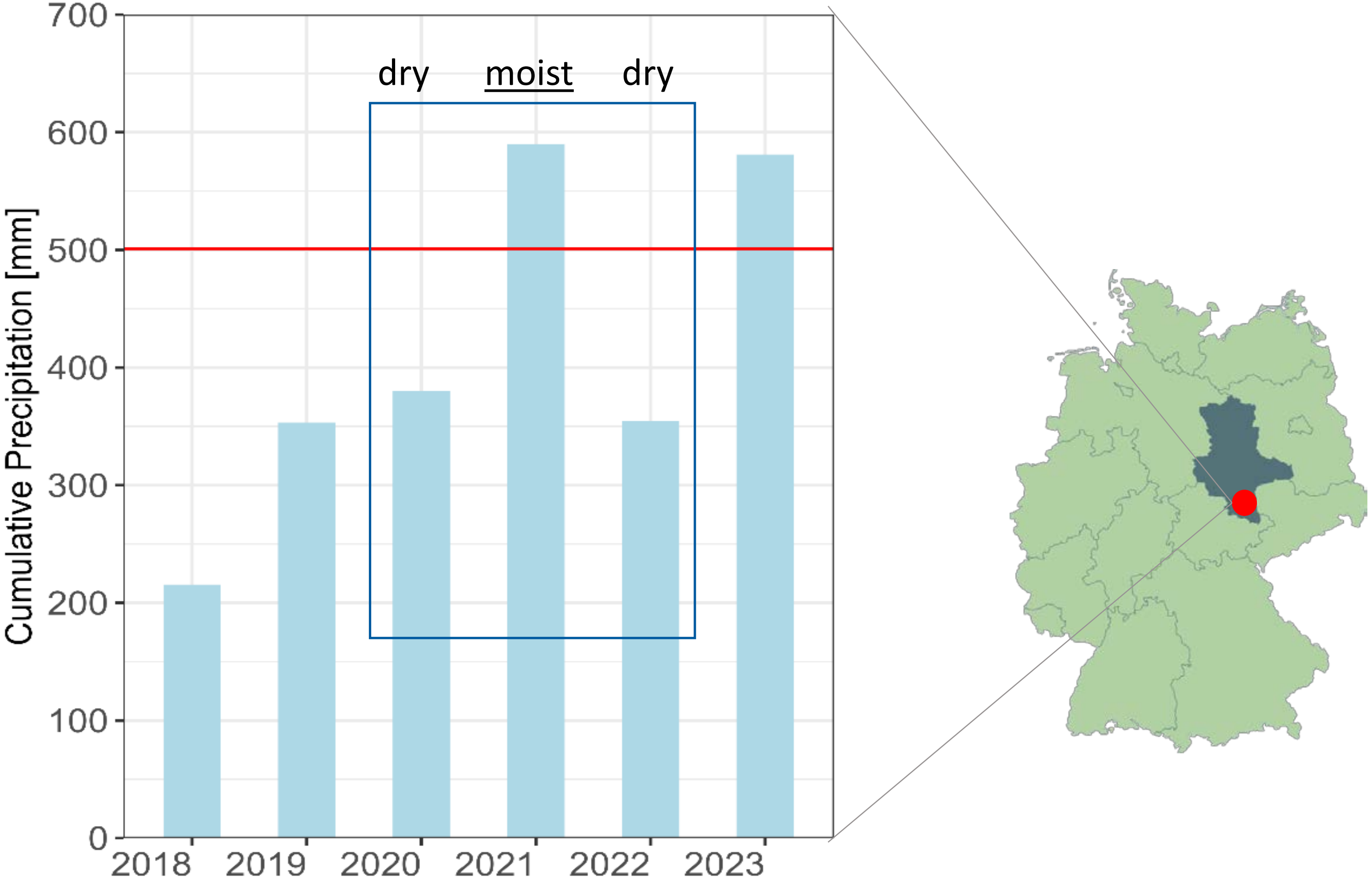
Sampling campaigns we joined:

