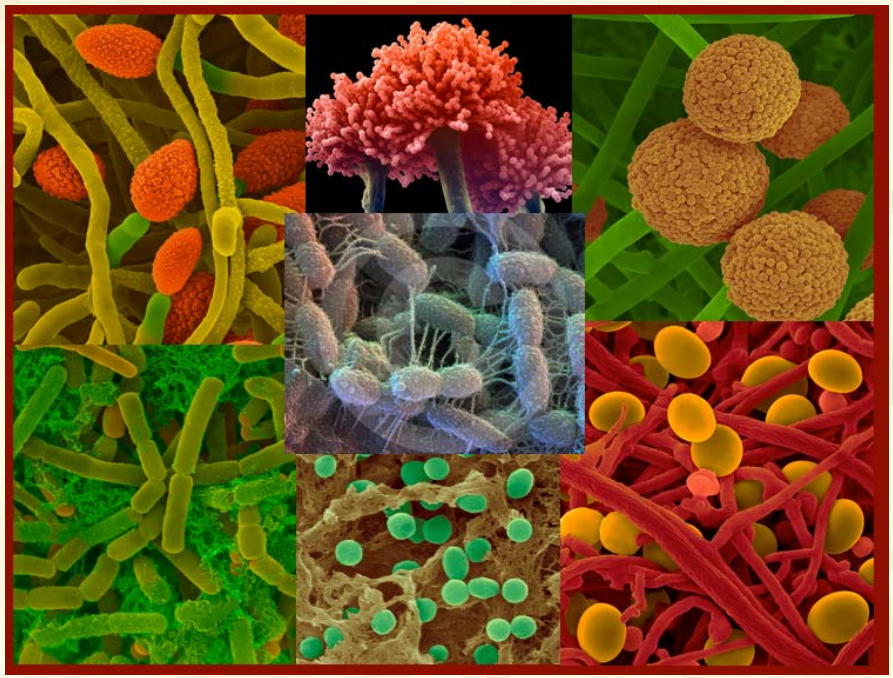
How microbes influence plant growth and productivity

Gwyn Beattie

Microbes are partners with plants



piremongolia.files.wordpress.com

Plants evolved and exist in intimate symbioses with microbes

(in and on their roots, leaves, stems, seeds, pollen, fruits and flowers)

Plants depend on the services provided by their microbial partners - both inside (endophytic) and on their surfaces

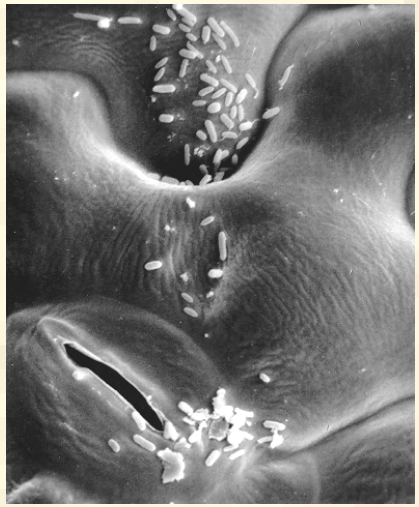
Crop yields can be influenced by microbial partners.

Who are these microbes?

Bacteria

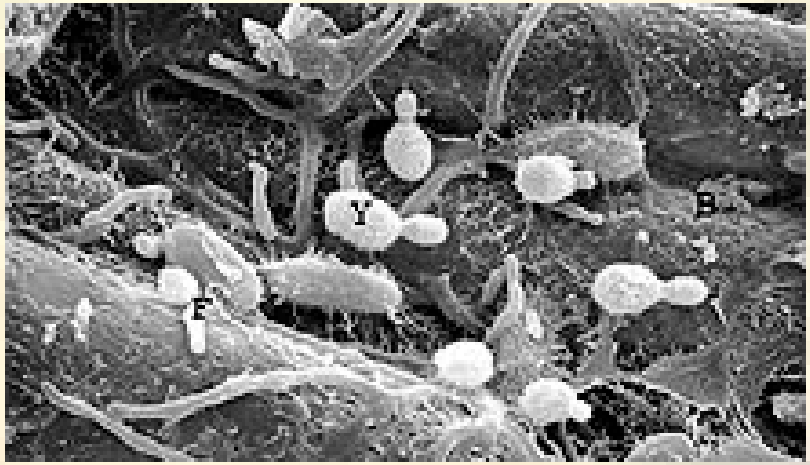
Up to 10 billion cells per gram of soil near plant roots

Up to 100 million cells per gram on leaves



Prokaryotes encompass astounding genetic and functional diversity

Microbes on leaves



www.sproutnet.com

Who are these microbes?

Fungi

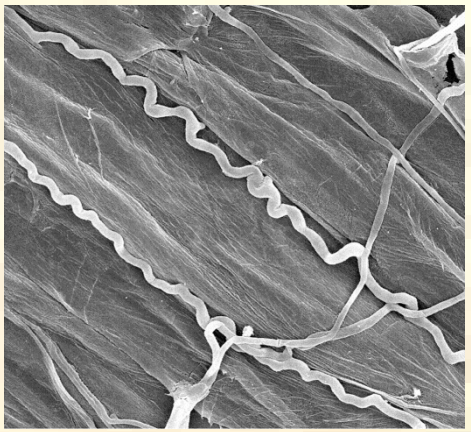
1 million cells per gram of soil

2.bp.blogspot.com

Filamentous networks extend throughout the soil

W. Schmidt, www.landwirtschaft.sachsen.de

Endophytic fungi have been found in most plants



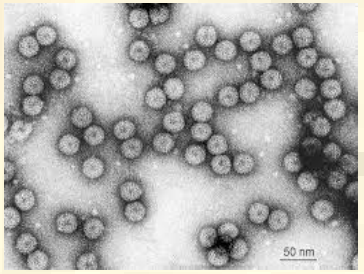
N. Hill, ww.caes.uga.edu

Eukaryotes also encompass astounding genetic and functional diversity

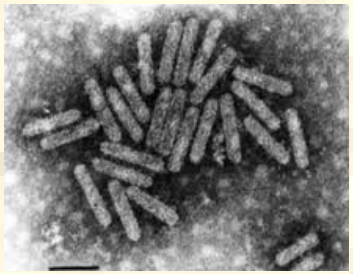
Who are these microbes?

Viruses

1 billion virions per gram of soil



ictvdb.bio-mirror.cn



www.agnet.org

Many are plant pathogens

www.dpvweb.ne

Many have been exploited for horticultural interest

Tulip leaf streak

Some appear to be mutualists and are vertically transmitted

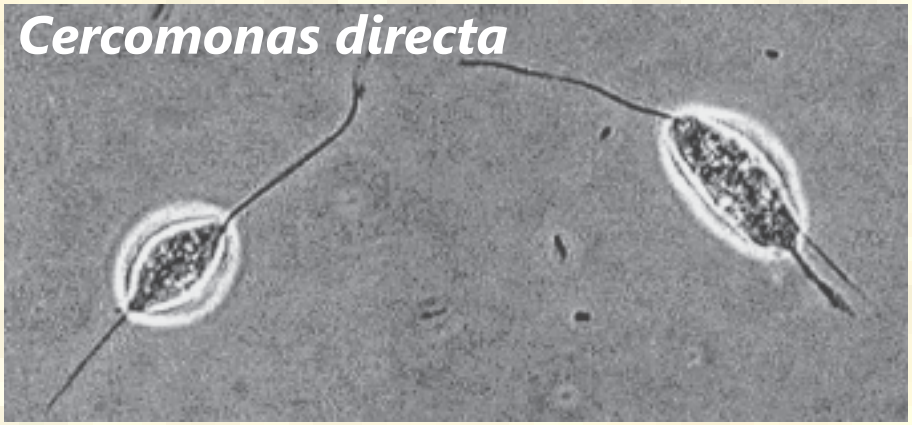
(Bao & Roossinck. 2013. Curr Opin Microbiol 16:514)

Functional impacts on plants poorly understood!

Who are these microbes?

