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Agroscope

Universität Zürich[UZH]

Soil Health and Regenerative Agriculture

Marcel van der Heijden et al.
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(marcel.vanderheijden@uzh.ch)
Twitter/X: vandeHeijdenLab

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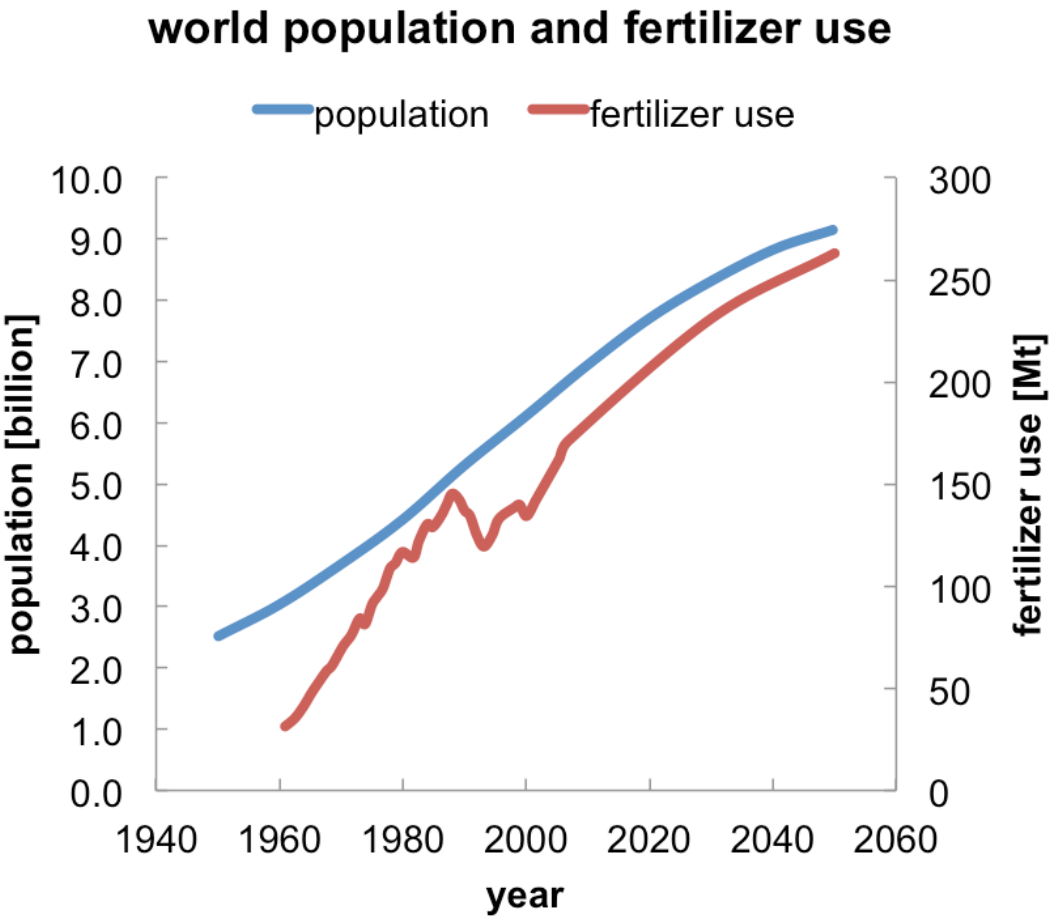
Global demand for food will increase with 60% in the coming 35 years: we have to produce more, but also more sustainably – a role for soil health and soil microbiomes?



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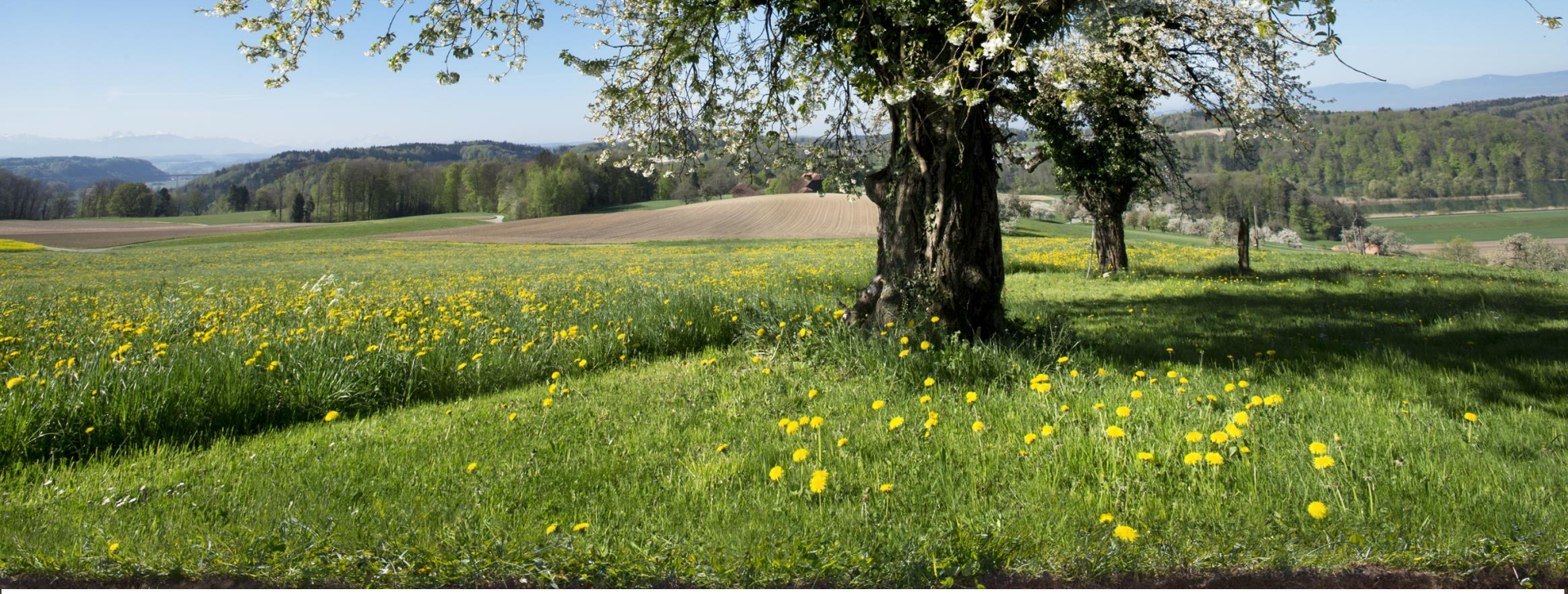


<u>Soil Processes:</u>

Plant Nutrition

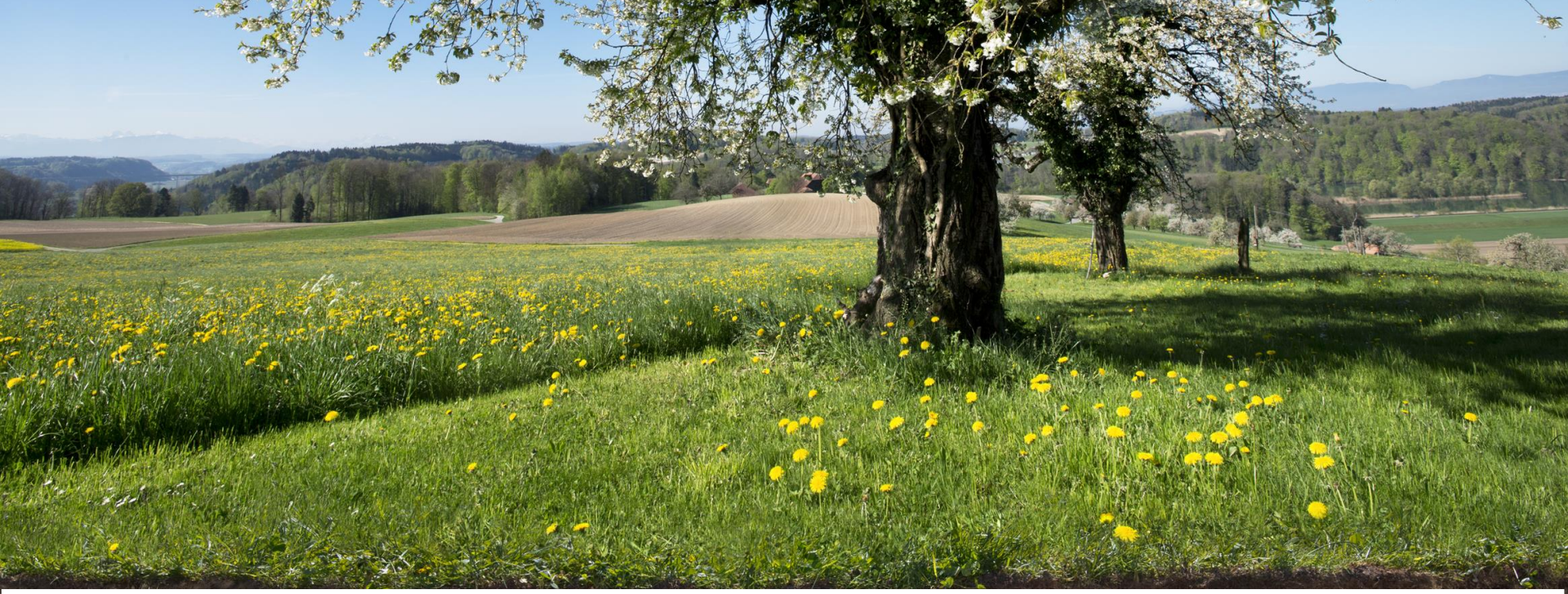
Biodiversity Reservoir

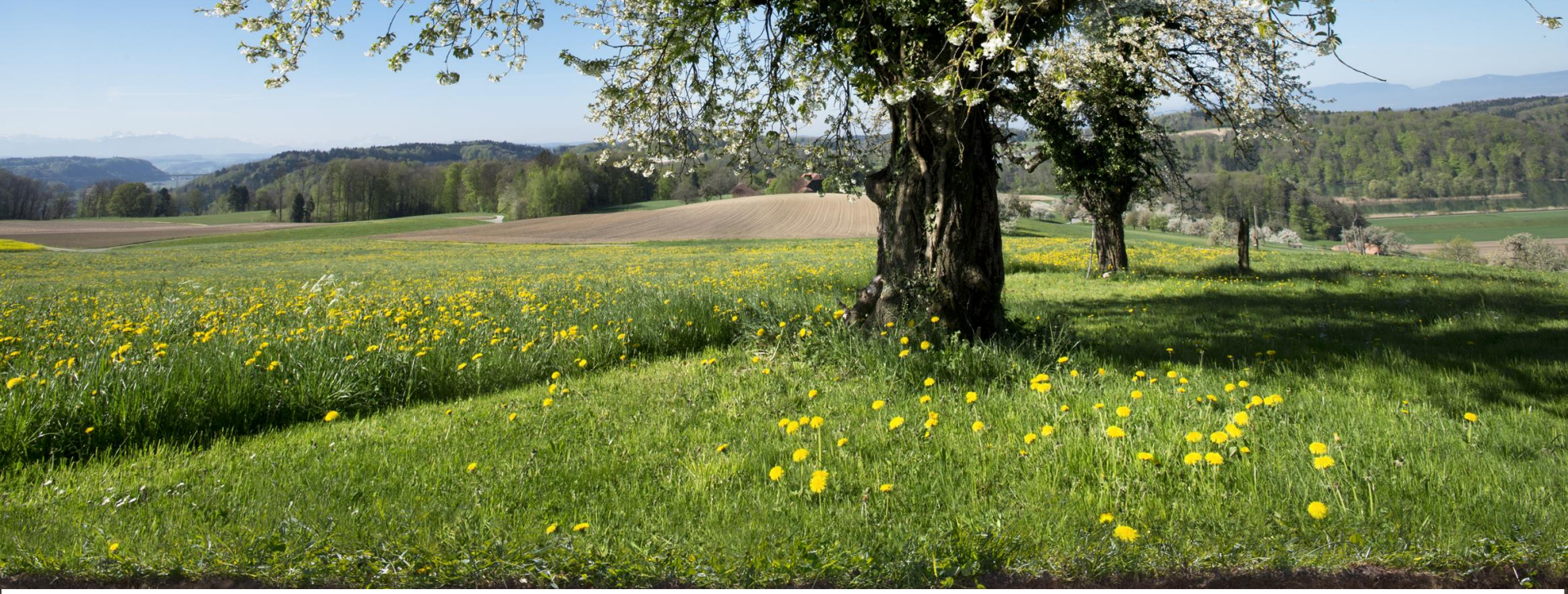
Carbon Storage

Water Storage

Filtration & Cleaning

Nutrient Cycling

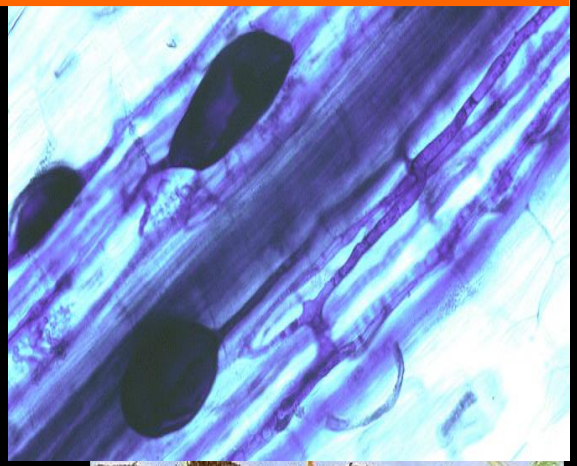




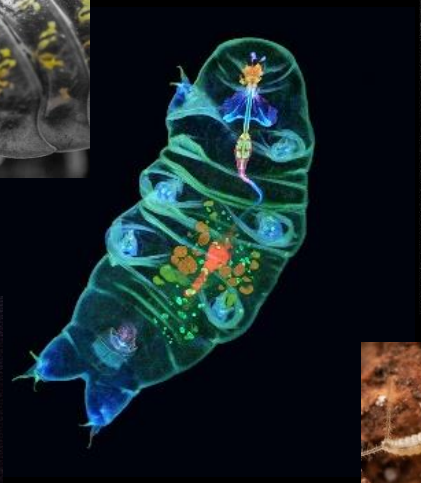
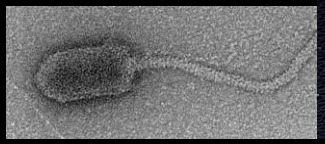
Soils are highly diverse: an estimated 59% of Earths Biodiversity is linked to the soil

1 gram of soil contains up to 10^{10} bacteria, >10.000 taxa and up to100 metre of fungal hyphae