- ➢ 2019: BBCH14, -19, -59
- ➢ 2020: BBCH19
- ➢ 2021: BBCH19
- ➢ 2022: BBCH19
- ➢ 2023: BBCH19

● Loam, WT
● Loam, rth3
● Sand, WT
● Sand, rth3

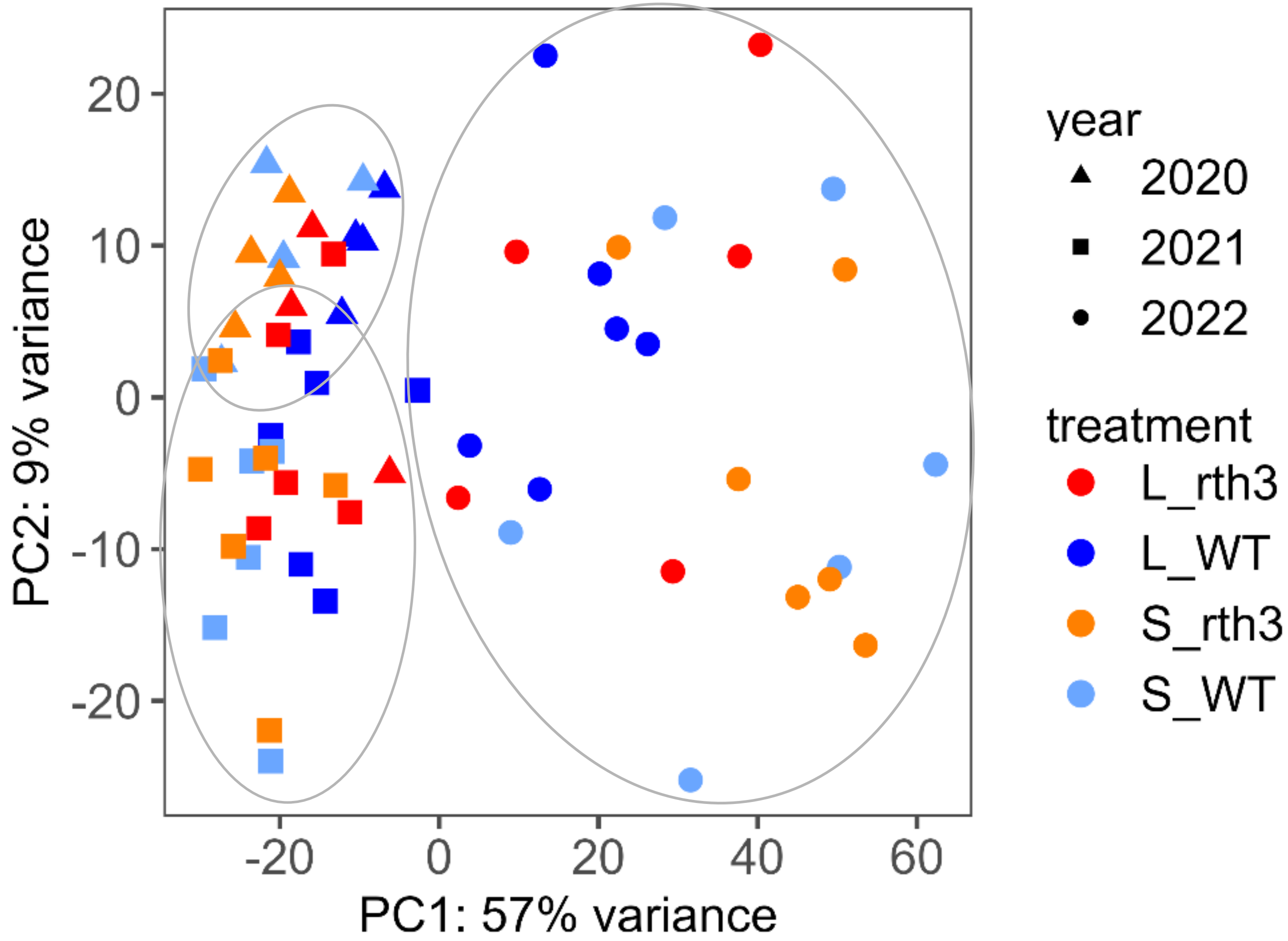
Climate in Bad Lauchstädt

“2018 – 2020 & 2022 dry years in Germany”



DWD Climate Data Center

Maize root gene expression



	R^2	
Year	0.34	***
Genotype	0.02	.
Substrate	0.03	**
Substrate:year	0.06	**
Residuals	0.57	

Henrike Würsig

Maize gene expression: Effects of year and substrate

2020 vs. 2021

	R^2	
Year	0.18	***
Substrate	0.09	***

2022 vs. 2021

	R^2	
Year	0.32	***
Substrate	0.04	*

Differential Expression Analysis

~ 1500 genes < ~ 3000 genes

2020 (dry)

	R^2	
Substrate	**0.16**	**

2021 (moist)

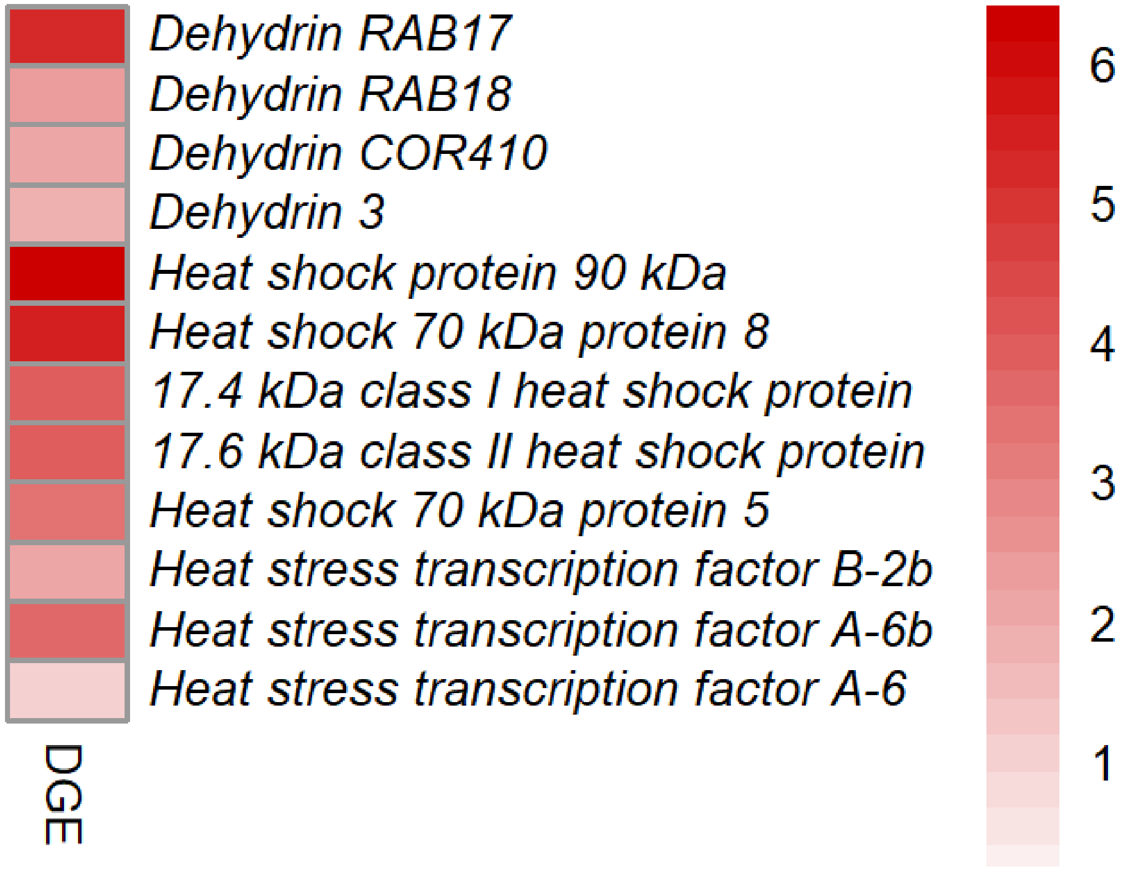
	R^2	
Substrate	0.13	***

2022 (dry)