Algae
10,000 per gram of soil

www.psmicrographs.co.uk



Brabender. 2012. Protist 163:495

Protists
10,000 per gram of soil

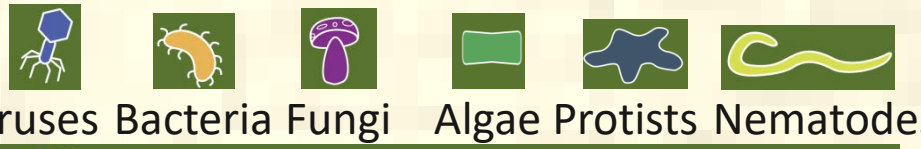
Nematodes
100 per gram of soil

en.wikipedia.org

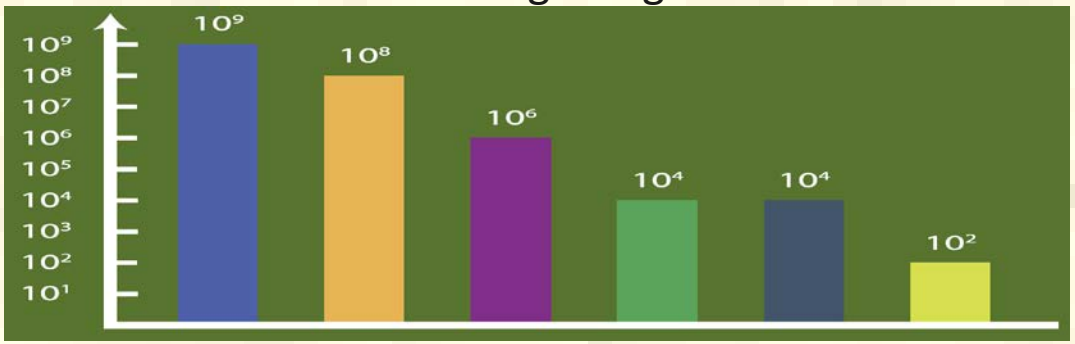
Soybean cyst nematode

jgi.doe.gov

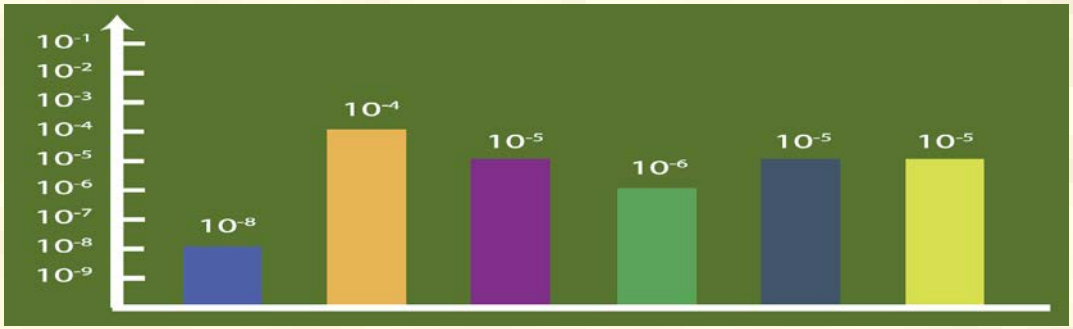
Microbes per gram of soil:



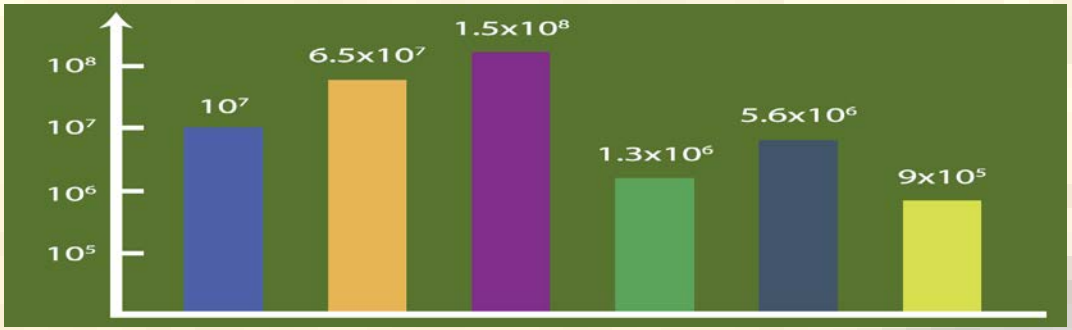
Number of organisms



Biomass (g)

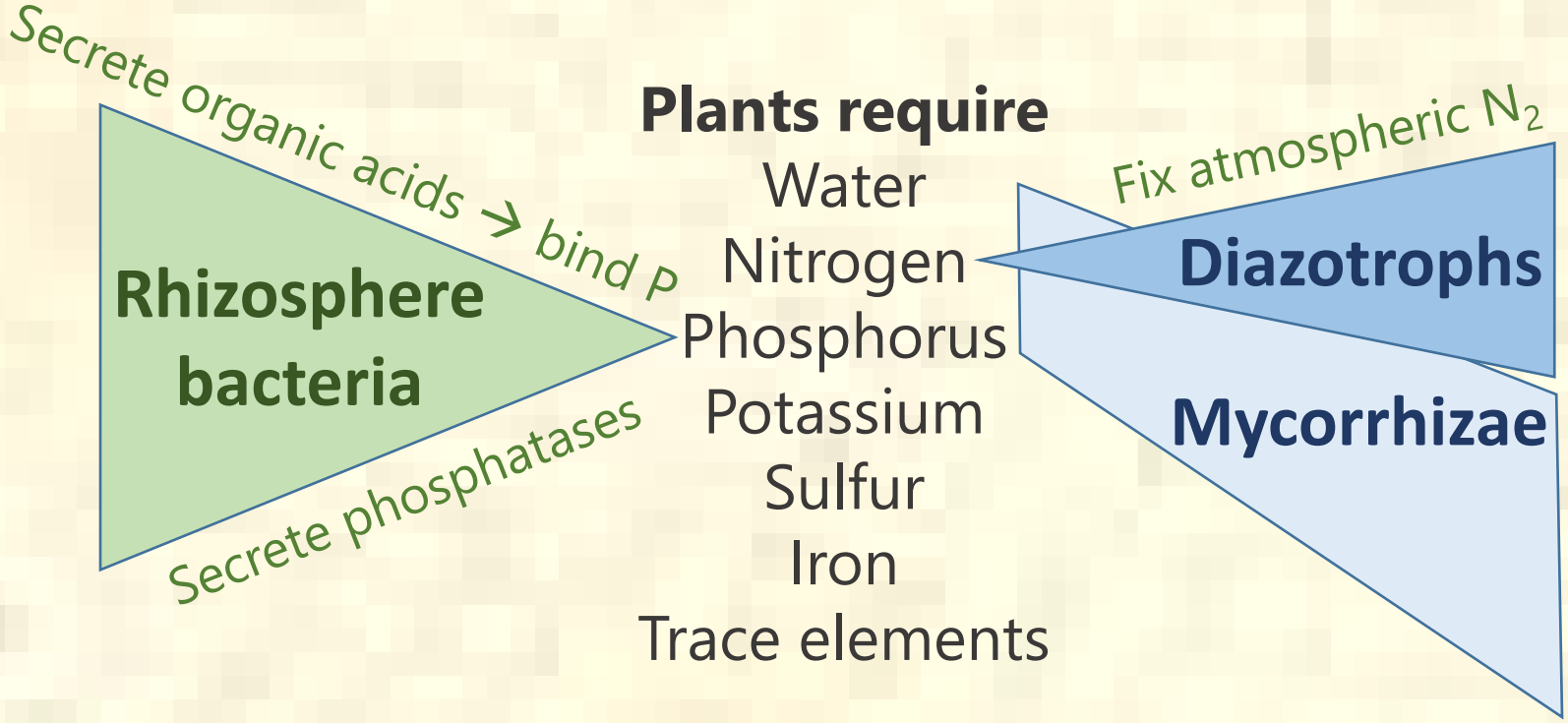


Estimated total genes



How do microbes influence plant growth, reproduction, and productivity?

Microbes help plants acquire nutrients



Who are the major microbial players?

Mycorrhizal fungi

Greek: *mycos* = fungus
rhiza = root

Mycorrhizal fungi can comprise 80% of the effective root system of a plant!

The hyphal network that ramifies through the soil can be more than 100 meters in a single cc of soil

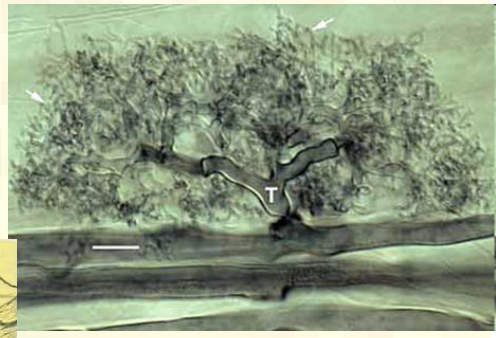
The white halo is hyphae

www.morning-earth.org

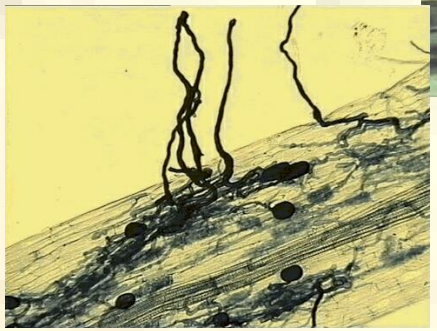
Mycorrhizal fungi are obligate biotrophs

Symbiosis believed to have originated 400-460 mya, at the time that plants colonized land