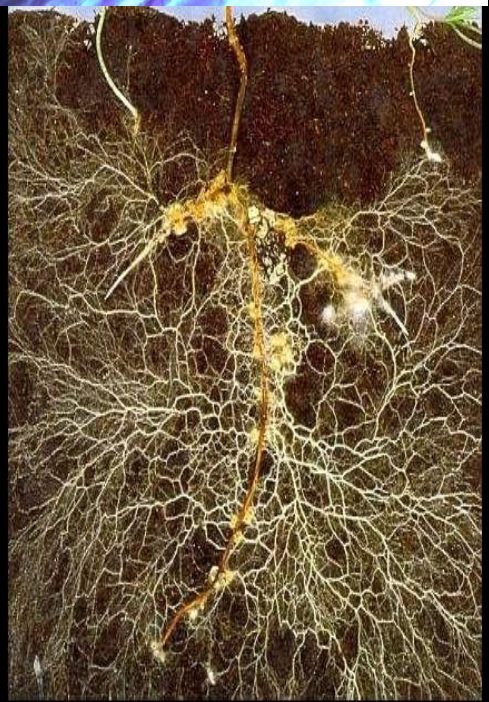






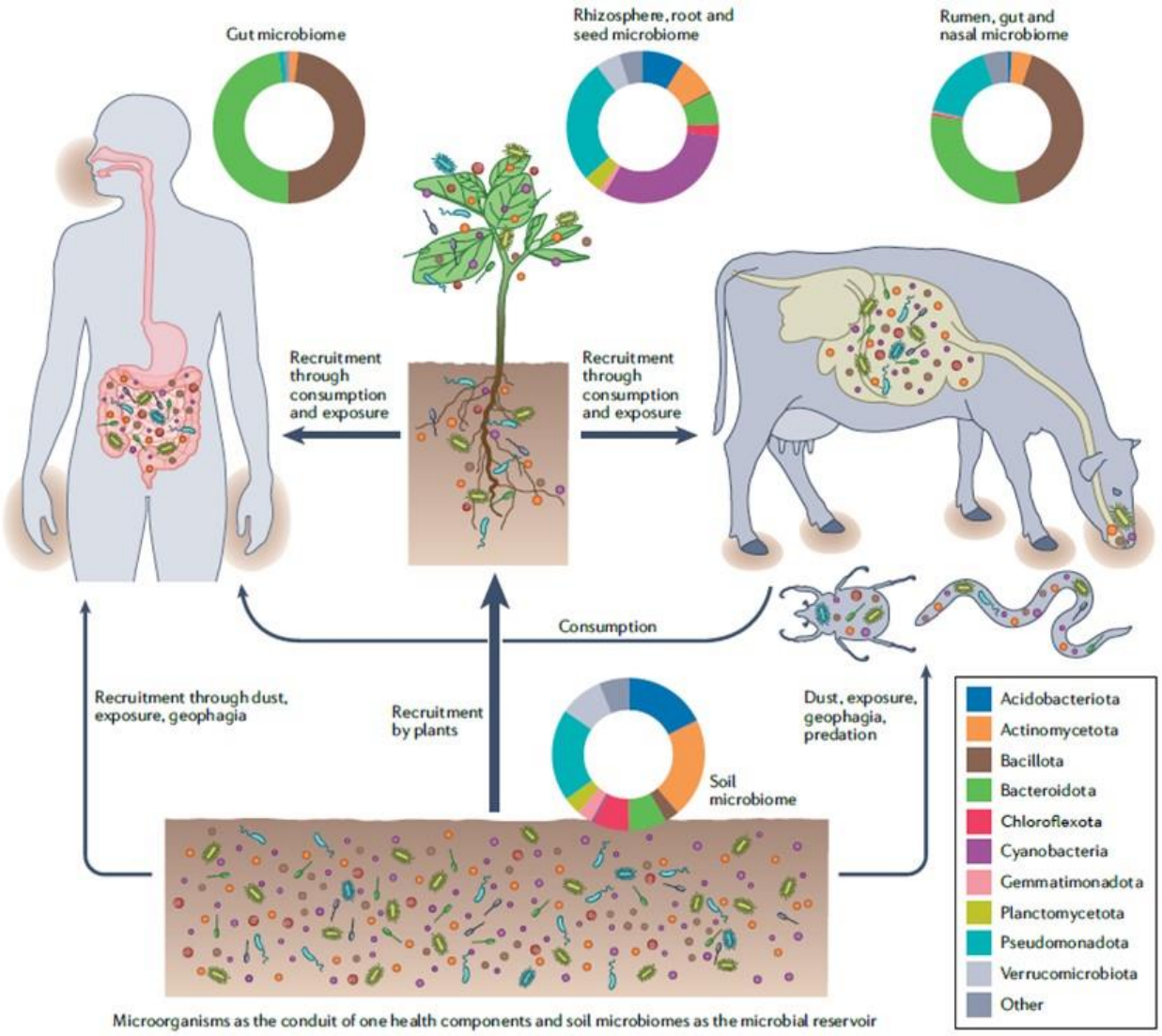




Anthony, Bender & van der Heijden (2023), PNAS:

Photos: F. Ashwood, G.Brändle, H. Conrad, D. Müller, A Murray, D. Müller, D. Read

The soil microbiome as a conduit of one health



Microorganisms as the conduit of one health components and soil microbiomes as the microbial reservoir

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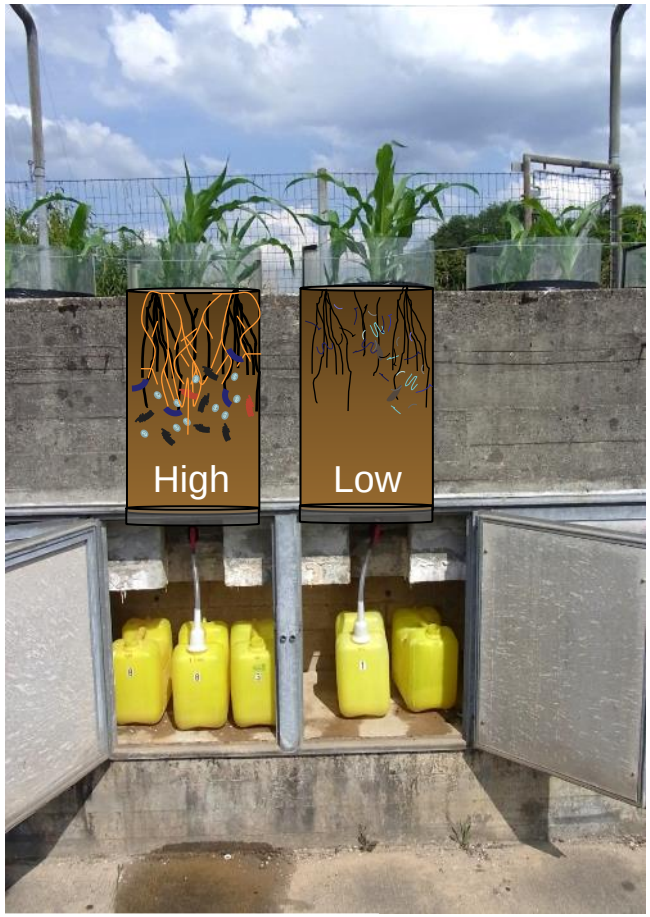
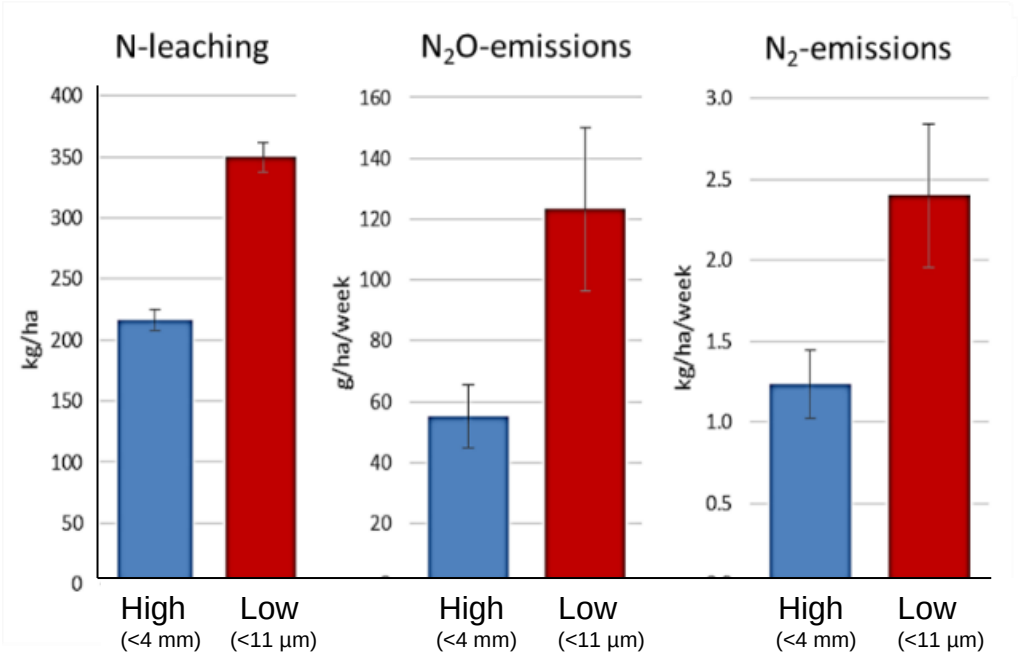
Banerjee & van der Heijden (2023) *Nature Reviews Microbiology*

Soil Biodiversity reduces nutrient losses when background soil biodiversity levels are very low





Bender et al. (2023), *New Phytologist*

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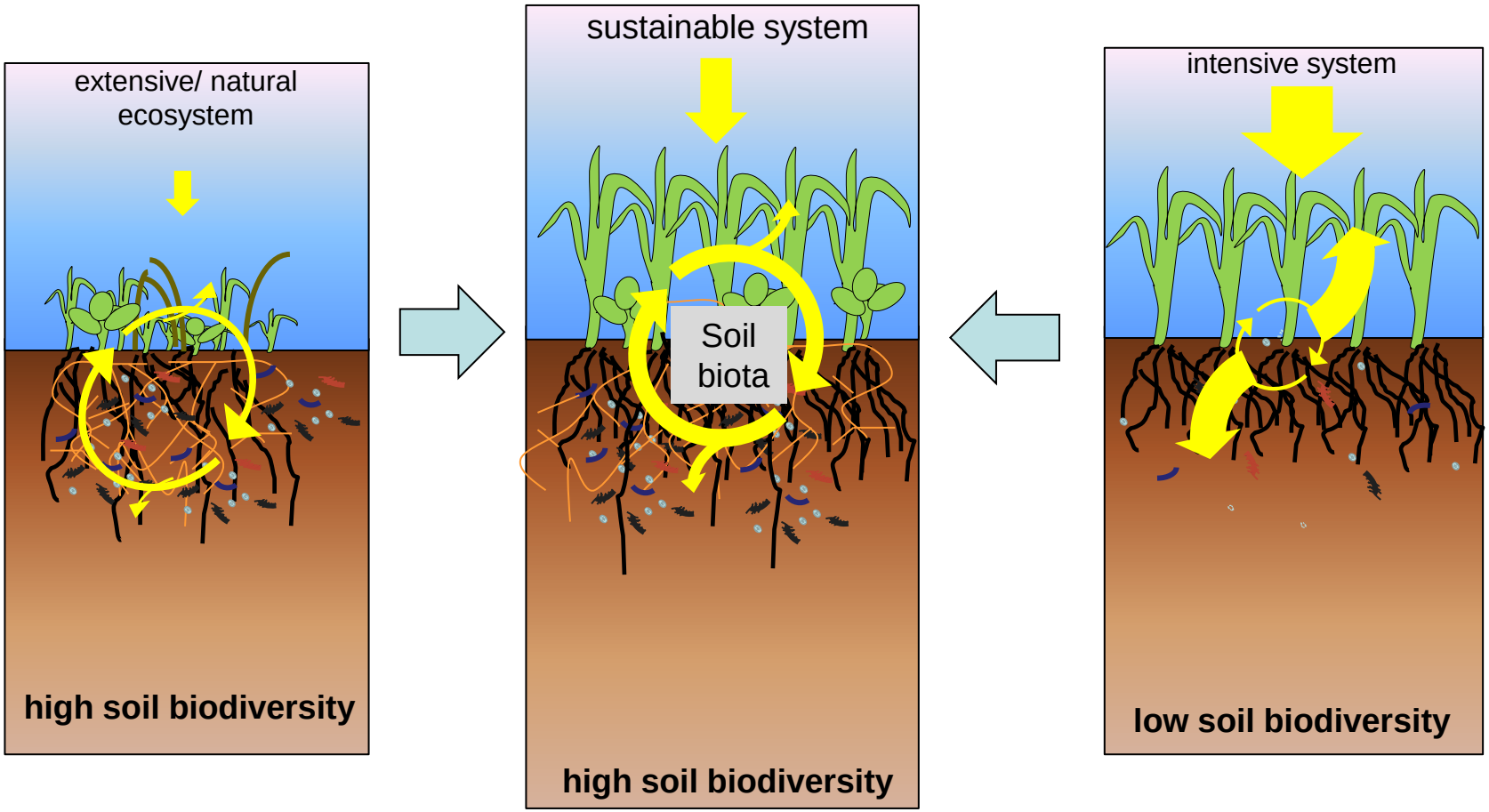
working model: microbiome management and soil ecological engineering as a tool to enhance ecosystem sustainability



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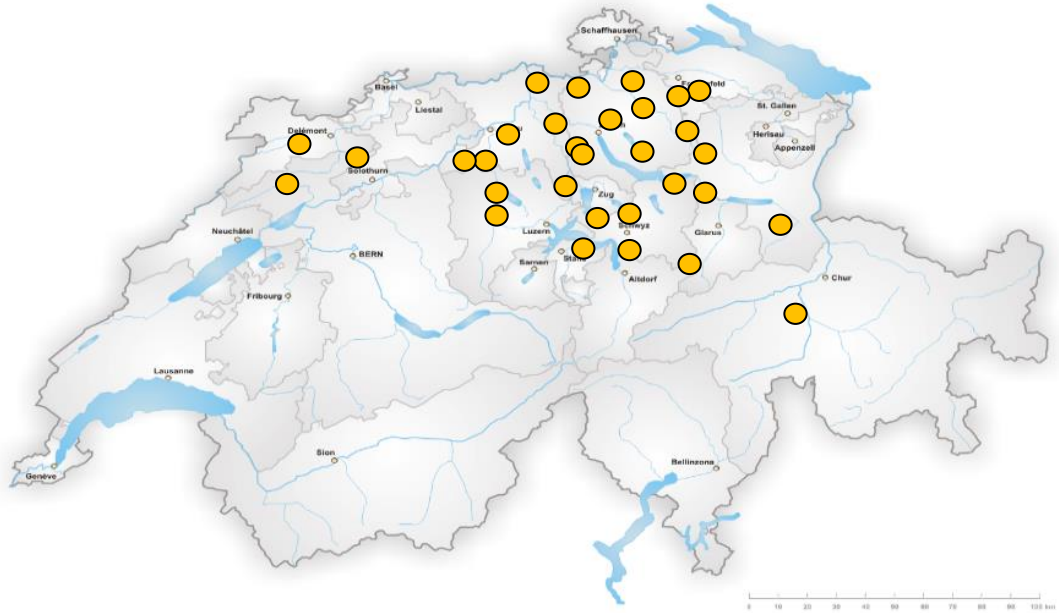
Bender, Wagg & van der Heijden 2016, *TREE*
Bender, Wagg & van der Heijden 2017, *TREE*

Research Goals

- Microbiome Engineering: Is it possible to enhance plant and soil health by altering the microbiome (e.g. inoculation with beneficial microbes).
- Soil Health & Regenerative Agriculture: How can we enhance soil health and how does it relate to plant yield and various environmental services.