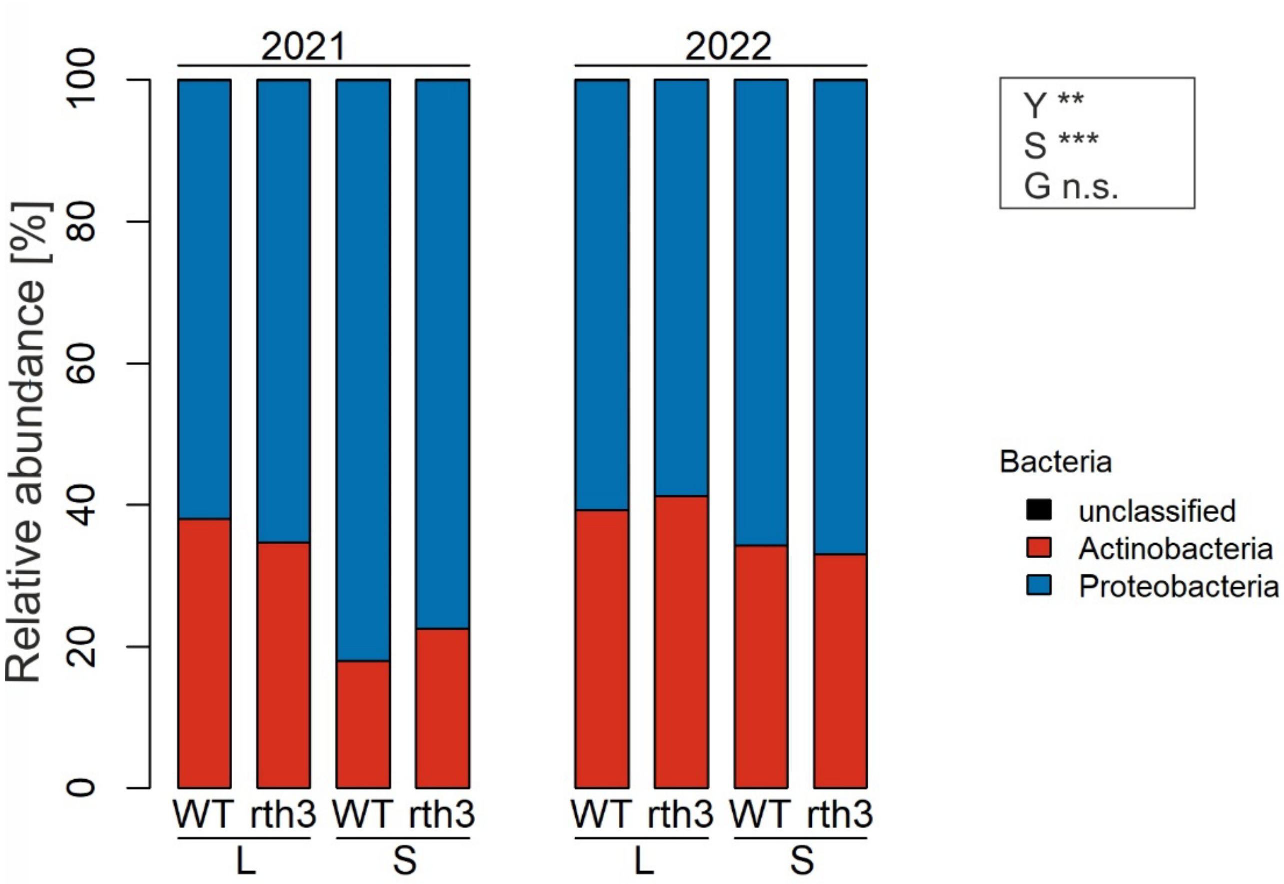
	R^2	
Substrate	**0.15**	**

Drought response related genes are more highly expressed during dry years

The genes were also differentially expressed in a column experiment with drought application



acdS gene carrying plant stress releasing bacterial community changes with characteristic drought related groups increased



	R^2	
Year	0.09	***
Genotype	0.02	
Substrate	0.24	***
Substrate:year	0.05	**
Residuals	0.57	

	2021 R^2		***2022*** R^2	
Genotype	0.03		0.03	
Substrate	0.35	***	0.27	***
Rest	0.59		0.67	

Dry and wet years in the maize experiment confirmed that drought is a driver of prokaryote community diversity

- Dry years led to changed maize gene expression and rhizosphere prokaryote community composition

- The magnitude of effect of drought depends on the „drought legacy“: how dry were the years before?

gcef
Global Change
Experimental
Facility

UFZ HELMHOLTZ
Zentrum für Umweltforschung

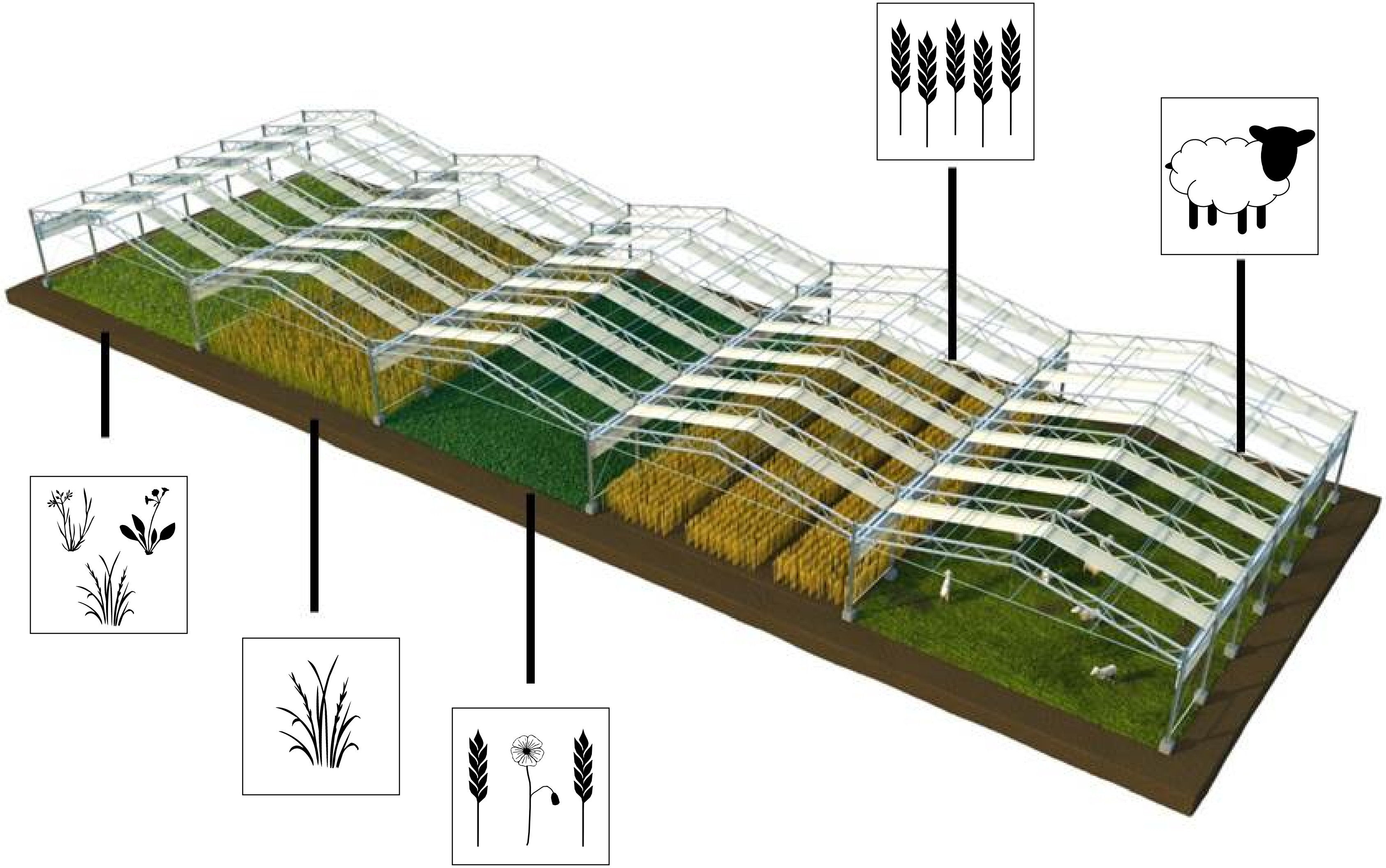
GCEF: Climate experiment with roofs and 5 types of land use in Bad Lauchstädt, Central Germany