Endomycorrhizae - in 80% of land plant species, including most crops (Arbuscular mycorrhizal fungi = AMF)



www.morning-earth.org

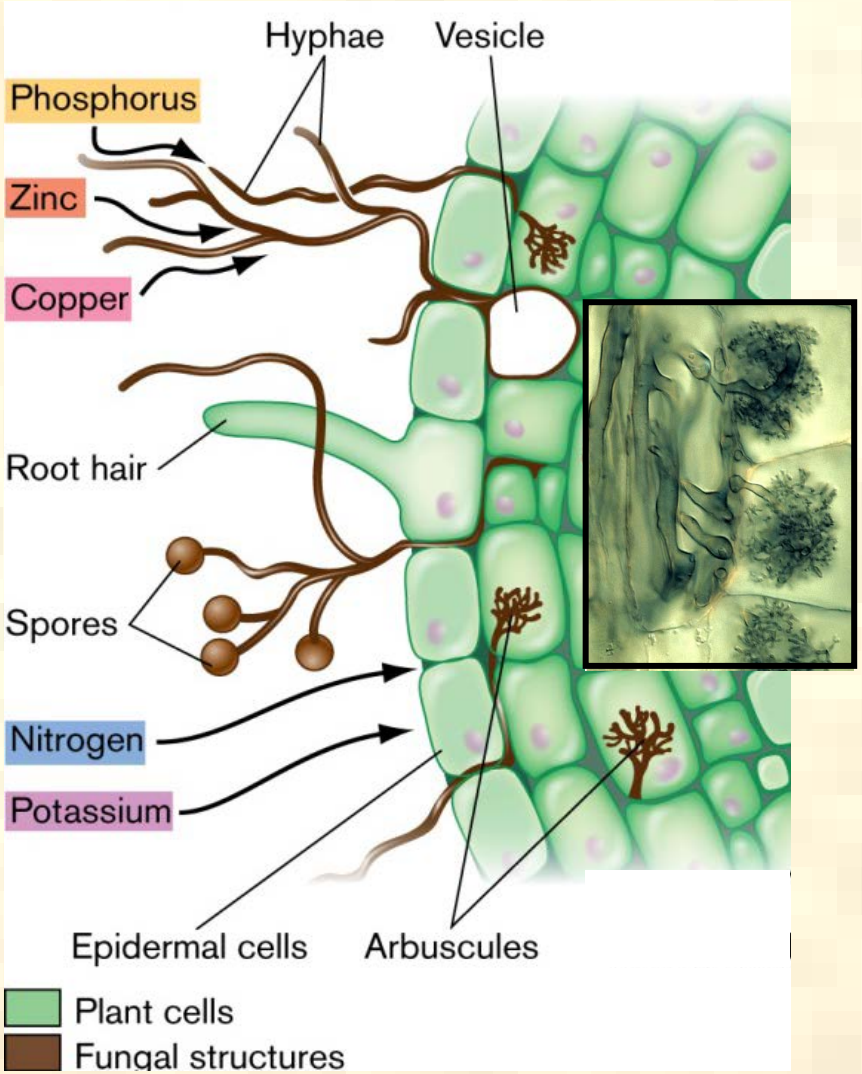


Archive.bio.ed.ac.uk

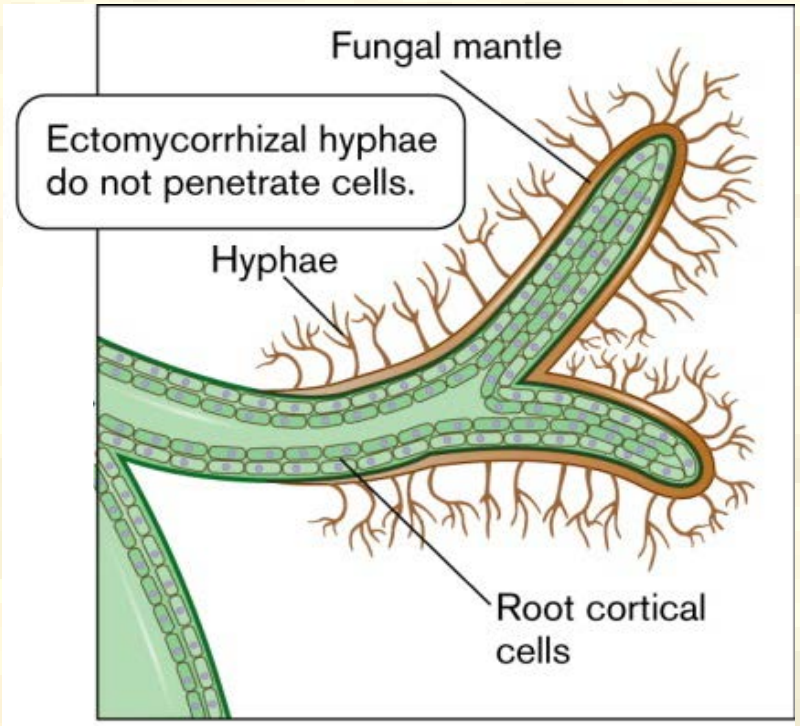
Archive.bio.ed.ac.uk

Ectomycorrhizae – in 10% of land plants, mostly woody species (e.g., oak, pine, birch)

Endomycorrhizae



Ectomycorrhizae



Mycorrhizal fungi acquire minerals & water for plants

Plant

Phosphorus
Nitrogen
Zinc
Water

Carbon (up to 20% of the photosynthate)

Mycorrhizae

www.ktsa.com

\+ -

www.blm.gov

Small hyphae can explore large soil volumes and offer high surface area for absorption

Questions on mycorrhizal fungi?

(Helgason and Fitter, 2009)

What crops do not form mycorrhizal symbioses?

Do individual mycorrhiza strongly prefer one plant species over another?

Are there management practices that reduce the benefits of these fungi?

Can crops be bred to enhance the benefits from these fungi?

Nitrogen-fixing bacteria

N-limitation is often a primary factor limiting plant growth

Bacteria are the only organisms that can reduce N_2 (atmospheric nitrogen) to a form that can be assimilated by plants

Currently, of the world's supply of fixed N:

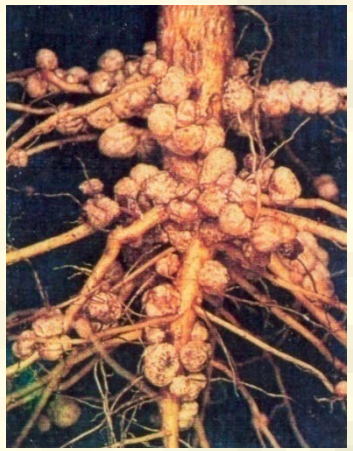
- 65% is biologically-fixed N
- 10% is from lightening, combustion, volcanoes,…
- 25% is industrially-fixed N

Nitrogen-fixing bacteria

- Associative N_2 fixers → root-associated, can provide *some* fixed N_2
- Symbiotic N_2 fixers → can provide *lots* of fixed N_2

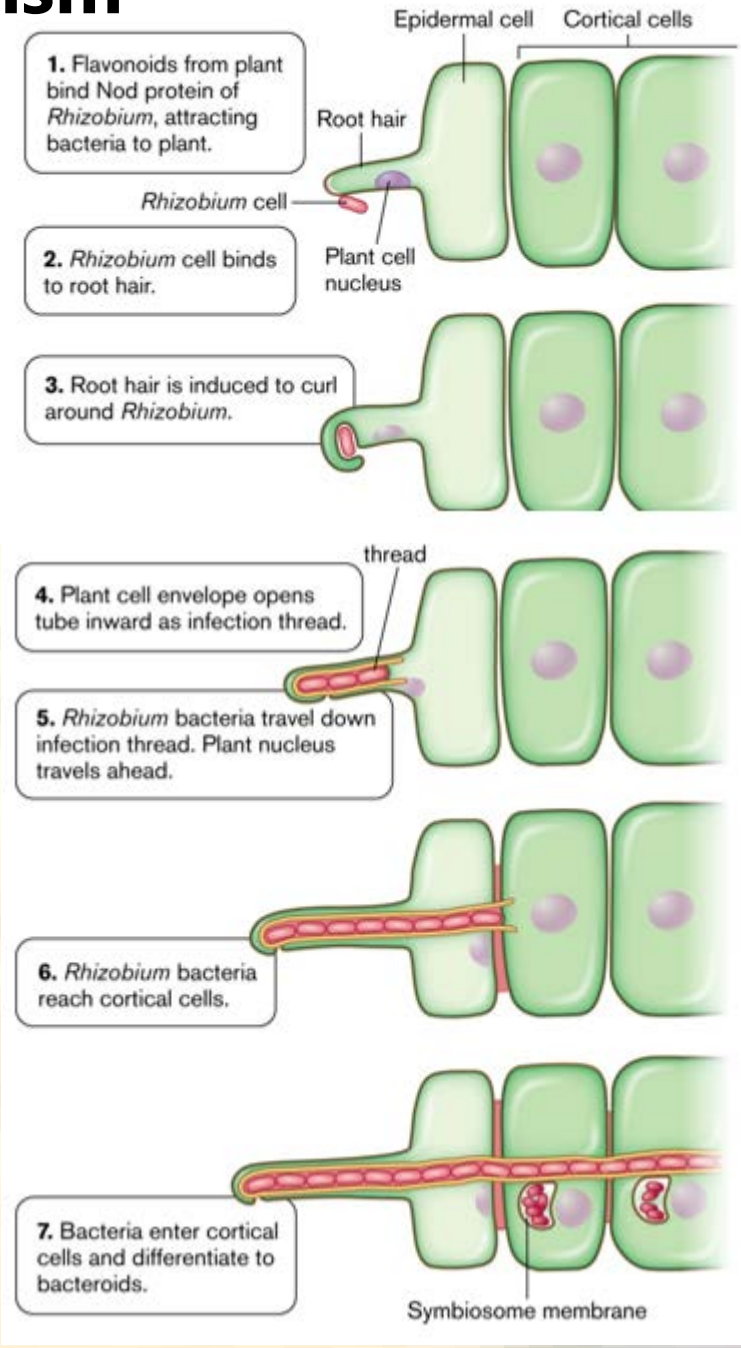
Rhizobium-legume mutualisms

Benefits of legumes have long been known in cropping systems, even before knowing the role of microbes