Microbiome Engineering: Is it possible to enhance plant yield by inoculating with biofertilisers (we focus on arbuscular mycorrhizal fungi)?



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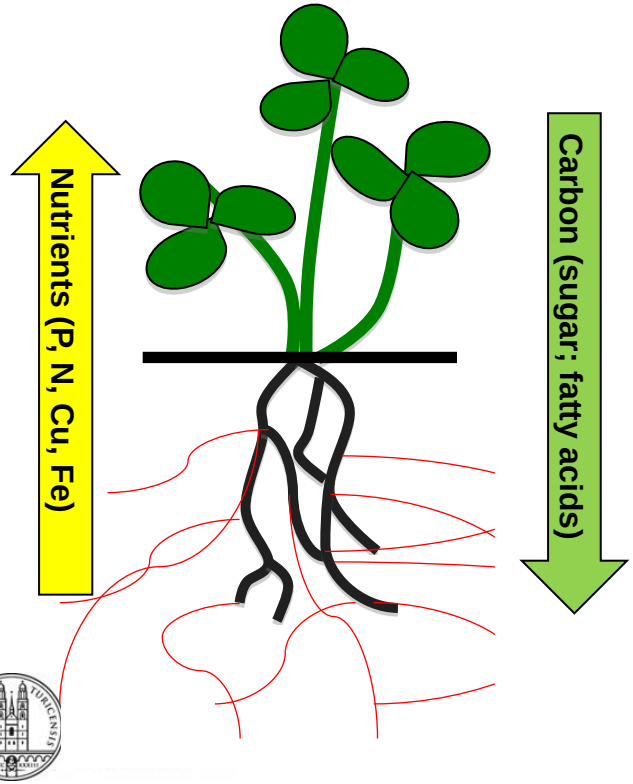
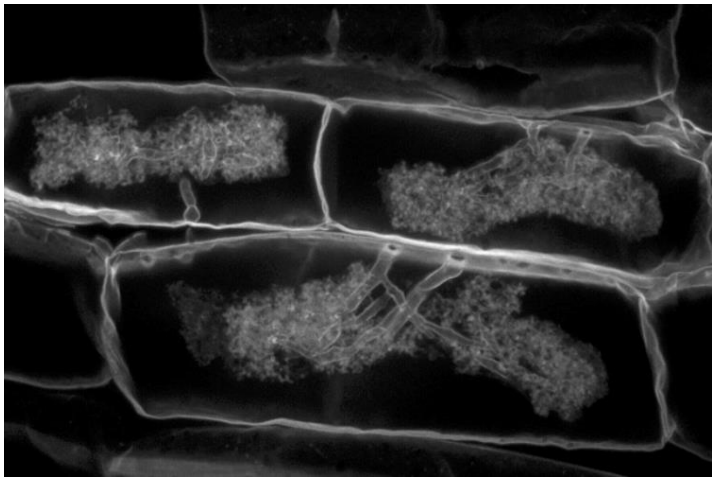
Arbuscular mycorrhizal fungi (AMF)

- Probably the most ancient and abundant plant symbionts on Earth.
- Up to 90% of plant P and plant N is acquired by mycorrhizal fungi
- Arbuscular mycorrhizal fungi associate with most major crops including arable crops (potato, cereals) and vegetables (e.g. salad, tomato, carrot)





van der Heijden et al. 1998, *Nature*
Smith & Read 2008, Mycorhizal Symbiosis
van der Heijden et al. 2015, *New Phytologist*
Martin & van der Heijden 2024, *New Phytologist*

half of the plots inoculated with AMF (*Rhizoglomus irregulare)*
half with a control inoculum

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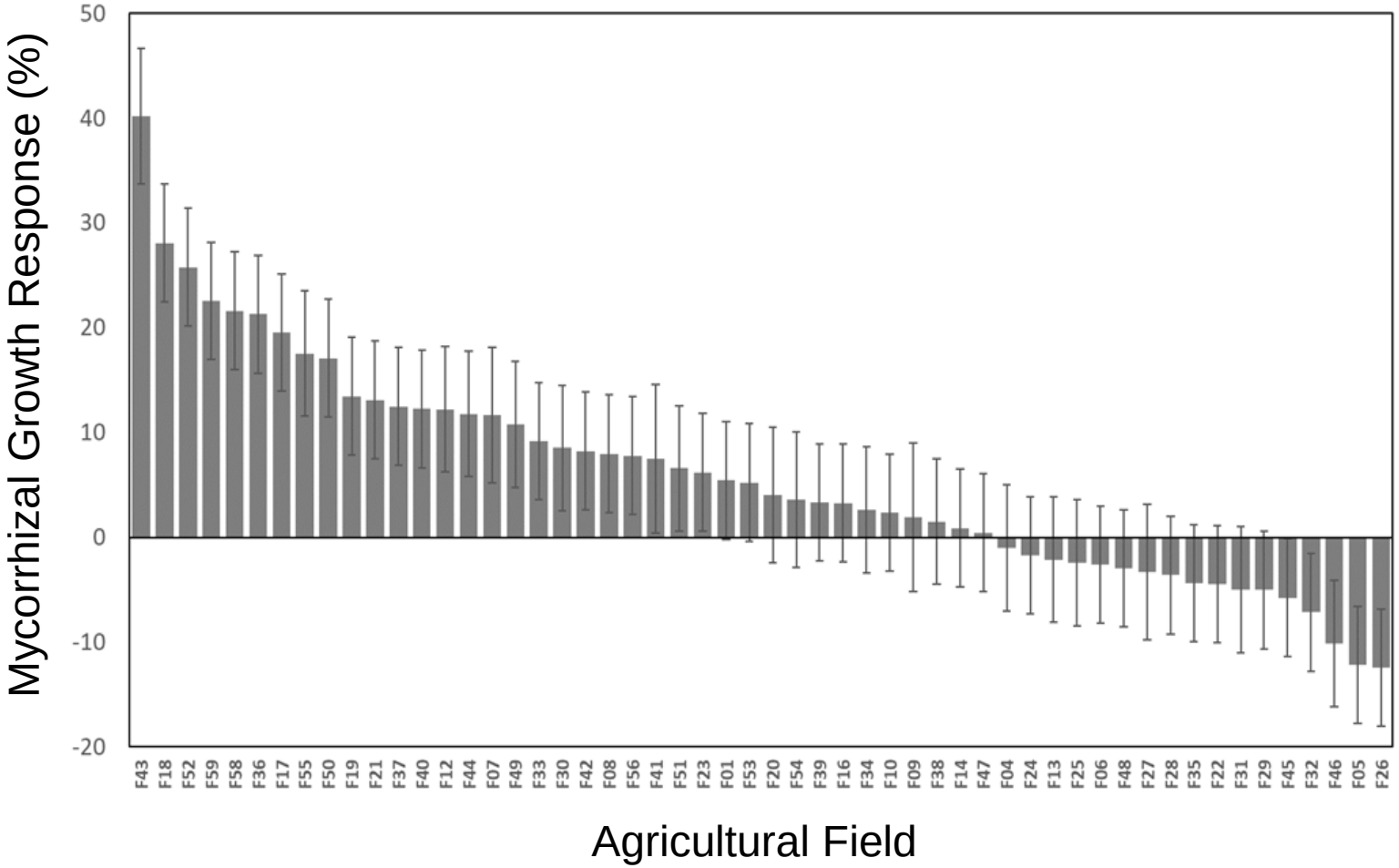
Field Inoculation has a lot of potential, but not always…

Steffi Lutz

Natacha Bodenhausen

Klaus Schläppi

Julia Hess



Lutz, Bodenhausen……. Schläppi, van der Heijden (2023), *Nature Microbiology*.

FiBL

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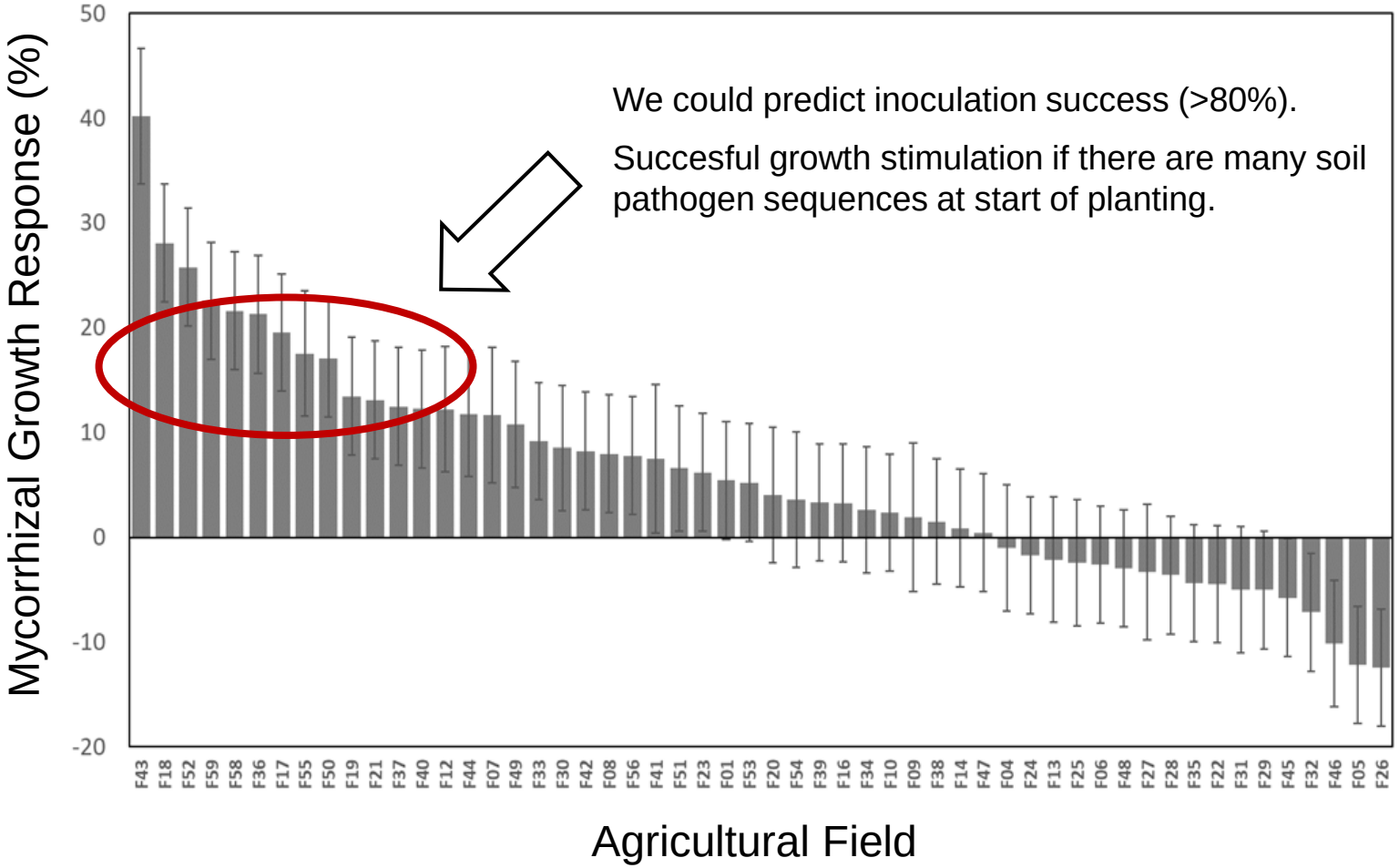
WISSENSCHAFT. BEWEGEN
GEBERT RÜF STIFTUNG

Succesful field Inoculation was linked to the occurrence of fungal pathogens



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Lutz, Bodenhausen……. van der Heijden (2023), *Nature Microbiology*.

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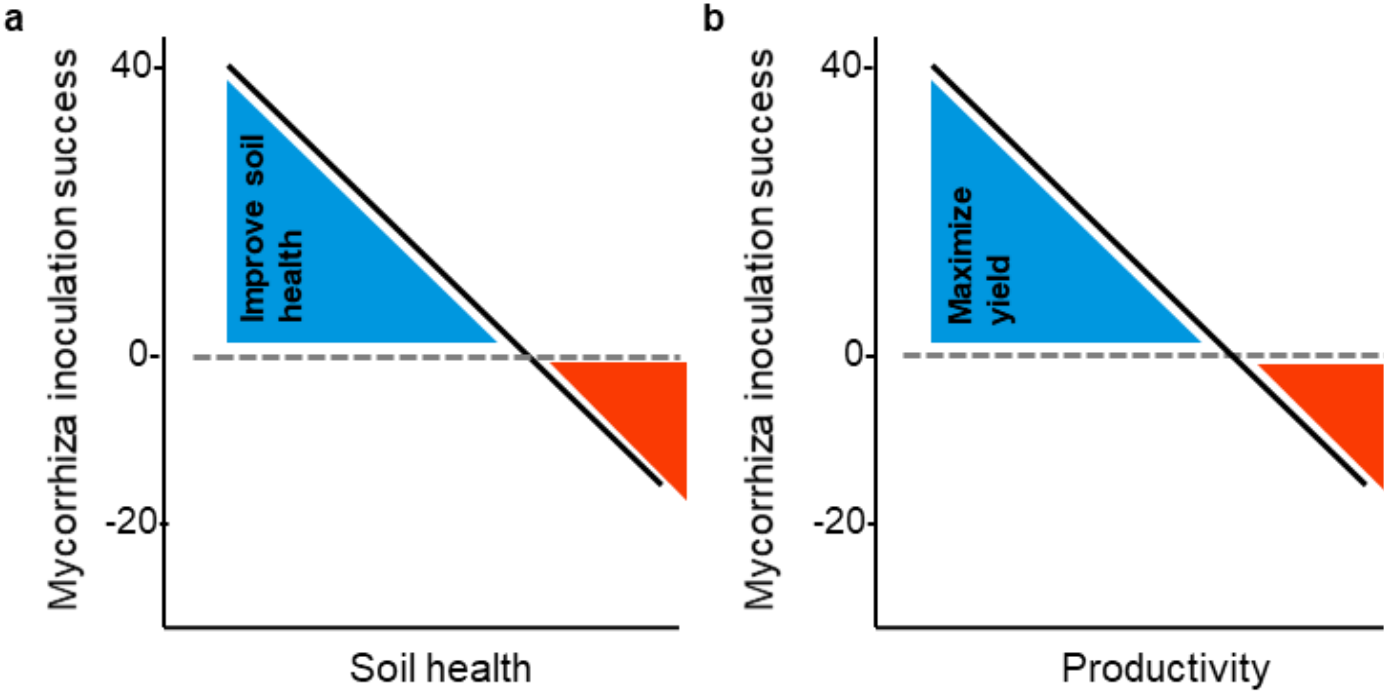
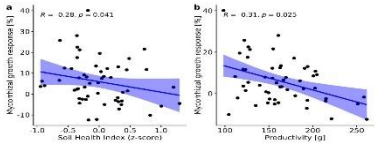
Inoculation success is linked to Soil Health and Plant productivity





Soil health: microbial biomass carbon, soil AMF richness, inverse pathogen abundance, plant-available phosphorus, organic carbon, and plant-available mineralised nitrogen

Rog, van der Heijden……. Lutz (2024), *submitted*.