gcef
Global Change
Experimental
Facility

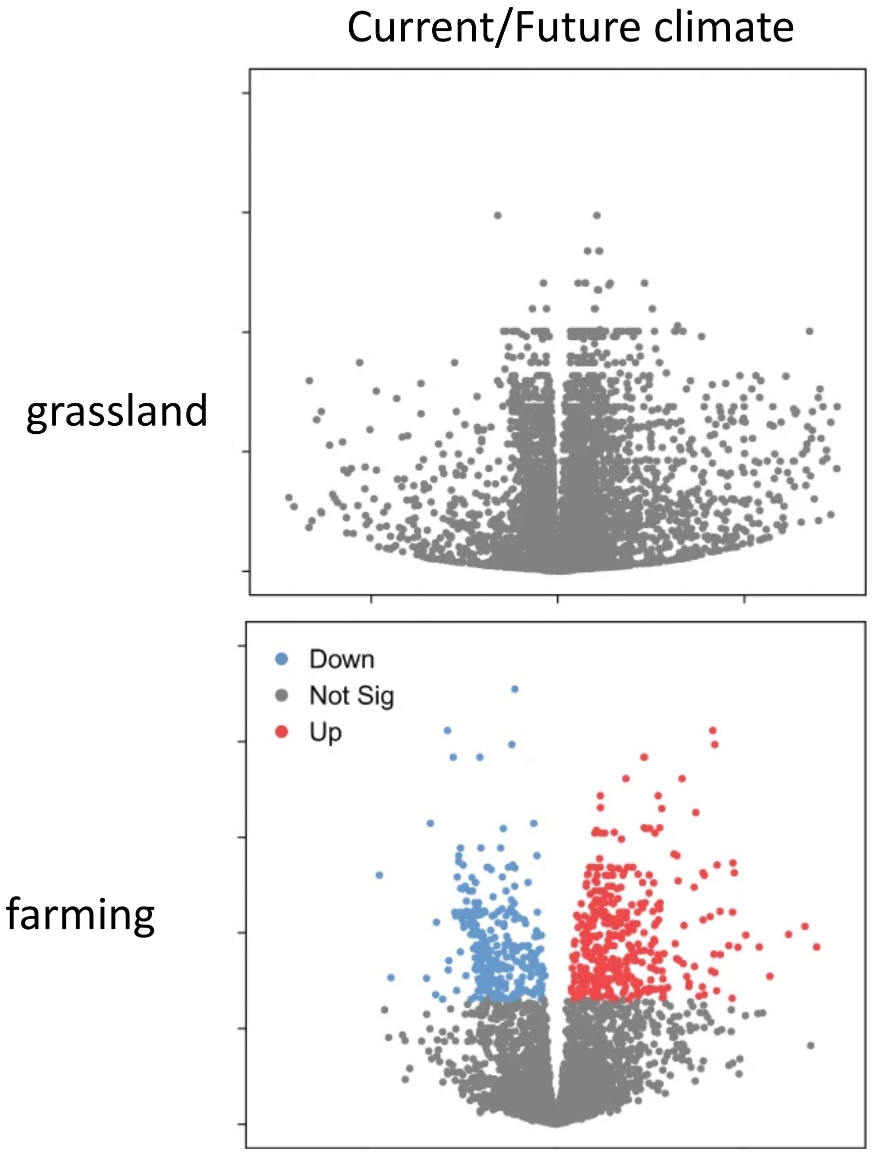
Crop rotation
Intensive farming
Organic farming

Grasslands
Intensive
Extensive
Extensive with grazing

Climate treatment: roofs
More rain in winter,
Less rain in summer



Climate treatment predominantly affects crop microbiomes



Prokaryote community changes by climate treatment in farming

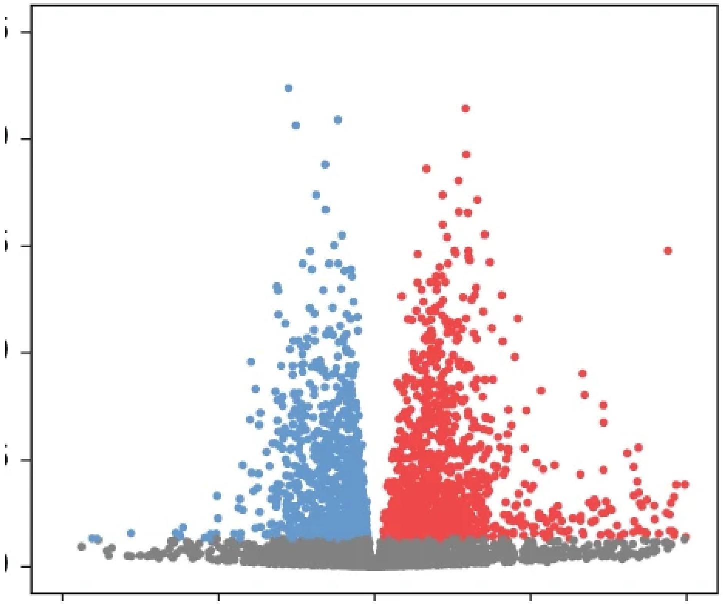
🔵 Groups that increase in future climate