Rhizobium-legume mutualism

Red color in a nodule is leghemoglobin ("legume hemoglobin"), which binds O_2 and keeps it away from nitrogenase, which is oxygen sensitive)



Nitrogen-fixing bacteria

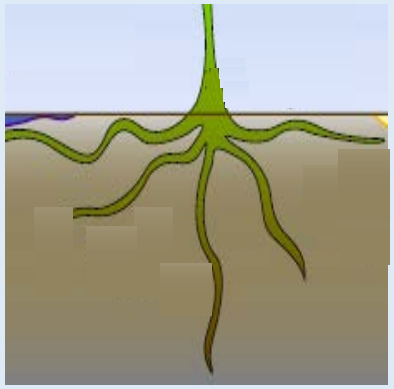
- Symbiotic nitrogen fixers

Actinorhizal mutualisms

Frankia (actinomycete) forms nodules on woody trees and shrubs. Important for reclamation of soils

Cyanobacterial mutualisms

Mycorrhizal and diazotrophic mutualisms are fine-tuned for maximum reciprocal rewards

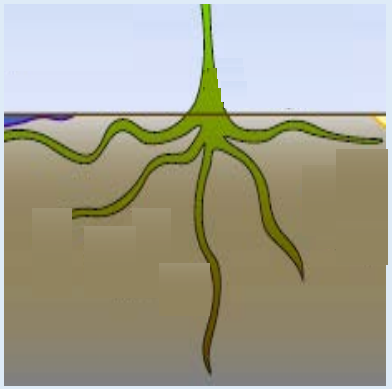


P — Mycorrhizal strain A

P — Mycorrhizal strain B

Carbohydrate

Kiers. 2011.Science 333:880



N — Rhizobium strain A

N — Rhizobium strain B

More resources

Sachs. 2010. J Evol Biol 23:1919

Questions on nitrogen-fixing symbioses?

How do microbes influence plant growth, reproduction, and productivity?

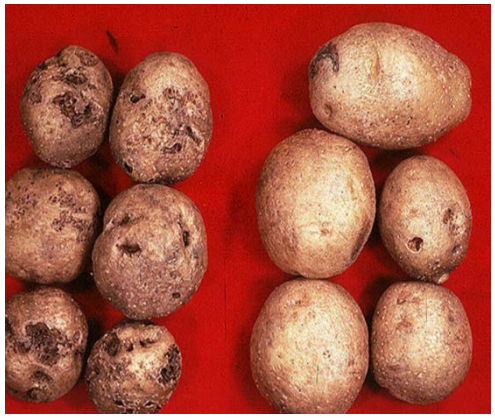
(1) Microbes help plants acquire nutrients

(2) Microbes can protect plants against pathogens and pests

Microbial communities can help suppress disease

- **Disease suppressive soils**
  - Examples:
    - Take-all decline of wheat
    - Rhizoctonia bare patch of wheat
- **Suppressive soils can yield inoculants for use in biological control**

Potato scab



Phytophthora root rot on alfalfa

Biocontrol Agent: — + — +

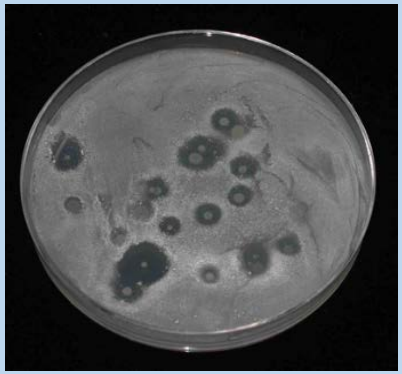
Microbial interactions involved in biocontrol

- Microbes may preemptively exclude, outcompete or kill pathogens

  Examples:

  Antibiobotic production

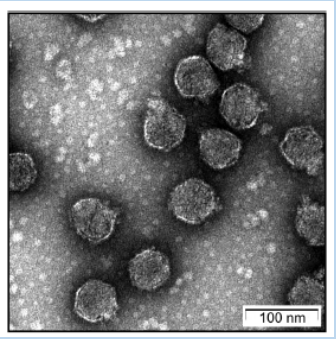
  More successfully scavenge iron

Microbial interactions involved in biocontrol

- Bacteriophage can lyse bacterial pathogens

Bacteriophage PP1 of *Pectobacterium carotovorum*

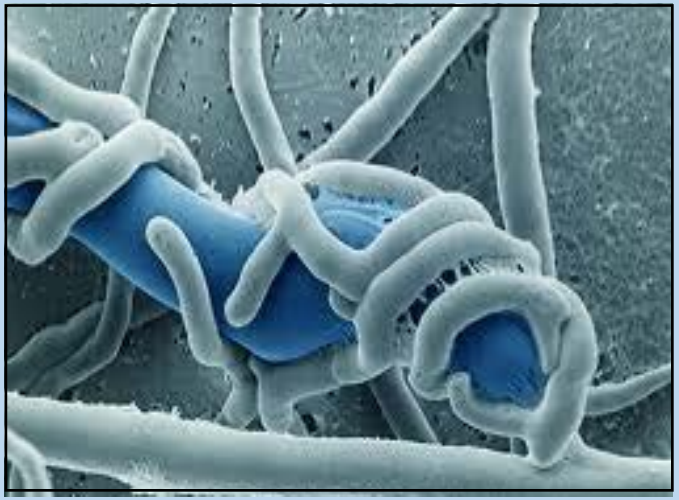


Lim. 2013. J. Microbiol. Biotechnol 23:1147

Microbial interactions involved in biocontrol

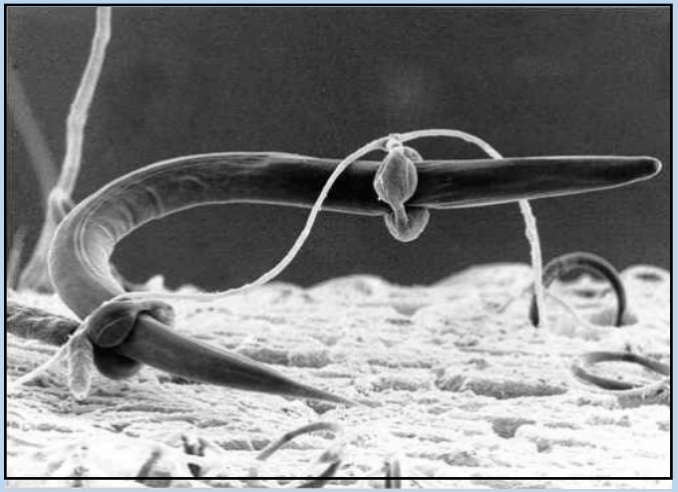
►Predatory fungi can parasitize other fungi and nematodes

Trichoderma killing another fungus



allplantprotection.blogspot.com

Predatory fungus attacking a nematode



www.uoguelph.ca/~gbarron

How do microbes influence plant growth, reproduction, and productivity (yield)?