Next? Large scale application of AMF in Swiss agricultural fields

(this year: 22 maize fields; 4 vineyards; 2 orchards; 4 onion fields; 2 exp. Trials)

contribution Martin Kupper

Contribution: Raphael Boussageon, Alain Held, Marco Eigenmann, Raphael Wittwer, SNF-Implementation Grant

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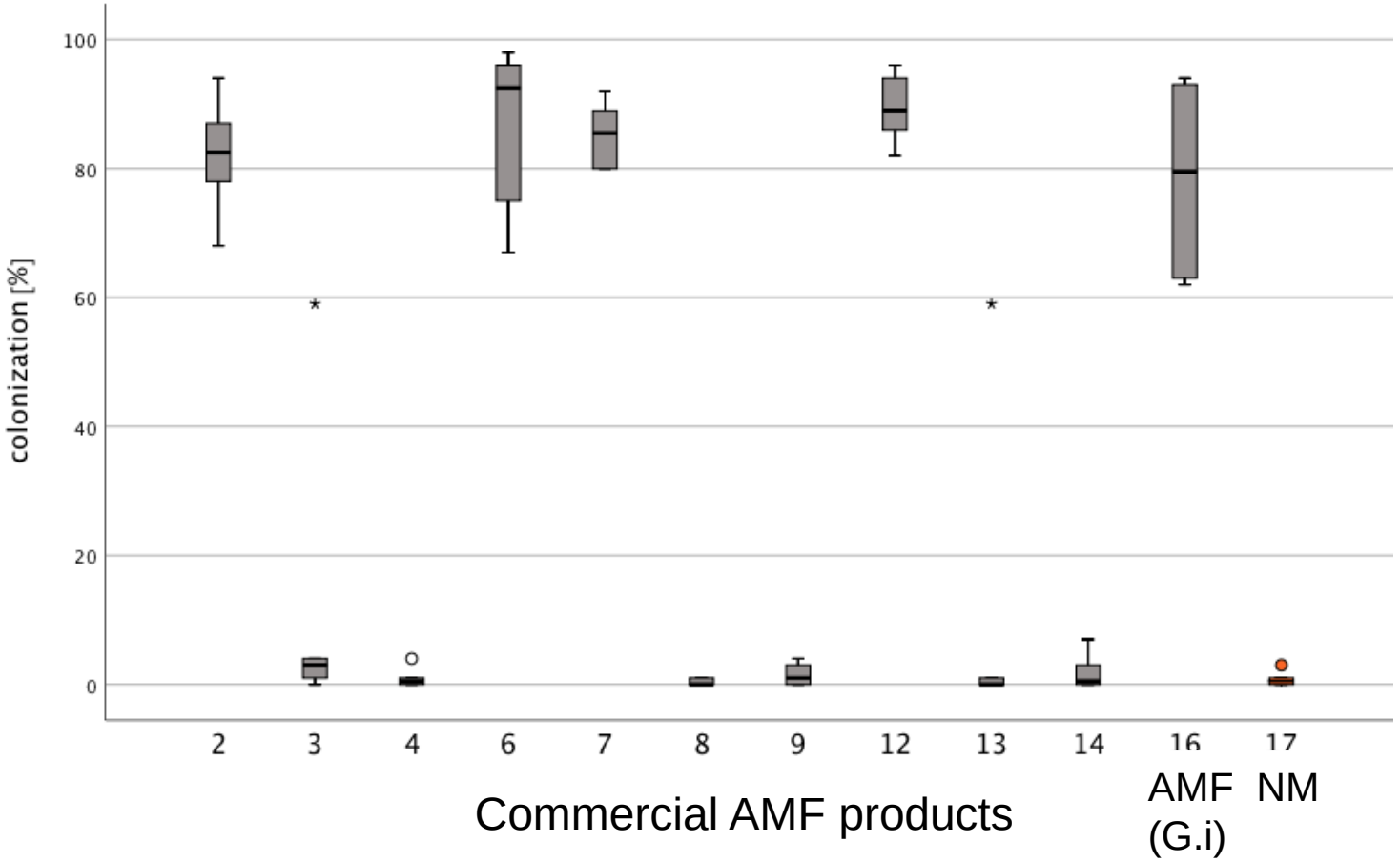
Global evaluation of commercial AMF products: >50% of products apparently contain no active AMF….

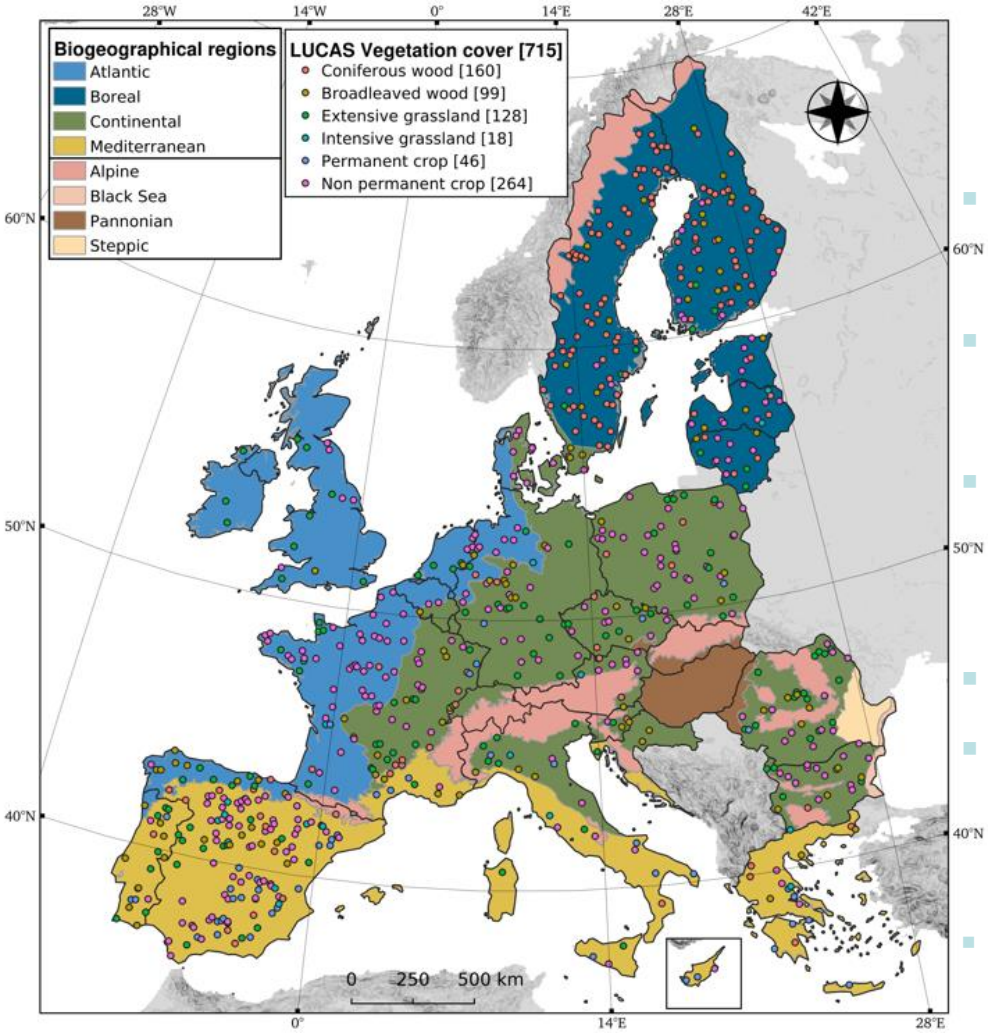


Salomon, Demarmels…. Cavagnaro, van der Heijden (2022) Applied Soil Ecology 169, 104225 (EU & CH)
Koziol et al. (2024) Applied Soil Ecology 202, 105559 (USA)

Conclusions

- Soil Microbiomes have a big impact on soil, plant and environmental health.
- Arbuscular mycorrhizal fungi can promote crop yield, especially in fields with high pathogen load, poor soil health and lower productivity.
- Microbiome Engineering has a large potential to contribute to sustainable plant production. Much more research is needed (which microbes, which conditions, how to apply, when does it work, when does it not work).

Soil Monitoring & Soil Health



LUCAS Soil Biodiversity

- Largest European soil survey
- 715 sampling points
- 3 land cover types (cropland, grassland, woodland)
- 4 biogeographical regions
- Microbial (bacteria & fungi) community (DNA metabarcoding)
- Labouyrie et al. 2023, *Nature Communications*

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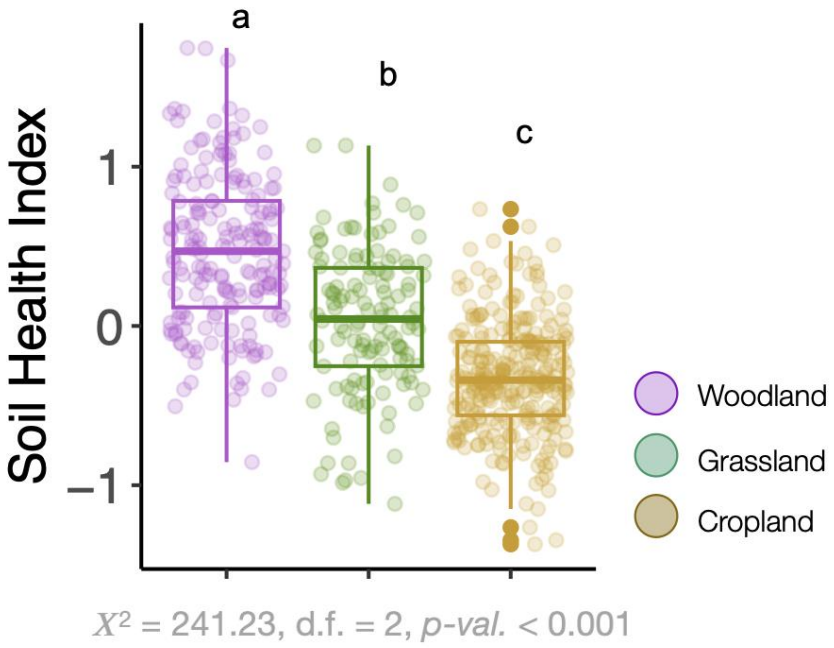
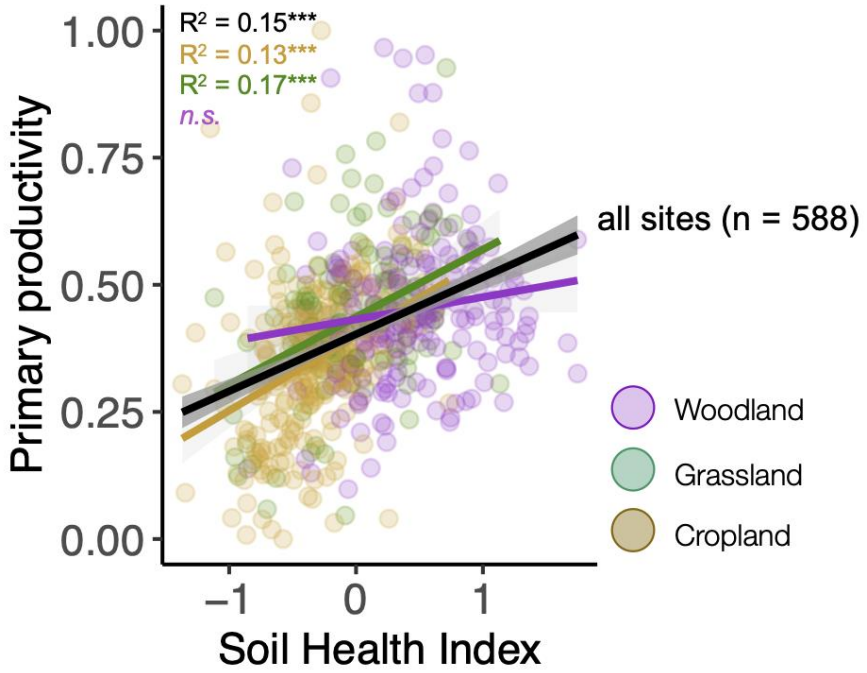
Collaboration between JRC & University of Zurich/Agroscope

Soil Health is positively linked to plant productivity across Europe





Soil Health: SOC, N content, P content, microbial biomass, soil density, mycorrhizal fungal abundance, nitrogen fixing bacteria abundance, inverse of pathogen richness