🔴 Groups that decrease in future climate

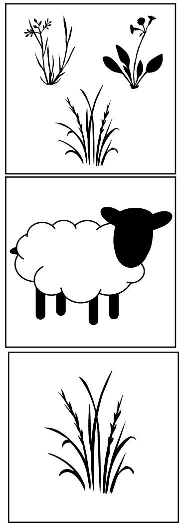
Bei et al. 2023 *ISME J*

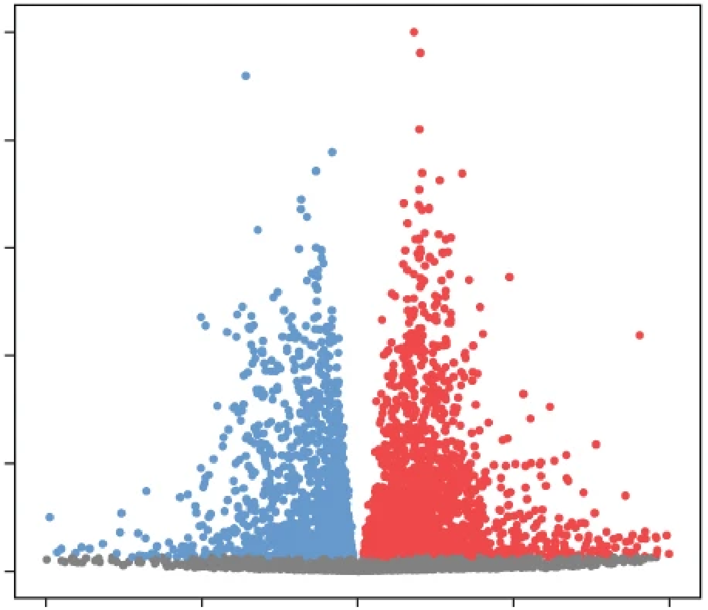
Dry years 2018 and 2019 had a major impact

BACTERIAL DIVERSITY
Normal/extremely dry years

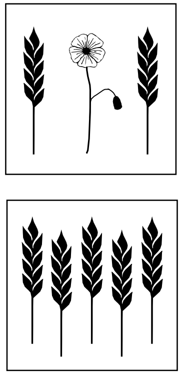


Grass-
land





Crop-
land



Bacterial diversity has changed considerably in both grassland and cropland as a result of the dry years.

- 🔵 Bacteria groups that have increased in the extreme years 2018 and 2019
- 🔴 Bacterial groups that have decreased in the extreme years 2018 and 2019

The changes have functional significance:
Strong reduction of soil enzyme activities

Untargeted soil gene (metagenome) analysis:
Changes in the abundance of C and N uptake and metabolism genes

Bei et al. 2023 *ISME J*

Resilience of the rhizosphere microbiomes

- Community composition changes drastically when a stress is prolonged or caused by multiple stressors simultaneously.
- Resilience results from high functional redundancy between microorganisms (for key functions)
- The potential risk of loss of functions for specific responses (e.g. pesticide degradation, production of certain secondary metabolites) remains.
- In the future, we should find markers of essential soil biodiversity,
  to be used for modelling purposes

Bei et al. 2023 *ISME J,* Rillig et al. 2023 *Nat Climate Change*, König et al. 2023 *Eur J Soil Sci*

Benefits for plant growth

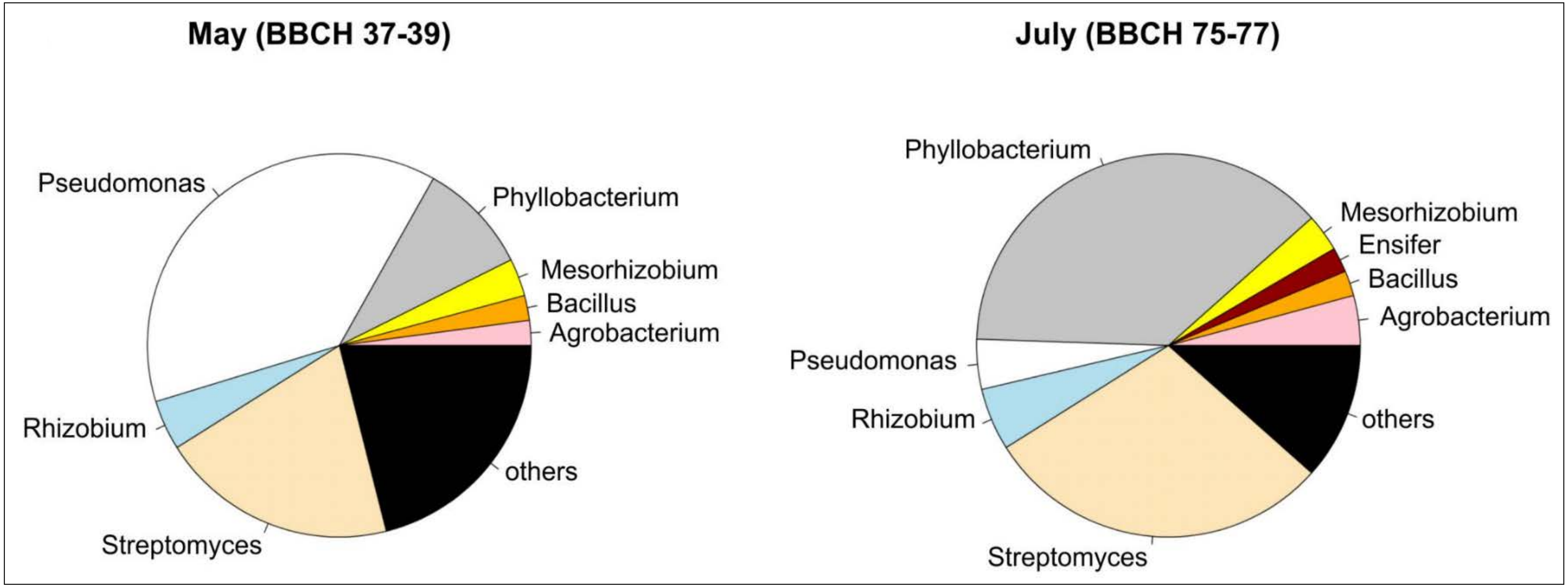
Collections of rhizosphere bacteria from wheat and barley rhizospheres