(1) Microbes help plants acquire nutrients

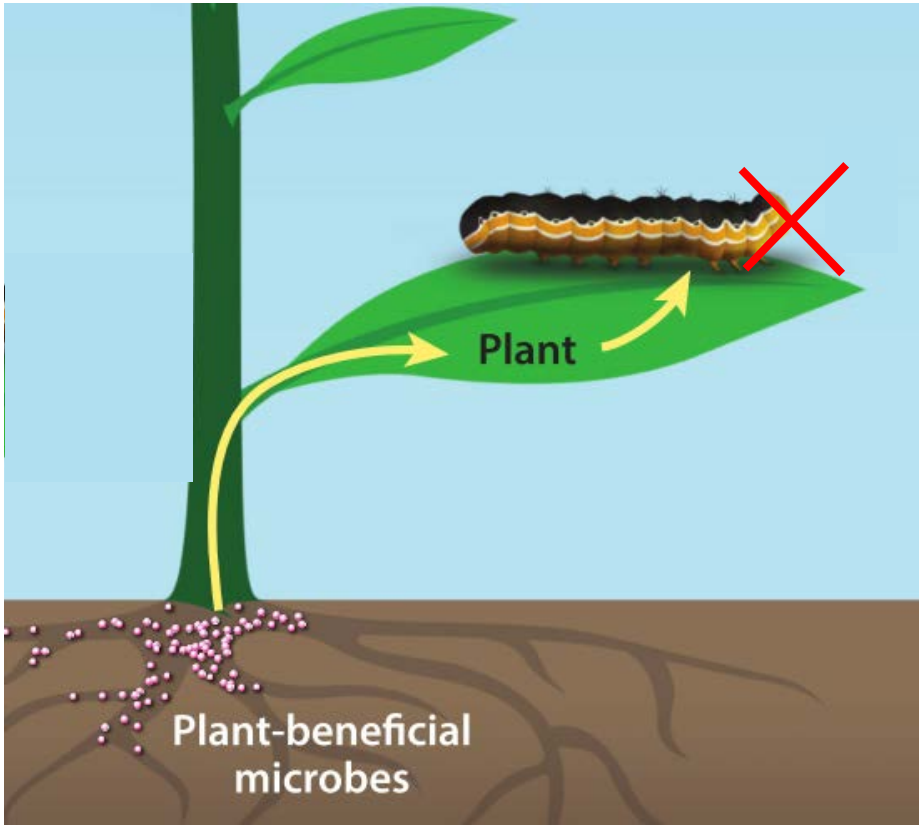
(2) Microbes can protect plants against pathogens and pests

(3) Microbes can help plants defend themselves

(3) Microbes can help plants defend themselves

- Microbes can induce plant genes involved in defense against a broad range of pathogens (fungi, viruses,…) and pests (nematodes, insects,…)

→Induced systemic resistance



(3) Microbes can help plants defend themselves

- Microbes can produce compounds that protect plants

Grass endophytes produce multiple alkaloids that can provide plants with:

- ►protection against seed predators
- ►defense against some plant pathogens
- ►defense against vertebrate and invertebrate herbivores

Toxicosis
Livestock
staggers

Endophyte inoculant

How do microbes influence plant growth, reproduction, and productivity (yield)?

(1) Microbes help plants acquire nutrients

(2) Microbes can protect plants against pathogens and pests

(3) Microbes can help plants defend themselves

(4) Microbes can help plants tolerate environmental stresses

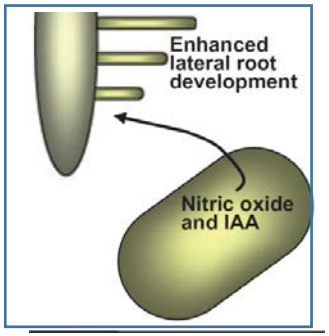
(4) Microbes can help plants tolerate environmental stresses

Plants can't move → strong selection for partnerships that help them cope with changes in the environment

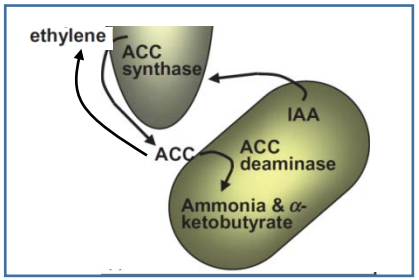
Partnerships are known that involve endophytic fungi, bacteria and even viruses

Drought, Flooding & Salinity

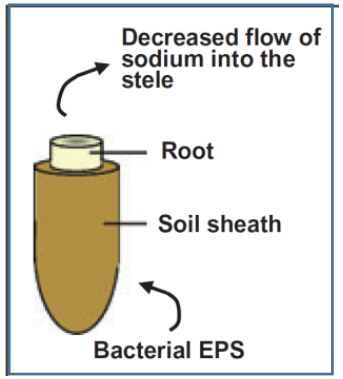
- Microbes can enhance root growth by producing plant growth hormones, and can serve effectively as plant roots (mycorrhizae)



- Microbes can minimize the inhibitory effect of ethylene on plant growth
  - produce ACC deaminase



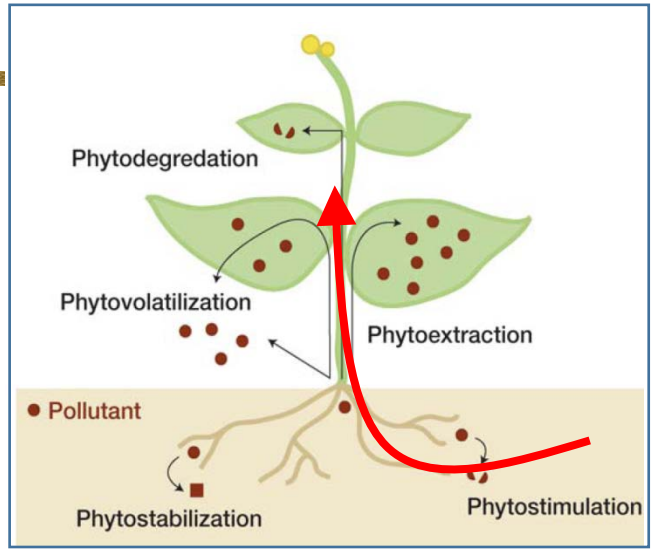
- Microbes can form biofilms that reduce ion movement into the plant



Dimkpa. 2009. Plant Cell Environ 32:1682

Soil pollutants

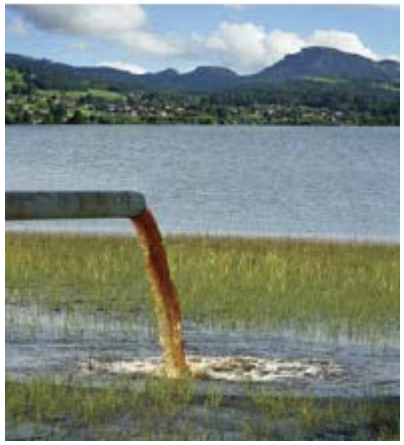
► Pollutants are transported to roots in the transpiration stream
→ degraded by the metabolically active rhizosphere microbes



Pilon-Smits. 2005. Annu Rev Plant Biol 56:15

Example: endophytic *Burkholderia* ↓ toluene evapotranspiration and phytotoxicity
(Barac. 2004. Nat Biotechnol 22:483)

► Microbes decrease toxicity of pollutants to plants & humans
→ Transform heavy metal pollutants
(e.g., arsenic and selenium on rice)



High temperatures

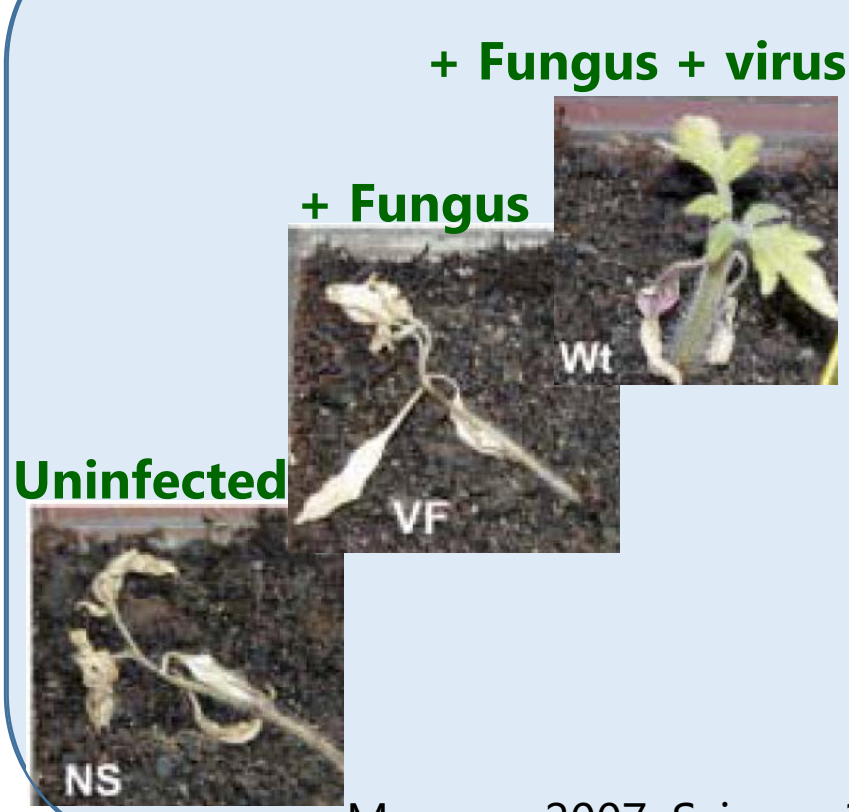
A three-way symbiosis confers thermotolerance in plants