Romero et al…van der Heijden (2024), Nature Ecology & Evolution

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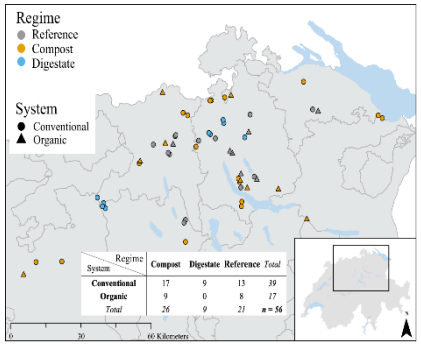
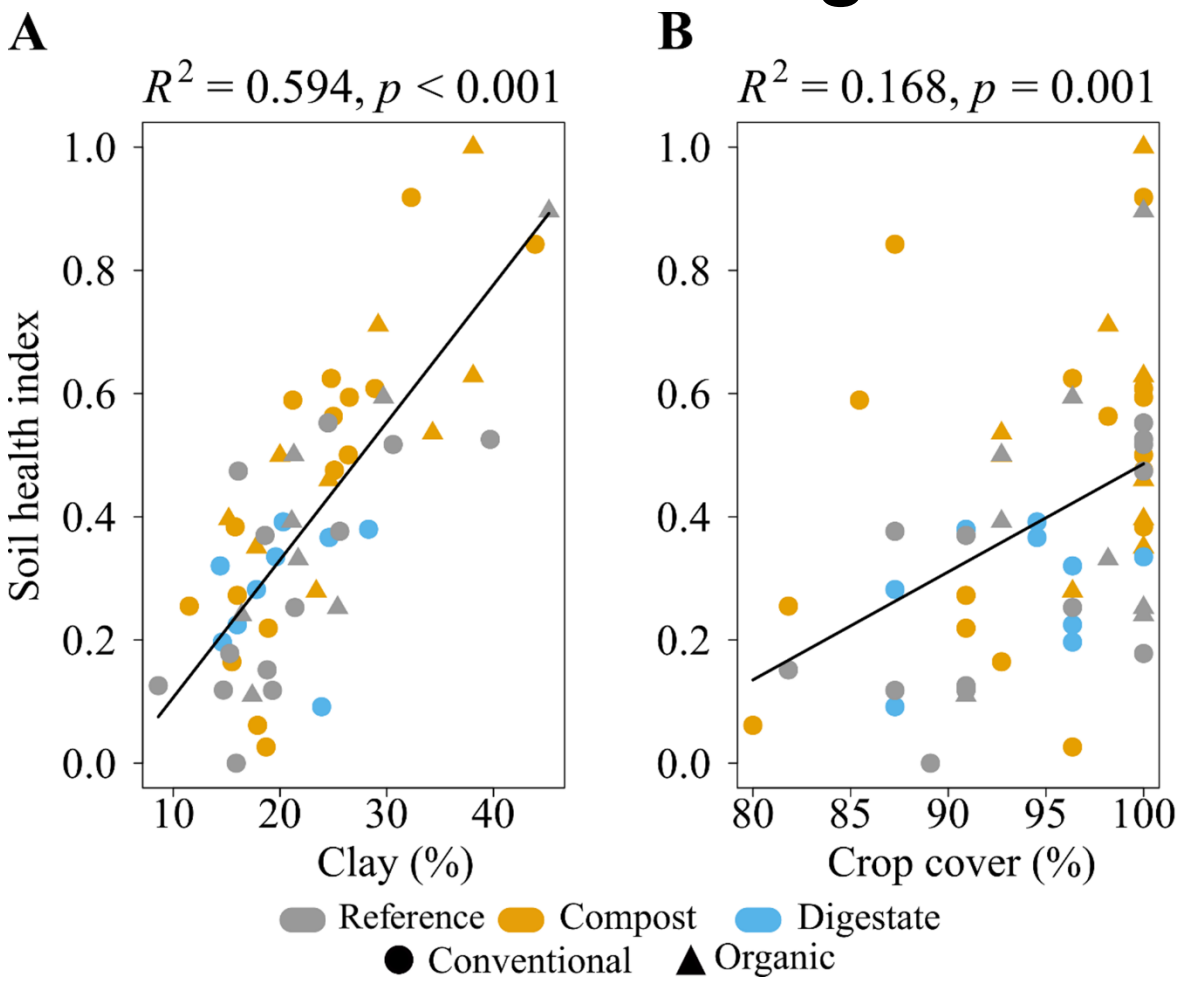
Soil Health relies both on abiotic conditions and farm management





Soil Health: SOC stocks, aggregate stability, bulk density, fungal richness, bacterial richness, basal respiration, CEC, and nutrient availability (averaged z-score of available P, K, and total N)

Edlinger, Herzog…van der Heijden (2025), Journal of Sustainable Agriculture and Environment

Garland et al (2021), Nature Food

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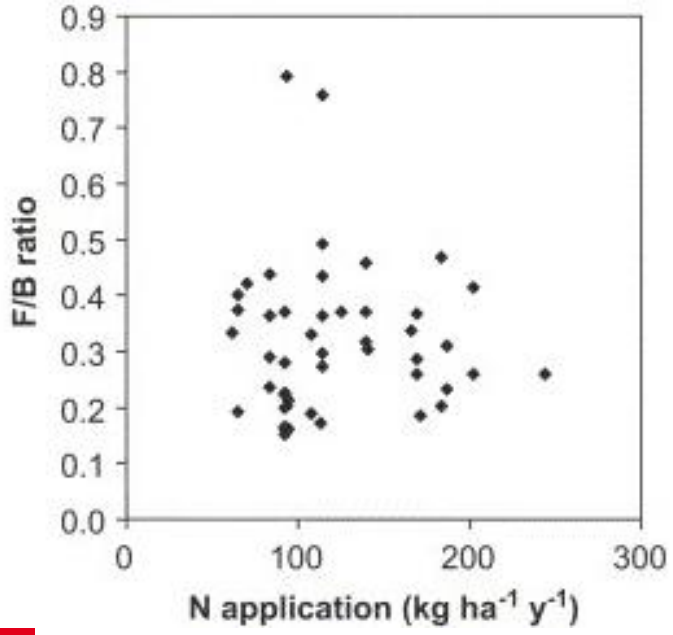
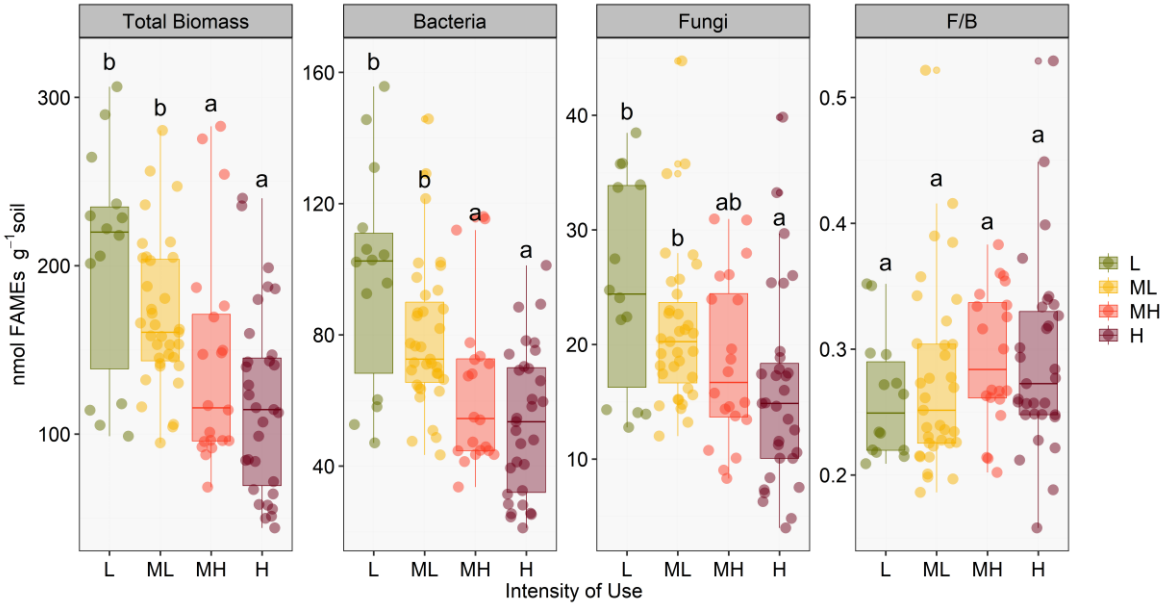
Fungal /Bacterial (F/B) ratio's as an indicator for soil health?



De Vries et al. 2007, SBB
(48 Dutch grasslands)



L -> Low intensity
(i.e. organic fertilization + no tillage)
ML -> Medium-low intensity
MH -> Medium-high intensity
H -> High intensity
(i.e. mineral fertilization + standard tillage)
8 Farming System Experiments in Europe

Bastida et al. unpublished (CEBAS-CSIC).

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EJP SOIL MINOTAUR

Regenerative Agriculture & Soil Health: Which Farming System is best?

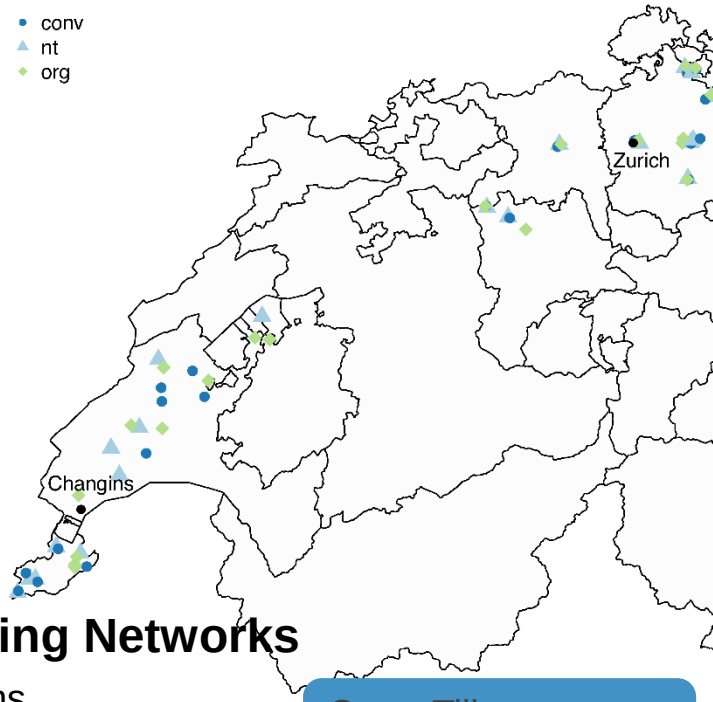
FAST Experiment

Farming System and Tillage experiment

- Conventional Tillage (C-IT)
- Conventional No Tillage (C-NT)
- Organic Tillage
- Organic reduced Tillage

Since 2009

Conv: +mineral fertilisers; + Pesticides
Org: +liquid Manure; no Pesticiden
Conv. & Org = same crop rotation (6 years):
GM-WW-GM-Maize-Beans-WW-Grass-Clover



Farming Networks

60 farms
1 Wheat field

- Conv. Tillage n=20
- Conv. No Tillage n=20
- Organic Tillage n=20; Bio Suisse; min. 5 Jahre

Soil as a Resource
National Research Programme NRP 68

With Lucie Büchi, Florian Walder, Raphael Charles, Thomas Keller, Jochen Mayer, Jo Six, Marcel van der Heijden et al.

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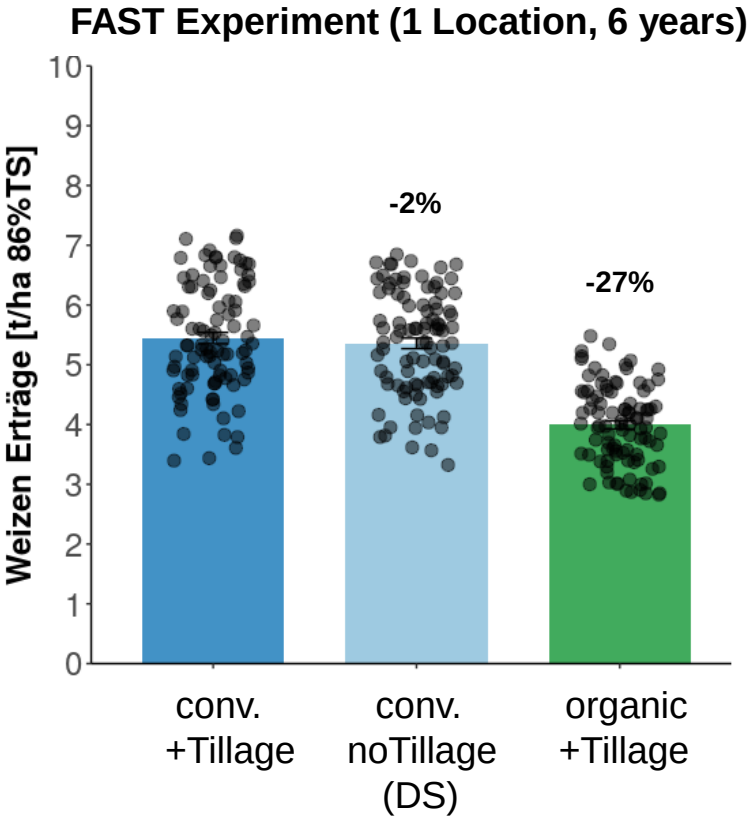
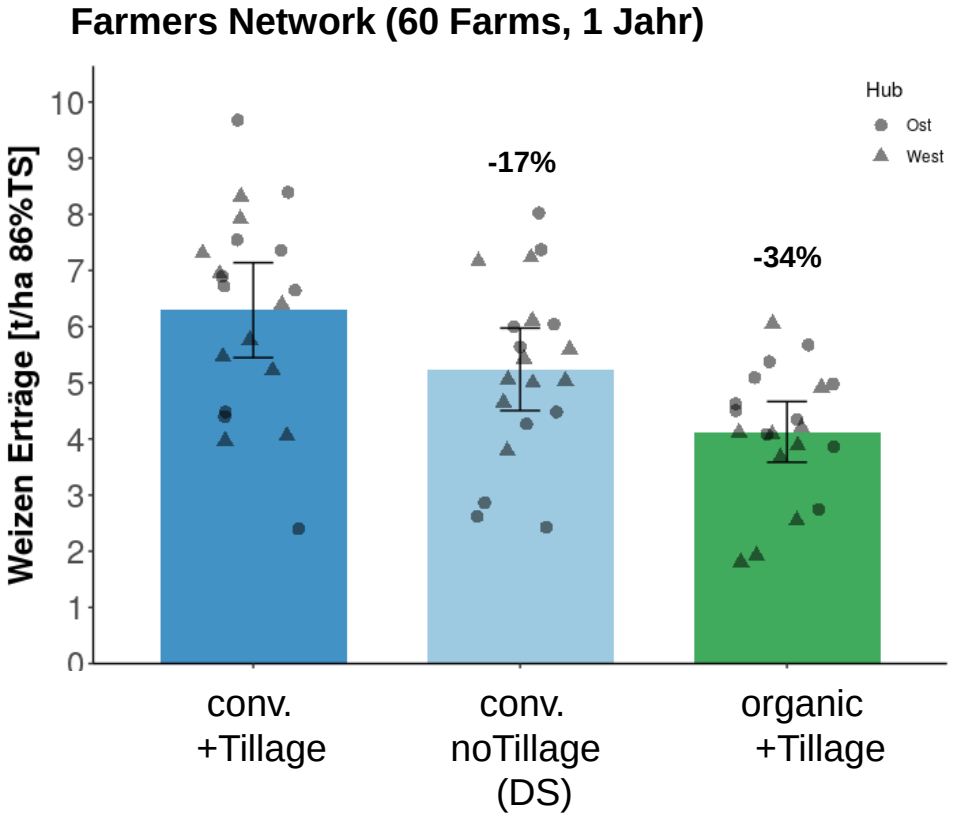
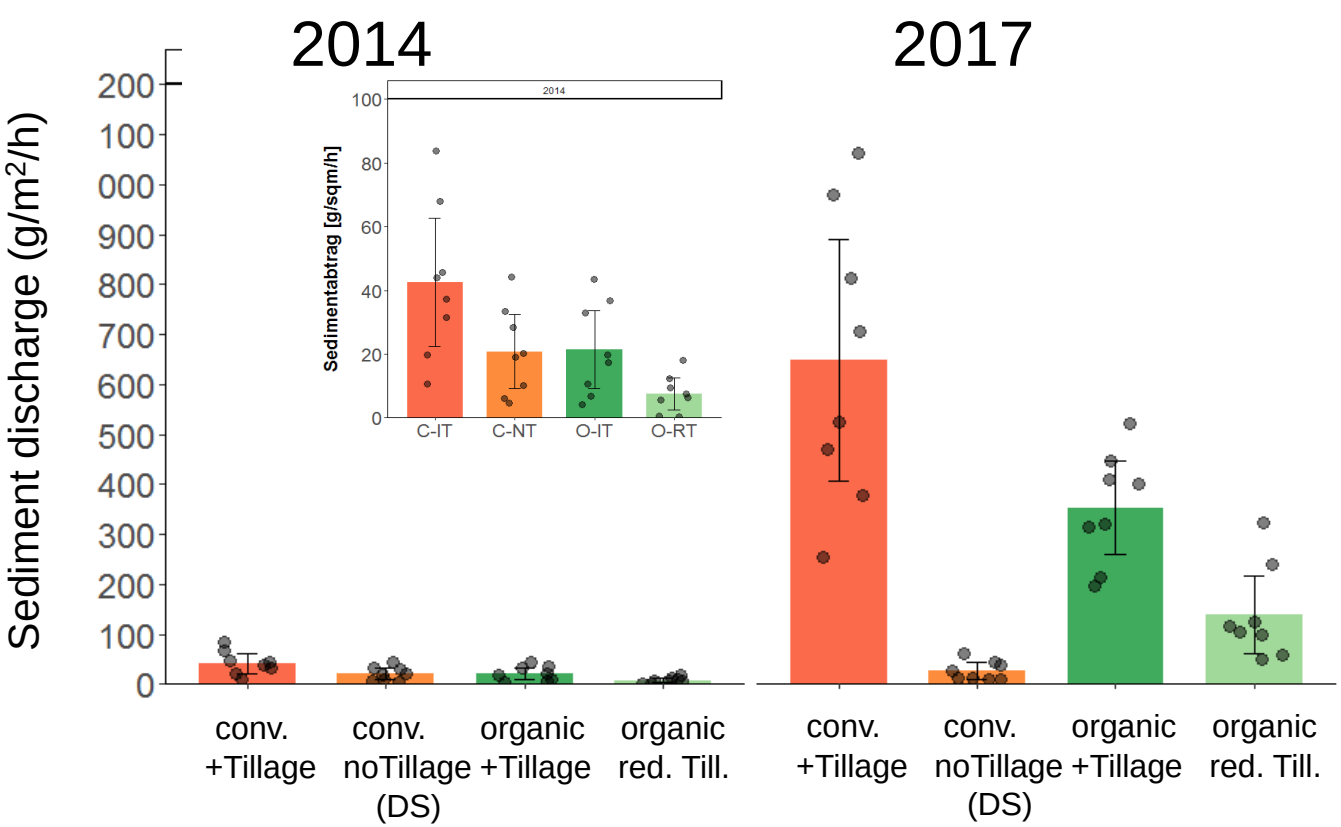
Winterwheat: higher yield in conventinal systems