Claudia
Breitkreuz

Schädler et al. 2019 *Ecosphere*

Photo: Andre Künzelmann

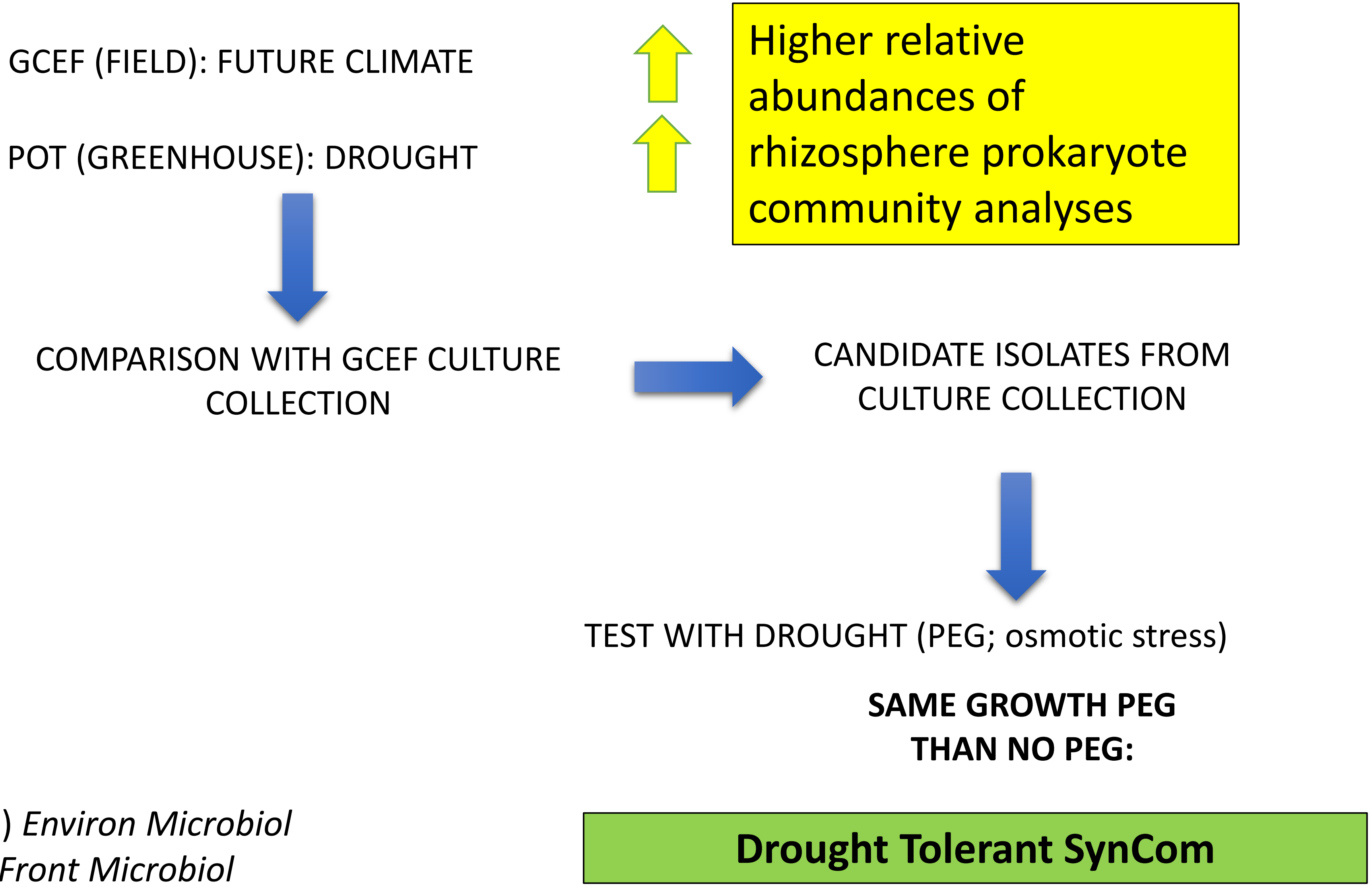
Seasonal change in P-solubilising bacteria from wheat rhizosphere during the growing season - from *Pseudomonas* to *Phyllobacterium*



In total 817 mineral P-solubilising bacterial Isolates from wheat rhizosphere

Breitkreuz et al. 2020 *Frontiers Microbiol*

Selection of drought-tolerant members for synthetic communities from barley and wheat rhizospheres