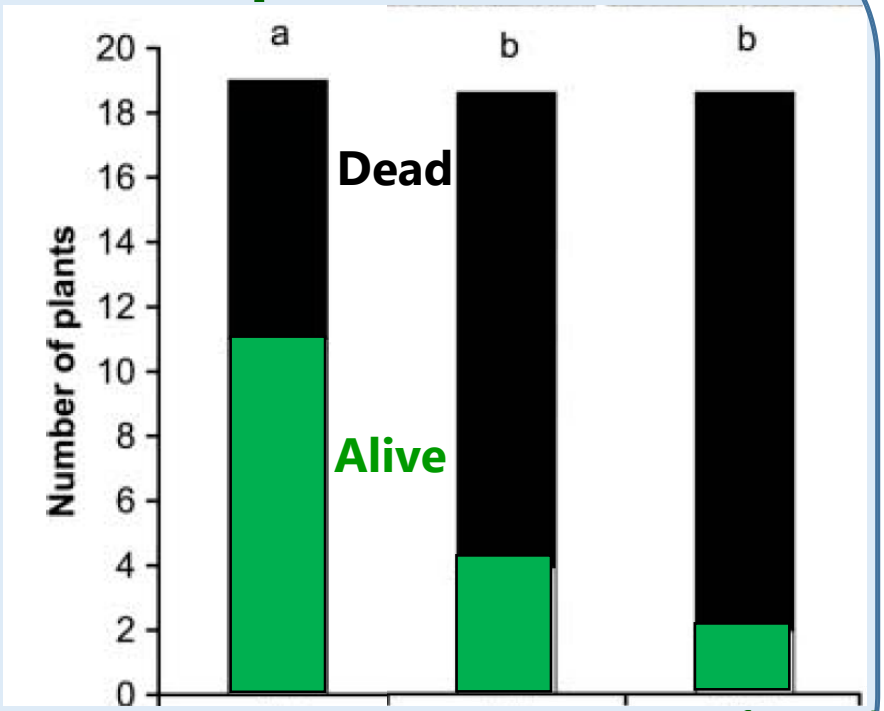
Virus —Inside→ Fungus —Inside→ Plant

Fungus → Thermotolerant

Plant → Thermotolerant

Heat-treated tomato plants





Marquez 2007. Science 315:513

(5) Microbes can help plants grow better

Even in the absence of pests, pathogens, and environmental stresses, microbes can increase plant growth

Primary players: plant growth-promoting rhizobacteria and endophytic fungi

Mechanisms

Associative nitrogen fixation

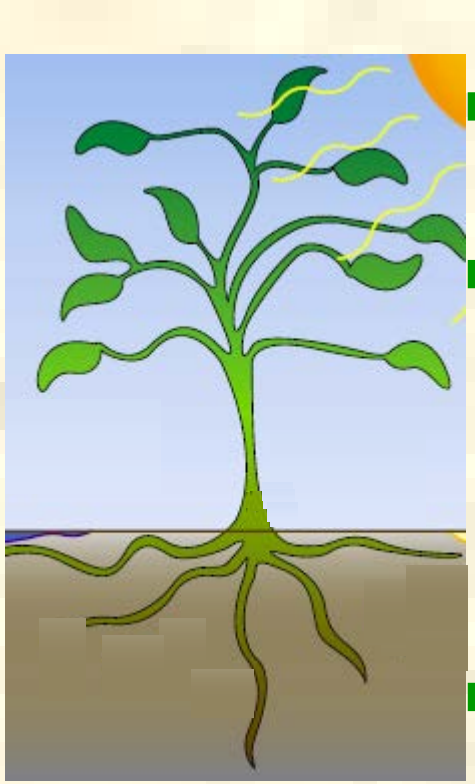
Production of plant growth hormones

Production of small molecules (lumichrome)

or volatile compounds (e.g., 2,3-butanediol)

Plants & microbes are highly co-evolved

Their behaviors are mediated by complex interspecies communications

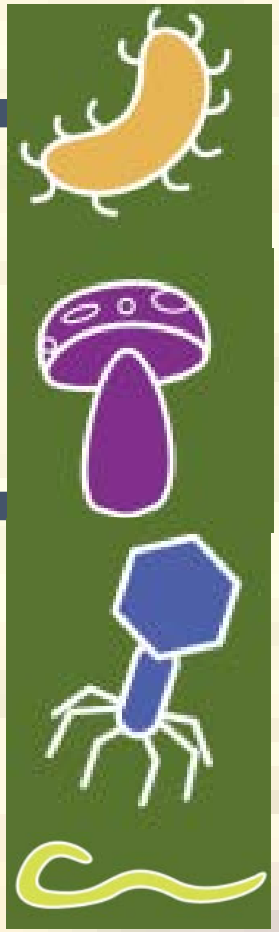


Flavanoids → **Nodules** ← Nod factors

Phenolics → **Galls** ← T-DNA

Protein effectors → **Disease**

HIF and chemoattractants → **N_2-fixing cyanobacterial symbioses**

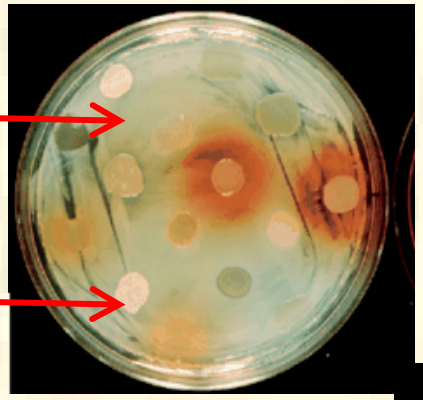


Microbes exist within interactive communities

Root colonist (*Pseudomonas aureofaciens*) → High density of autoinducing (quorum) signal → Produces **orange** antibiotics (phenazines)

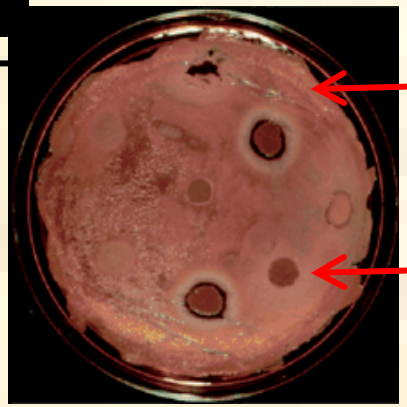
Lawn of a non-signal-producing mutant

Isolates from roots



Cross-talk:
Other root isolates make signals that induce phenazines

Quorum-quenching:
Other root isolates interfere with phenazine production



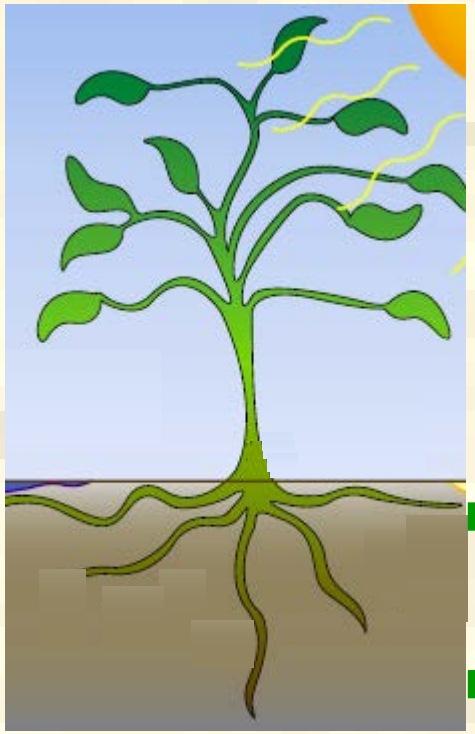
Lawn of *P. aureofaciens*

Isolates from roots

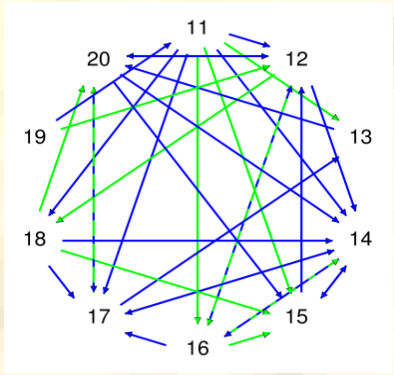
Morello. 2004 Appl Environ Microbiol 70:3103