FAST: Wittwer et al. (2021), *Science Advances*
Betriebsnetz: Walder, Büchi et al. (2023), *Journal of Applied Ecology*

Soil Erosion: conservation agriculture and organic farming protect the soil



Seitz et al. (2018) *Agronomy for Sustainable Development*

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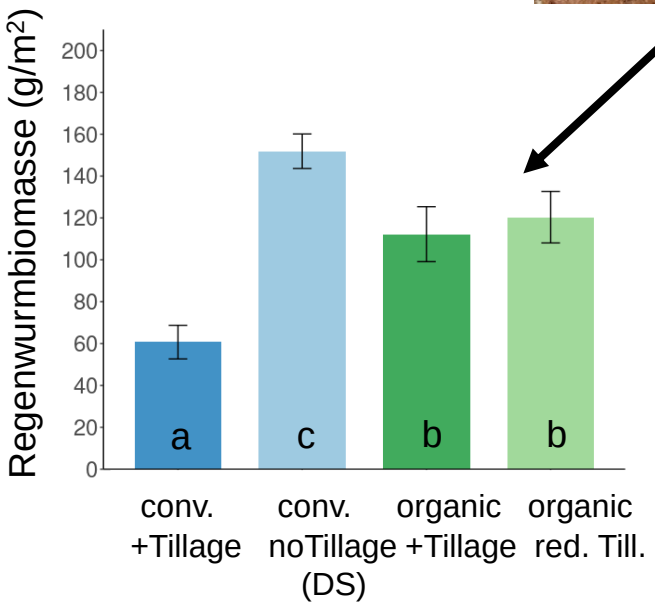
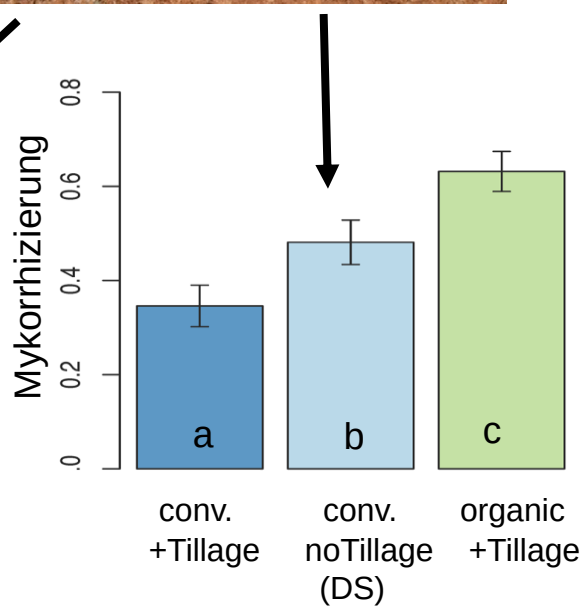
Conservation Agriculture and Organic Farming promote Earthworms and Mycorrhizal Fungi





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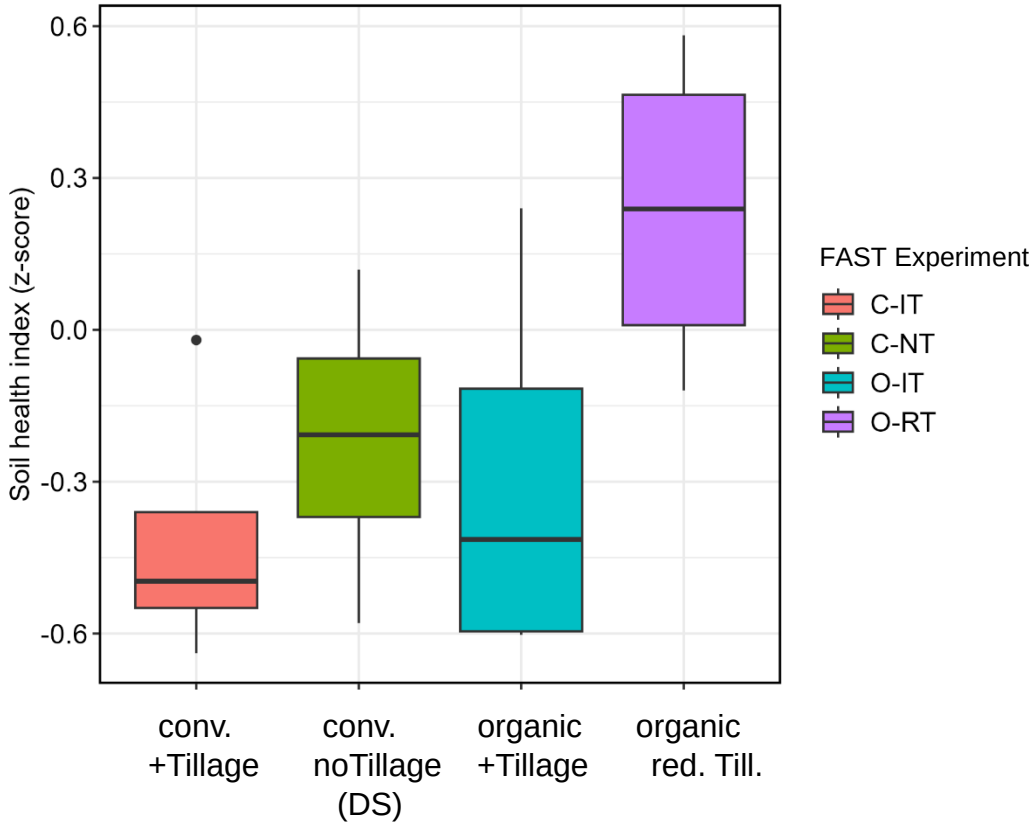
Soil Health is highest when organic farming and conservation agriculture are combined



Soil Health: Microbial biomass C, Microbial biomass N, AMF NLFA, AMF PLFA, Nitrogen fixation bacteria (relative abundance), -Pathogen (shanon index), Bulk soil density, Earthworm (number), Soil organic C, Soil N total, Soil available P.

Unpublished results: Ido Rog, Raphael Wittwer, Marcel van der Heijden et al.

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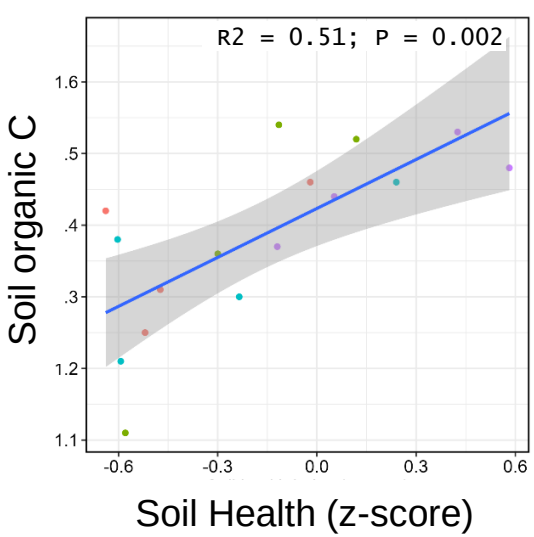
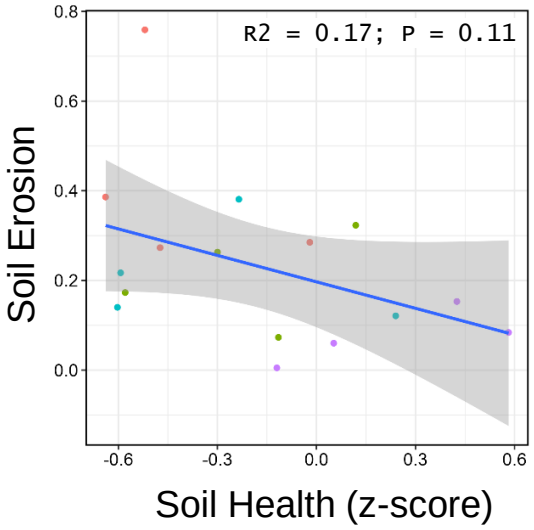
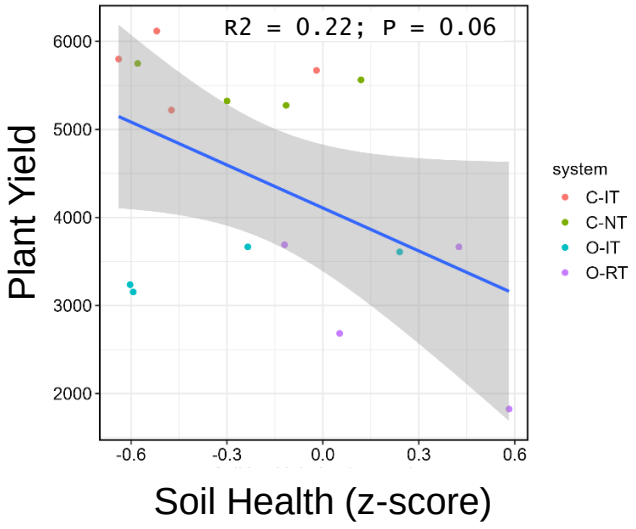
In our farming systems trial soil Health is positively linked to Soil Carbon Storage and Erosion Protection, but not linked with enhanced Plant Yield







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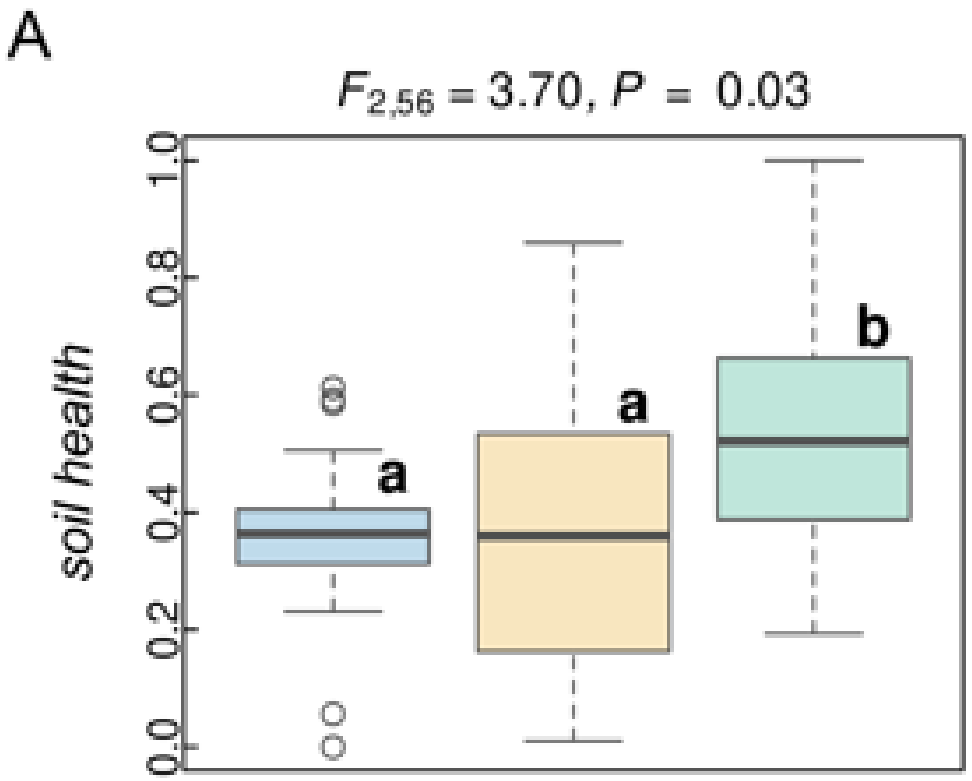
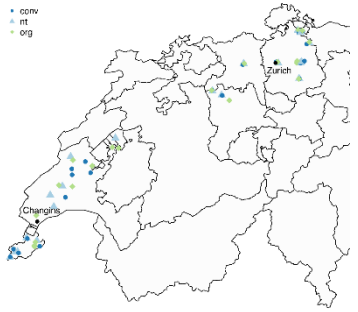
Unpublished results: Ido Rog, Raphael Wittwer, Marcel van der Heijden et al.