GCEF (FIELD): FUTURE CLIMATE

POT (GREENHOUSE): DROUGHT

Higher relative abundances of rhizosphere prokaryote community analyses

COMPARISON WITH GCEF CULTURE COLLECTION

CANDIDATE ISOLATES FROM CULTURE COLLECTION

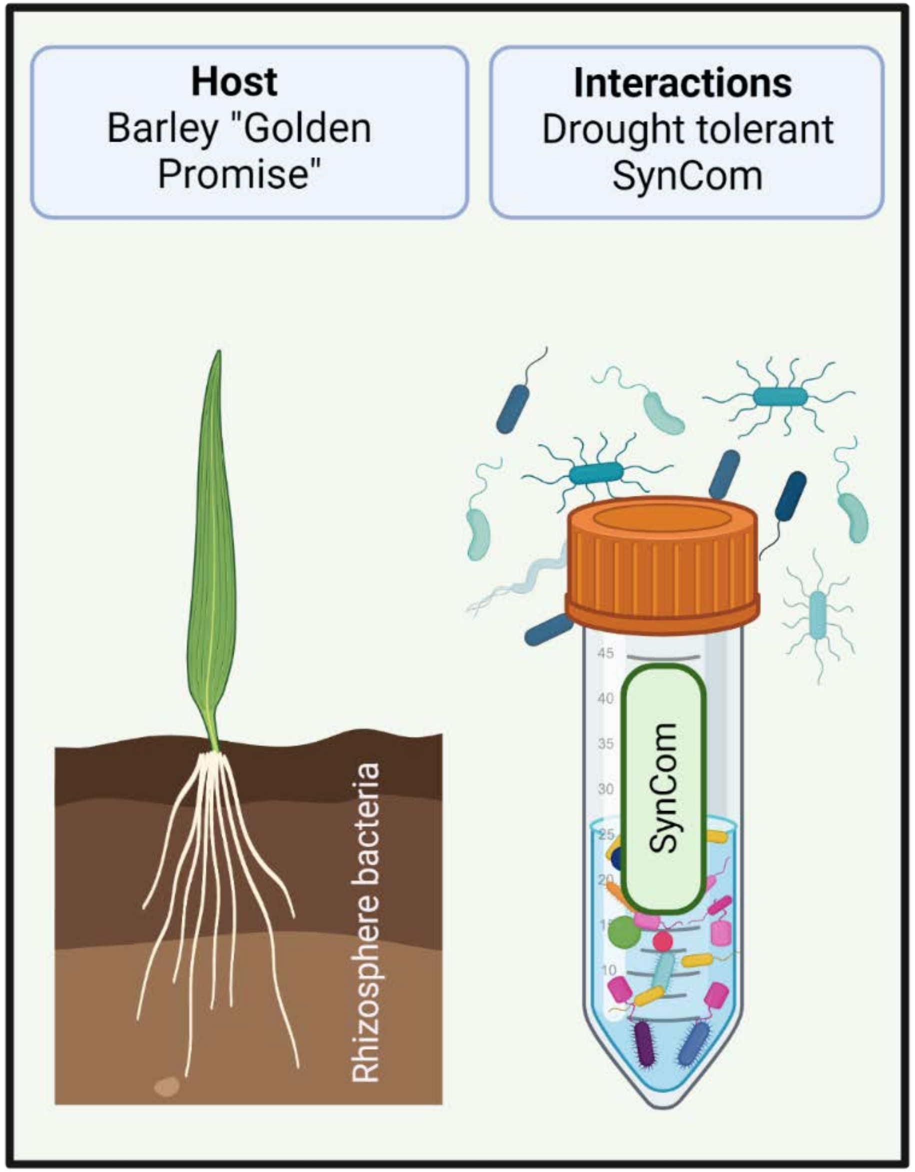
TEST WITH DROUGHT (PEG; osmotic stress)

SAME GROWTH PEG THAN NO PEG:

Drought Tolerant SynCom

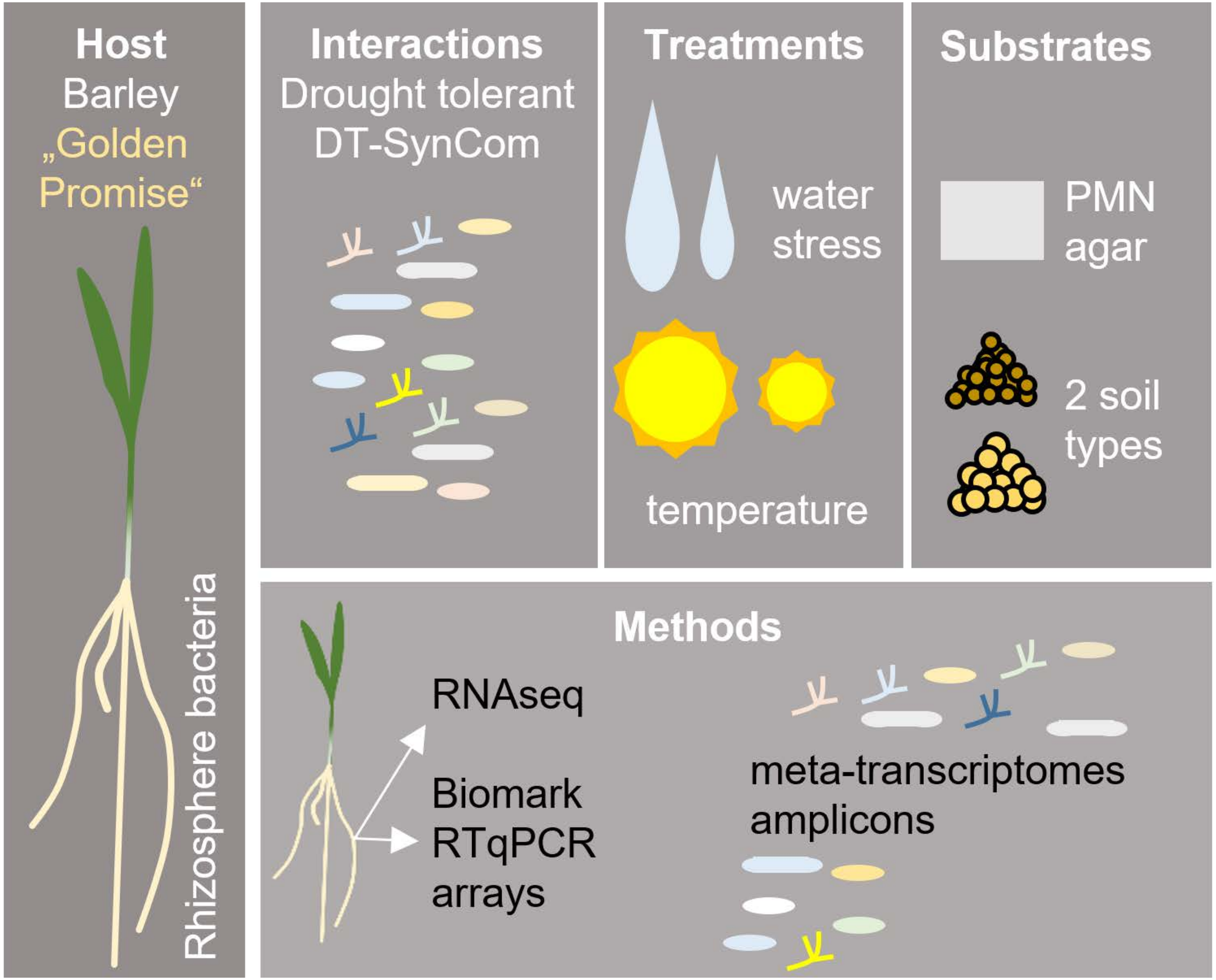
Breitkreuz et al (2021) *Environ Microbiol*
Gebauer et al (2022) *Front Microbiol*

Benefits for the host plant?



Community analyses and cultivation of rhizosphere microorganisms to assess their potential to increase the stress tolerance of plants

Linda Rigerte



Approach: To assess interactions between bacteria and their influence on barley under drought, high temperature and plant disease

Aim: To elucidate bacterial community factors involved in plant drought tolerance.