Microbes exist within interactive communities

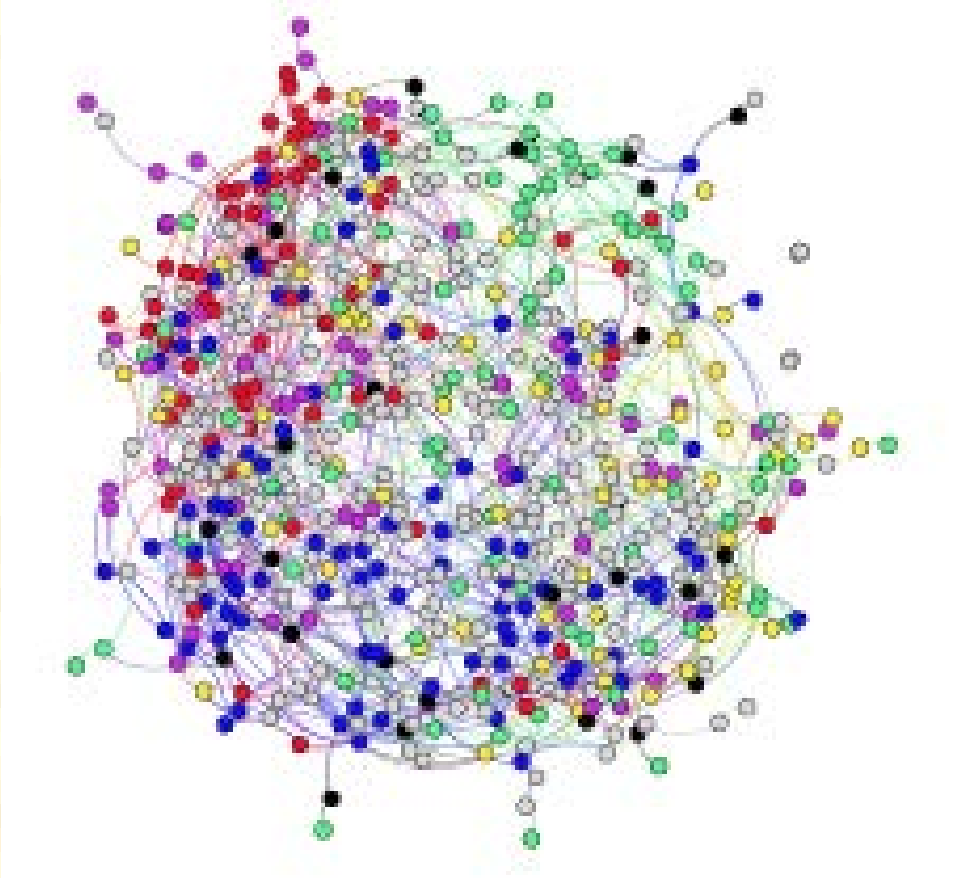
…and plants are influencing the conversation



- Quorum mimic compounds
- Quorum antagonists



The net effects of plant-microbe interactions may be quite different for microbes in communities than for individual microbes



How can the potential benefits of plant-microbe associations be captured to enhance crop production?

(1) Through microbial-based products

Current market:

$44 bil/yr Chemical pesticides

$2 bil/yr Biological pesticides (insecti-, herbi-, fungi-cides)

$1 bil/yr living microbes

Galltrol - Agrobacterium radiobacter

AgBioChem, Inc.

Biopesticide registration

→ 4-6 yrs and up to $10 million

Plant growth promotion registration

→1-2 yrs and up to $1 million

How can the potential benefits of plant-microbe associations be captured to enhance crop production?

(2) Apply knowledge of microbial community-level benefits to improve crop production practices (tillage, crop rotation, inputs, …)

→ requires a conceptual shift toward understanding the network of interacting components of an agricultural ecosystem

We need to understand the complete plant biome – the Phytobiome

Biological and Environmental Context

Plants

Micro- and Macroorganisms

Viruses
Archaea
Bacteria
Amoeba
Oomycetes
Fungi
Algae
Nematodes

Soils

Arthropods, Other Animals and Plants

Insects
Arachnids
Myriapods
Worms
Birds
Rodents
Ruminants
Weeds

Climate

Their environment

All of the associated organisms

Advances in characterizing microbiomes

Genome-enabled technologies
Computational biology and modeling

PCR amplify (16S-18S rRNA, ITS, *cpn60*)

Amplicon sequencing

Metagenome sequencing

Meta-transcriptome sequencing

Metaproteome analysis

Metabolome analysis

Species (taxa) number, abundance, composition	Community function	Community activity
"Who is there?"	**"What can they do?"**	**"What are they doing?"**

Organism	Identification	Relative abundance
Organism 1	Phylum: Proteobacteria Class: Alphaproteobacteria Order: Rhizobiales Family: Bradyrhizobiaceae Genus: *Bradyrhizobium*	0.004%
Organism 2 : :	Phylum: Nitrospirae Class: Nitrospira Order: Nitrospirales Family: Nitrospiraceae Genus: *Nitrospira*	0.0008%
Organism 10,249	Phylum: Verrucomicrobia Class: Spartobacteria Order: Chthoniobacterales Family: DA101 soil group Genus: Uncultured bacterium	0%