Organic farming promotes Soil Health





conventional (n=20)

no-till (n=20)

organic (n=20)

Soil health: summary of 17 variables: soil organic matter, soil nutrients, microbial abundance, microbial diversity, soil structure and soil compaction

Walder et al. (2023), Journal of Applied Ecology

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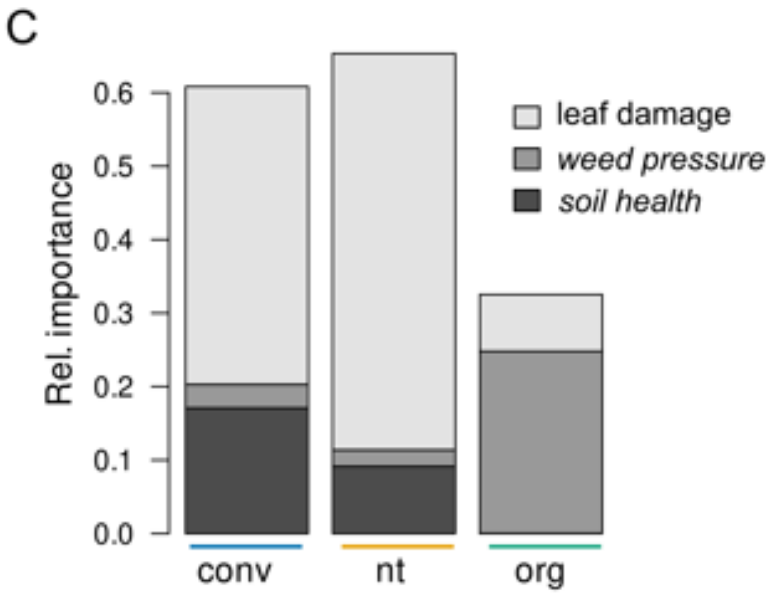
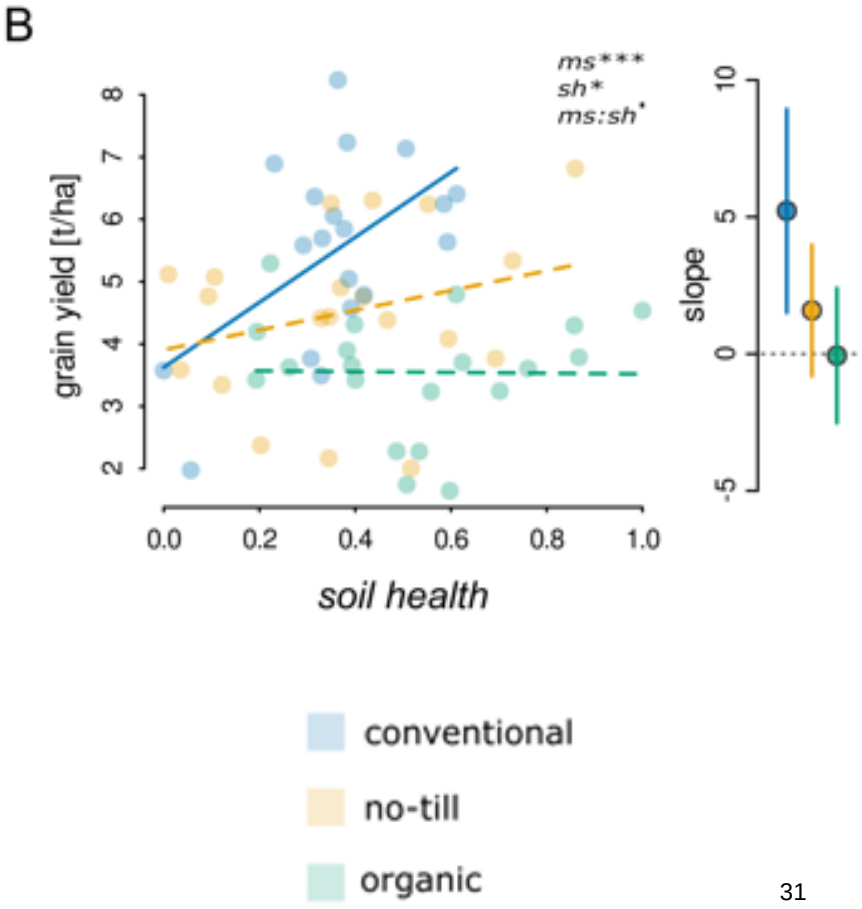
When it comes to explaining plant yield, soil health appears to more important for conventional cropping systems





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Compost Experiment: Testing the impact of compost and biogas- digestate on soil health and plant yield

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STIFTUNG MERCATOR SCHWEIZ

COFEE: COmpost Fertilisation Experiment Ehrendingen
FAST Trial: Wittwer et al… (2021), *Science Advances*
Farmer Networks: Banerjee et al. 2019, *ISME*; Garland et al. 2021; *Nature Food*

Conclusions & Questions

- Regenerative farming practices, Organic farming and Conservation Agriculture promote Soil Health.
- Soil Health is positively linked to Plant Productivity at large scale. Soil Health is usually closely linked Clay content and to Soil Carbon in agricultural fields.
- Soil Health can be promoted by year-round Soil Cover.
- Soil Health does not always result in higher yields (e.g. if there are other limiting factors such as high weed densities or reduced nutrient availability).

Acknowledgement

Steffi Lutz, Alain Held, Cygni Armbruster, Natacha Bodenhausen, Klaus Schläppi, Julia Hess

Raphael Wittwer, Ido Rog, Franz Bender, Matthias Salomon et al.

Thomas Bucheli, Katie Mackie-Haas, Judith Riedo, Elias Barmettler, Florian Walder, Pierre-Henri Dubuis et al.

Ferran Romero, Maeva Labouyrie, Alberto Orgiazzi, Panos Panagos, Arwyn Jones et al.

Anna Edlinger, Chantal Herzog, Gina Garland, Kyle Hartman, Andrea Bonvicini & Biodiversa Team

Research Group Plant-Soil Interactions AGS & Team Agroecology and Plant-Microbiome Interactions UZH

Participating farmers, scientists

Many other scientists for exchange and c

EJP SOIL European Joint Programme

STIFTUNG MERCATOR SCHWEIZ

biodiversa

HORIZON 2020

Universität Zürich[UZH]

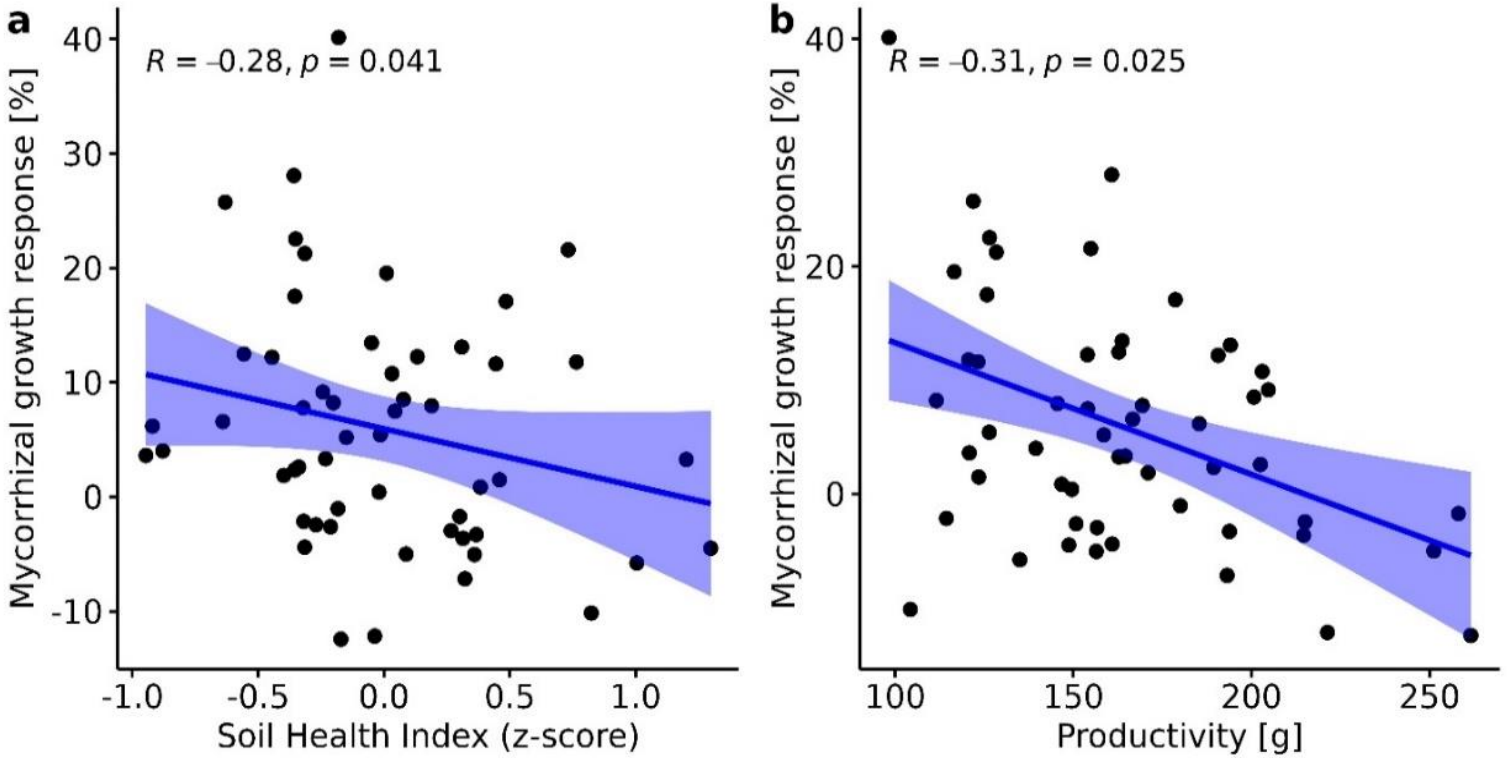
FNSNF Schweizerischer Nationalfonds zur Förderung der wissenschaftlichen Forschung

WISSENSCHAFT. BEWEGEN GEBERT RÜF STIFTUNG

PARTIZIPATIVE WISSENSCHAFTSAKADEMIE

category	variable	Unit	C-IT	C-NT	O-IT	O-RT	F-value, sig
supporting	Weed richness	# species	2.0 ± 0.3	1.8 ± 0.2	6.6 ± 0.2	6.0 ± 0.2	$F_{3,101}$ = 42.4 ***
	Bacterial richness	# OUT	1193 ± 21	1119 ± 39	1216 ± 26	1144 ± 45	$F_{3,21}$ = 3.1 °
	Fungi richness	# OUT	550 ± 18	557 ± 10	590 ± 16	563 ± 12	$F_{3,21}$ = 1.9 ns
	AMF spore richness	# species	19.1 ± 0.3	24.0 ± 1.2	21.5 ± 0.5	25.6 ± 1.2	$F_{3,9}$ = 11.4 ***
	Soil C_{org}	%	1.39 ± 0.04	1.39 ± 0.08	1.38 ± 0.06	1.44 ± 0.02	$F_{3,21}$ = 0.5 ns
	Soil N_{tot}	%	0.17 ± 0.003	0.17 ± 0.006	0.17 ± 0.008	0.18 ± 0.003	$F_{3,21}$ = 0.6 ns
	Soil $P_{available}$	mg P kg^{-1}	1.175 ± 0.074	1.328 ± 0.131	0.856 ± 0.04	0.986 ± 0.1	$F_{3,21}$ = 6.2 ***
	Soil.$K_{available}$	mg K kg^{-1}	28.8 ± 2.4	37.5 ± 4.3	26.5 ± 2.2	32.4 ± 2.6	$F_{3,21}$ = 3.7 *
	Microbial biomass C	mg C kg^{-1}	502 ± 23	516 ± 55	512 ± 35	566 ± 22	$F_{3,21}$ = 1.5 ns
	Bacteria PLFA	nmol g^{-1}	96.5 ± 4.8	103.2 ± 6.1	103.3 ± 3.2	106.8 ± 5.5	$F_{3,9}$ = 2.5 ns
	Fungi PLFA	nmol g^{-1}	14.2 ± 0.4	14.8 ± 1.3	14.6 ± 1.2	16.6 ± 0.7	$F_{3,9}$ = 1.6 ns
	AMF NLFA	nmol g^{-1}	11.6 ± 0.6	12.8 ± 1.5	13.2 ± 1.0	15.5 ± 1.4	$F_{3,9}$ = 1.8 ns
	AMF PLFA	nmol g^{-1}	8.8 ± 0.2	9.6 ± 0.9	9.4 ± 0.8	10.6 ± 0.4	$F_{3,9}$ = 1.6 ns
	AMF spore density	Spores g^{-1}	22.7 ± 1.1	18.8 ± 1.2	21.2 ± 1.3	23.0 ± 1.0	$F_{3,9}$ = 2.6 ns
	Earthworms density	g m^{-2}	359 ± 40.1	737 ± 23.2	656 ± 81.4	603 ± 79.5	$F_{3,21}$ = 5.7 *
	Earthworms weight	# m^{-2}	61 ± 7.8	152 ± 7.5	112 ± 16.0	120 ± 16.2	$F_{3,21}$ = 14.5 ***
	C_{org} / Clay ratio	-	0.065 ± 0.001	0.069 ± 0.003	0.067 ± 0.002	0.066 ± 0	$F_{3,21}$ = 0.5 ns
	Aggregate (MWD)	micrometer	923 ± 26	1075 ± 41	991 ± 38	1136 ± 33	$F_{3,21}$ = 11.9 ***