Product: Plant stress tolerance-enhancing bacterial community

Isolating and enriching plant beneficial microorganisms

- Strategies for finding beneficial plant growth promoting bacteria and ensuring their functionality in the field are under intensive analysis

- Approaches to support the beneficial members of plant microbiome are to
  - -apply stress (drought, pathogen)
  - -change management (crop rotation, cover crops, soil amendments, intercropping)
  - -change plant variety (plant selects for beneficial microbes /plant responds to them)

Integration between disciplines

Integration at national level

German Science Foundation (from 2024):
Permanent Senate Commission on the Transformation of Agricultural and Food Systems
advises various target groups in politics, research and society on developments relating to upcoming transformations in agricultural and food systems

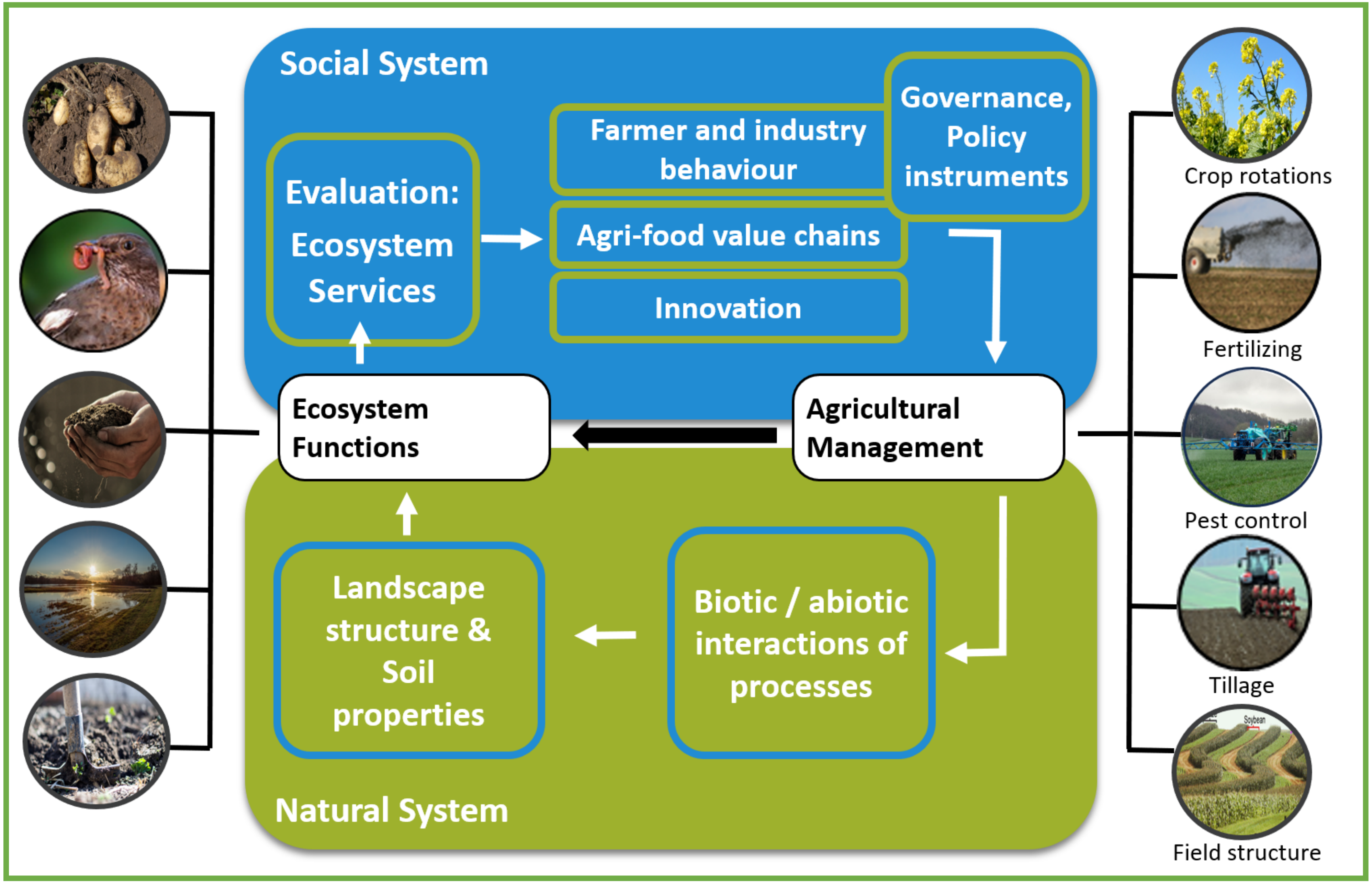
- ways of achieving food security within planetary boundaries
- ways of diversifying the cultivation of crops
- ways of bringing about a societal transformation in the production and consumption of meat and animal products.

Chair: Doris Vetterlein

UFZ HELMHOLTZ Zentrum für Umweltforschung

Funded by DFG Deutsche Forschungsgemeinschaft

Integration at research programme level of an interdisciplinary institute



Social System

Evaluation: Ecosystem Services

Farmer and industry behaviour

Governance, Policy instruments

Agri-food value chains

Innovation

Ecosystem Functions

Agricultural Management

Landscape structure & Soil properties

Biotic / abiotic interactions of processes

Natural System

Crop rotations

Fertilizing

Pest control

Tillage

Field structure

Thematic area Ecosystems of the Future

Vogel,
Rode,
Möckel,
Tarkka

UFZ HELMHOLTZ Zentrum für Umweltforschung

Figure:
Hans-Jörg Vogel

At which level do soil scientists, microbiologists, landscape ecologists and sociologists meet?

ECOSYSTEM FUNCTIONS (processes to maintain life) and SERVICES (for human beings)

Provisioning Services
Food Production, Fiber and Raw Materials

Regulating Services
Climate Regulation, Water Regulation,
Pollination, Pest and Disease Control

Supporting Services
Soil Formation, Nutrient Cycling, Biodiversity Maintenance

Acknowledgements

Thomas Reitz
Doris Vetterlein
Eva Lippold
Susanne Schreiter
Marie-Lara Bouffaud
Anna Heintz-Buschart
Evgenia Blagodatskaya

Kerstin Hommel
Minh Ganther
Lucie Gebauer
Henrike Würsig
Linda Rigerte
Maria Roldan

Kornelia Smalla
Bunlong Yim
Michael Bonkowski
Lioba Rüger
Eva Oburger
Michael Santangeli
Corina Vlot Schuster

Deutsche Forschungsgemeinschaft
DFG

DBU

UFZ
HELMHOLTZ
Zentrum für Umweltforschung