Total: ***100%***

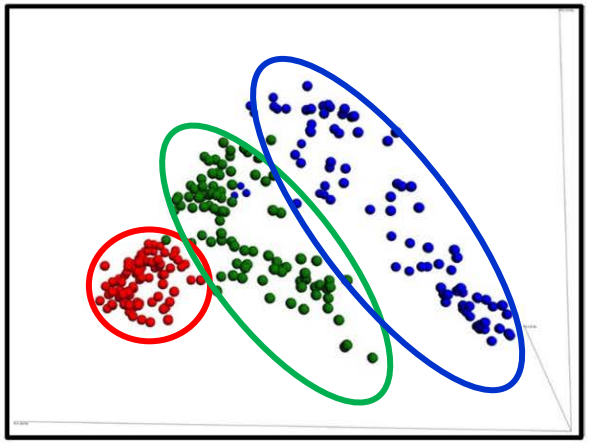
Bacterial Communities

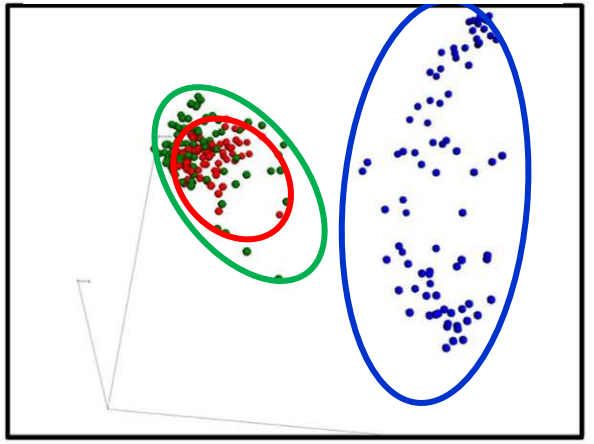
Fungal Communities

Soil

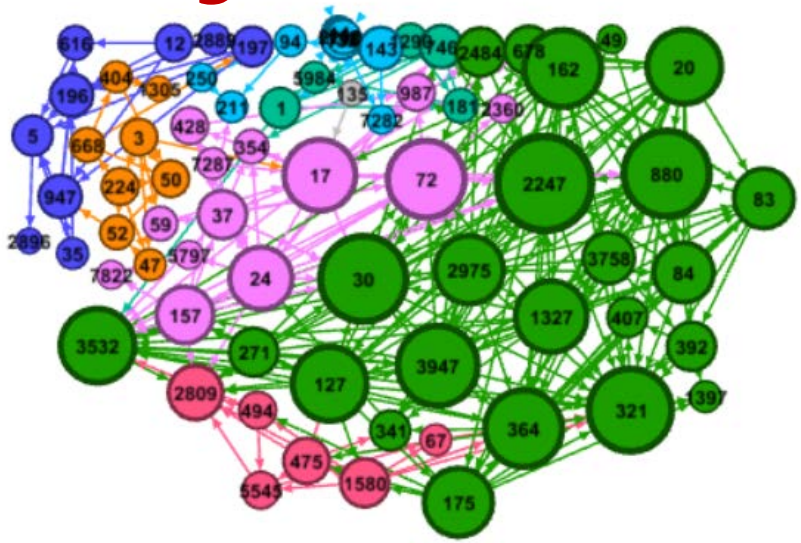
Rhizosphere

Endosphere

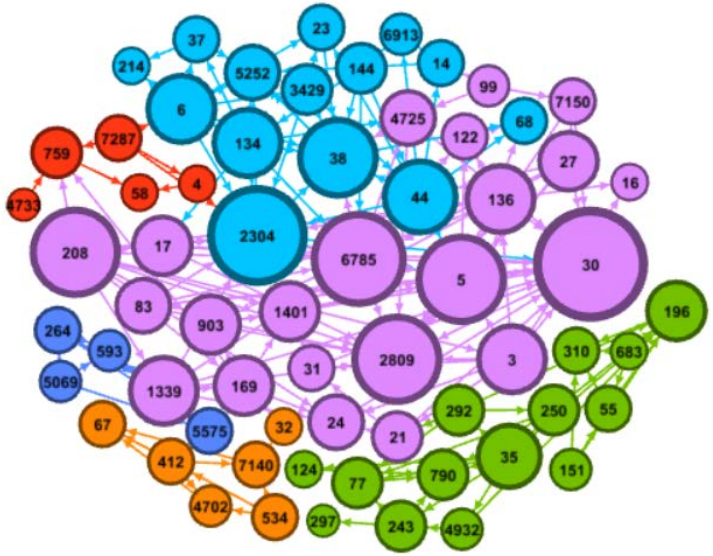




High soil water



Low soil water



We need to understand the complete plant biome – the Phytobiome

Management Context

Crop choices

Species Cultivar

GMO/Non-GMO

Monoculture

Cover crops

Crop rotations

Inputs

Application methods

Timing

Herbicides

Insecticides

Organic/Inorganic fertilizers

Fungicides

Site choices

Irrigation Tile drainage

Livestock Mgt

Till/No-till

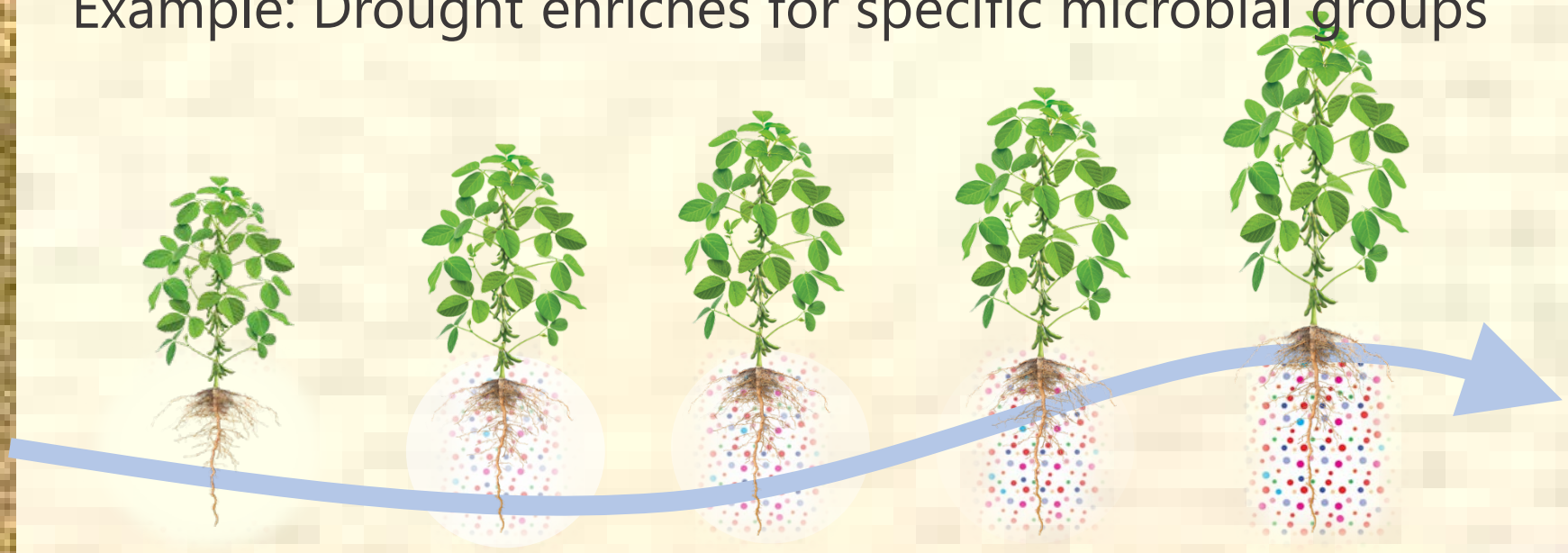
Planting time

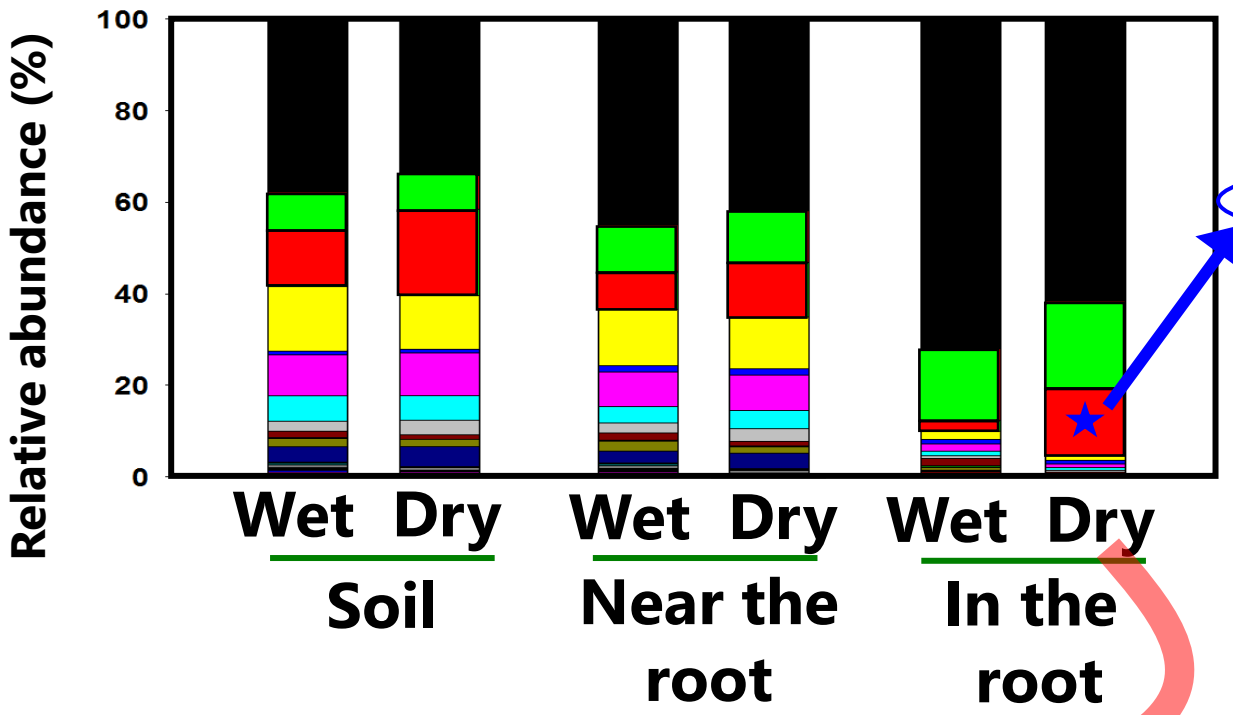
Harvest time

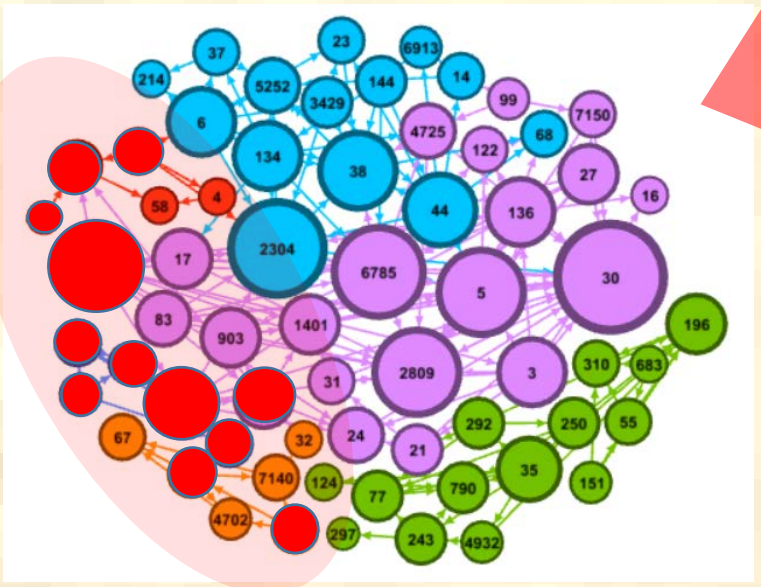
How can the potential benefits of plant-microbe associations be captured to enhance crop production?

(3) Capture the ability of the plant to *select* or *enrich* for favorable organisms in our plant breeding and germplasm development efforts

Example: Drought enriches for specific microbial groups







Actinobacteria generally co-occur (interact) with other Actinobacteria

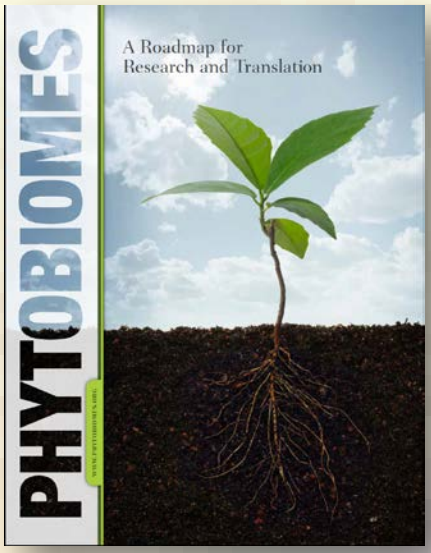
How can the potential benefits of plant-microbe associations be captured to enhance crop production?

→ *Breed plants that select for beneficial communities*

→ *Develop biologicals and predictors of crop and soil health*

→ *Design improved management practices based on knowledge of the phytobiome*

→ *Incorporate biological information into the next generation of precision agriculture technologies*



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