Inoculation success is linked to Soil Health and Plant productivity



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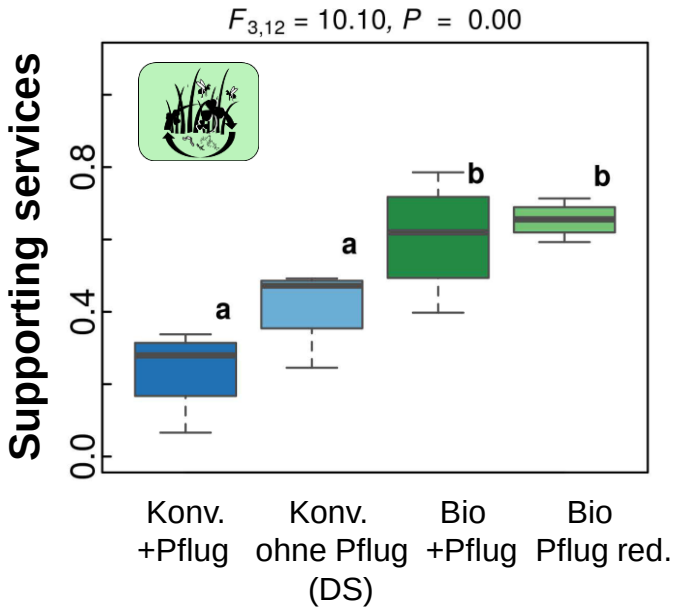
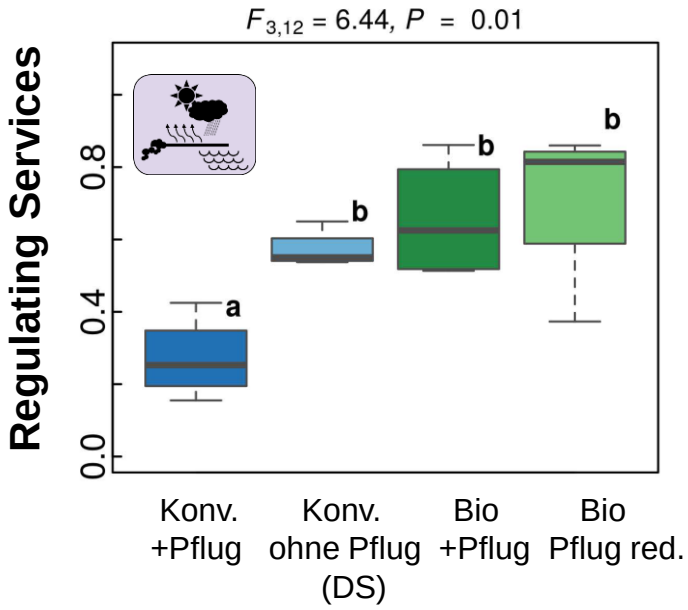
Regenerative Agriculture and Organic Farming promote Ecosystem Multifunctionality





Biodiversität
Bodenfruchtbarkeit

Bodenschutz
Wasser-schutz
Klima-schutz

We assessed 43 Variables for 9 agroecosystem services

Wittwer et al. (2021) Science Advances

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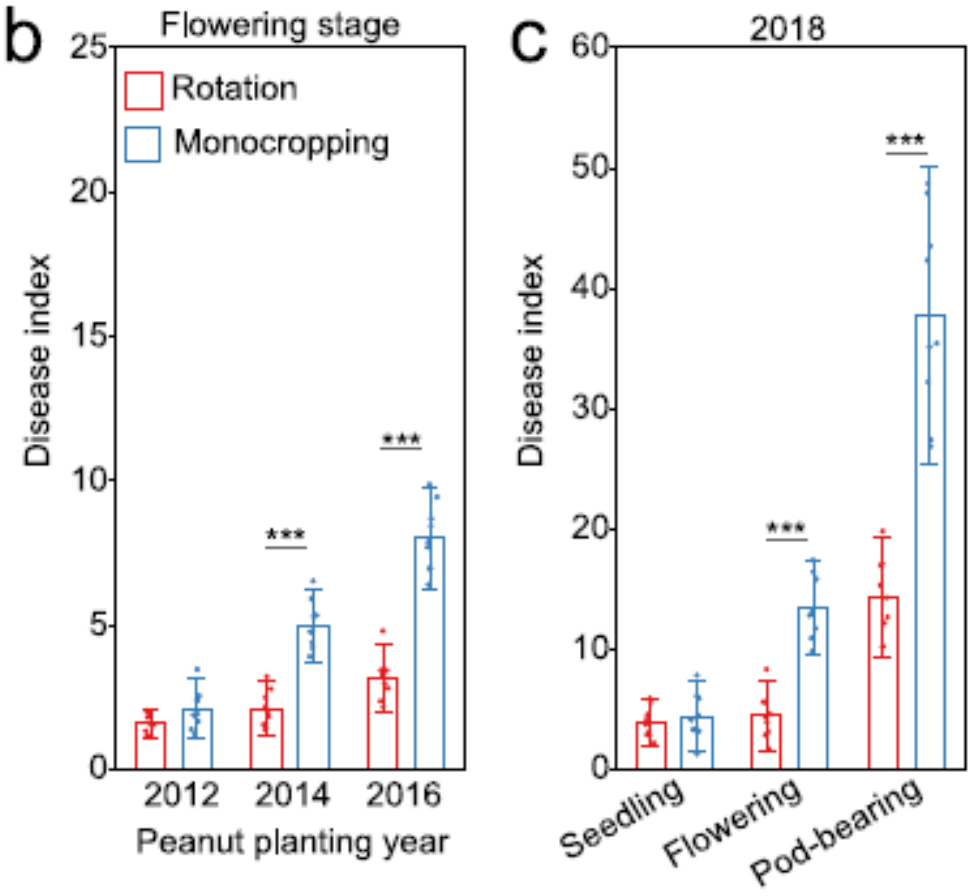
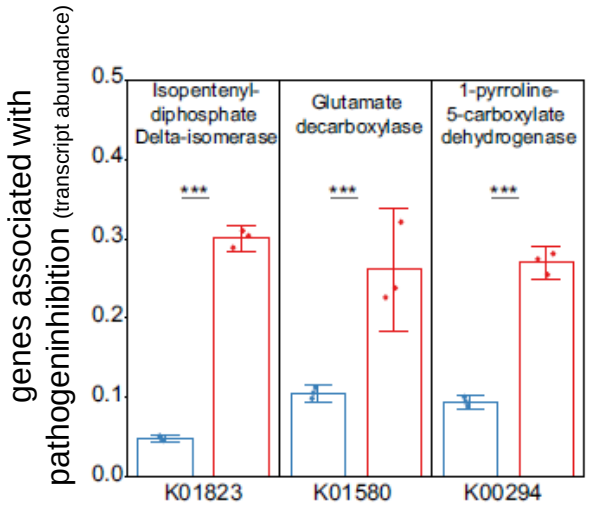
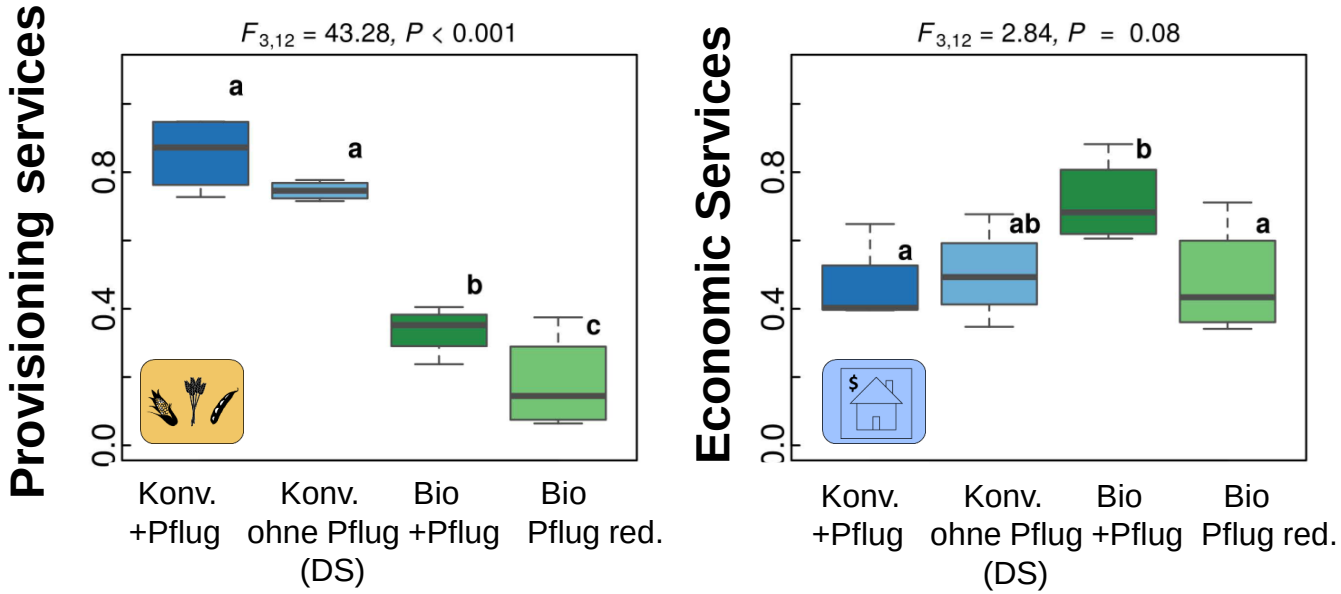
Crop rotation enhances soil disease resistance





Zhou et al. (2023), Nature Communications

Trade-Off between Yield (provisioning services) and Environmental Services



Produktivität

Einkommen
Unabhängigkeit (finanz.)
Arbeitsaufwand

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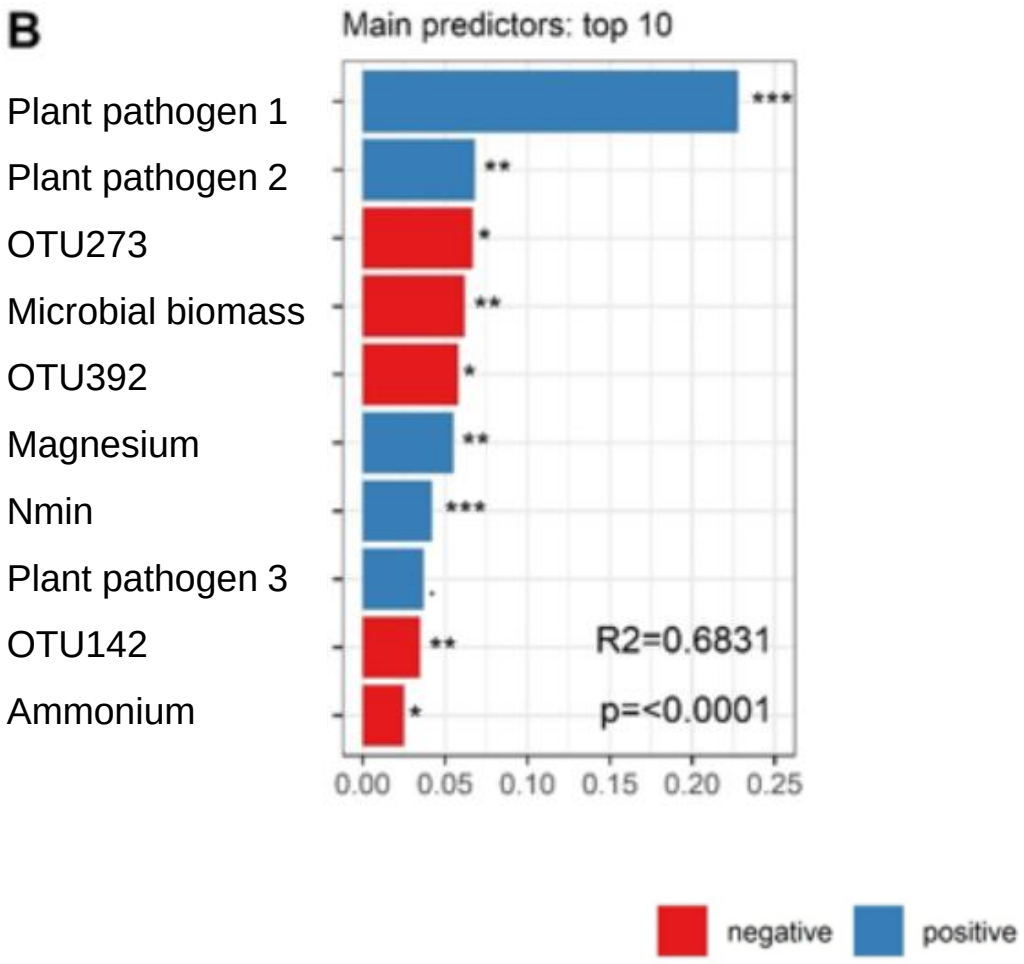
Definitions

- **Regenerative Agriculture:** rejuvenate the soil and land and provide environmental, economic, and social benefits to the wider community. It focuses on topsoil regeneration (often with no/reduced tillage; enhanced plant cover), increasing biodiversity (rotations), improving the water cycle, enhancing ecosystem services, supporting biosequestration (agroforestry), increasing resilience to climate change, and strengthening the health and vitality of farm soil (Wikipedia; Khangura et al. 2023; Sustainability).

- **Organic Agriculture:** integrated farming system that strives for sustainability, the enhancement of soil fertility and biological diversity and prohibiting synthetic pesticides, antibiotics, synthetic fertilizers, genetically modified organisms, and growth hormones.

- **Soil Health:** Soil health is the continued capacity of soil to function as a vital living ecosystem that sustains plants, animals and humans, and connects agricultural and soil science to policy, stakeholder needs and sustainable supply- chain management (e.g. Lehman et al. 2020, Nature Reviews, Earth & Enviroment).

Predicting inoculation success:The presence of plant pathogens in the field best explained inoculation succes



Cover crops

		CC1 before winter wheat	CC2 before maize
Legume	L	Common vetch (*Vicia sativa*)	**Hairy vetch** (*Vicia villosa*)
Non-legume	NL	White mustard (*Sinapis alba*)	White mustard (*Sinapis alba*)
Mixture	M	UFA-Alpha Phacelia, Persian clover, Egyptian clover	SM-ART Phacelia, **Hairy vetch**, Buckwheat, Camelina
Control	C	no CC, bare fallow	no CC, no CC, bare fallow

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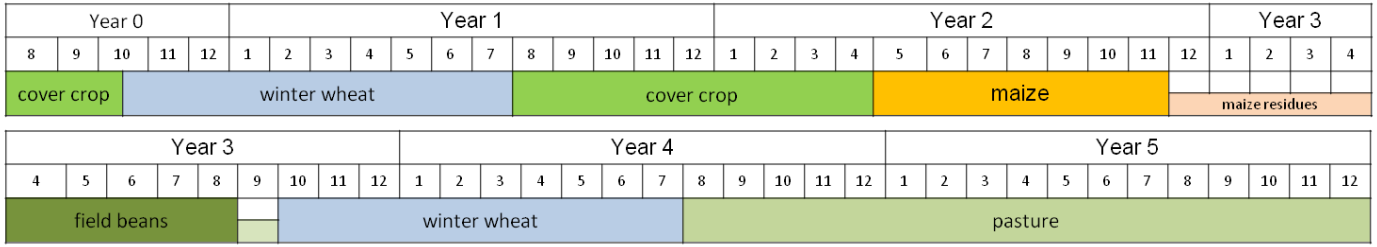
Management

1st Crop rotation:



	CCP	CNT	OCP	ORT
Tillage	**Plough (20cm), Rotary harrow**	**-**	**Plough (20cm), Rotary harrow**	**Disk harrow, Rotary harrow (<10cm)**
Weed control	Herbicides	**Glyphosat**, Herbicide	Mechanical (hoeing, raking)	
Fertilization	**Mineral**		**Organic (slurry** 1.4 GVE)	

	Average y^{-1}	Total 4 year		Average y^{-1}	Total 4 year
N	80	320	**N_{tot} (N_{min})**	86 (39)	346 (158)
P_2O_2	78	232	**P_2O_2**	27	158
K_2O	54	294	**K_2O**	158	632
Mg	11	45	**Mg**	20	78

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