USDA
United States Department of Agriculture

Latest Insights on Soil Biology as Influenced by Soil Management

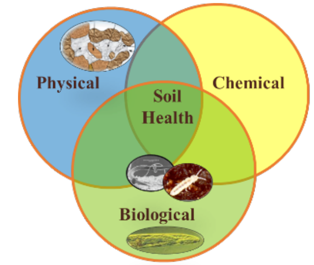
Jennifer Moore-Kucera, Ph.D.
USAD-NRCS Soil Health Division

April 3, 2018

SARE Our Farms, Our Future Conference

St. Louis, MO

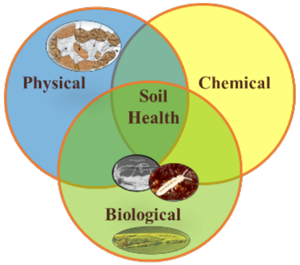
A Healthy Soil is…



A living system that supports a **diverse, <u>active biological community</u>** that aids crop production by providing essential functions…

Soil photo source and slide design: Jennifer Moore-Kucera, USDA-NRCS-SHD; Soil organisms images from Orgiazzi, Bardgett, Barrios et al. 2016. Global Soil Biodiversity Atlas. Publications Office of the European Union.

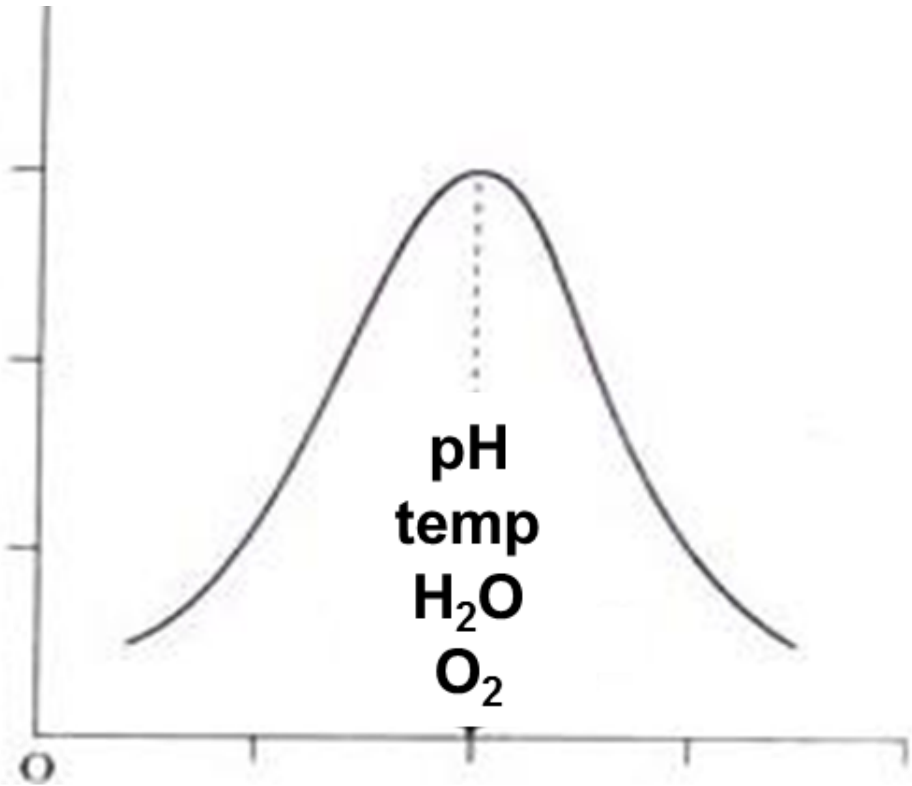
Key Functions of Soil Organisms That Support Plant Productivity



- Decomposing residues & forming SOM
  Enhancing nutrient cycling
- Improving soil structure
- Improving H_2O & nutrient holding capacity
- Protecting plants from disease & pests
- Protecting plants from stress
- Detoxifying pollutants

Soil photo source and slide design: Jennifer Moore-Kucera, USDA-NRCS-SHD; Soil organisms images from Orgiazzi, Bardgett, Barrios et al. 2016. Global Soil Biodiversity Atlas. Publications Office of the European Union.

Optimal Biomass & Activity in Most Ag Systems Occurs When Conditions are 'Just Right'



Near neutral pH
Moderate temps
Moist conditions
Aerated
Abundant food (carbon)

Most Soil Organisms Are At ‘Rest’

Sleeping Beauty & Prince Charming

Bacteria on the fungal highway

https://www.youtube.com/watch?v=AnsYh6511Ic

- Fungi, earthworms, nematodes, & other fauna act as ‘Prince Charming’

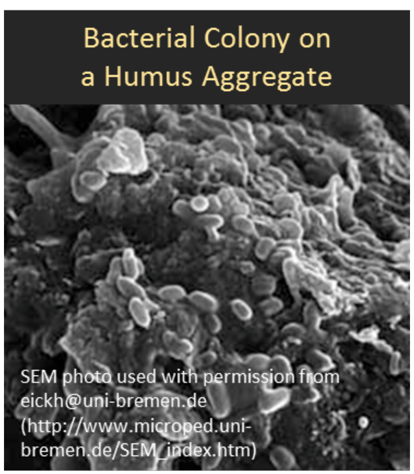
- What about management?

Biological Hot Spots of Life & Action

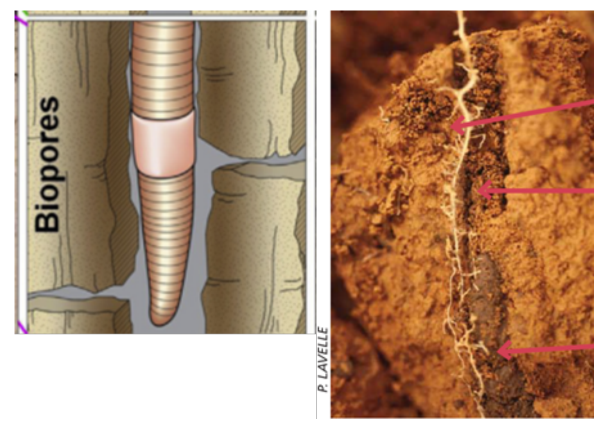
Rhizosphere

Litter Layer

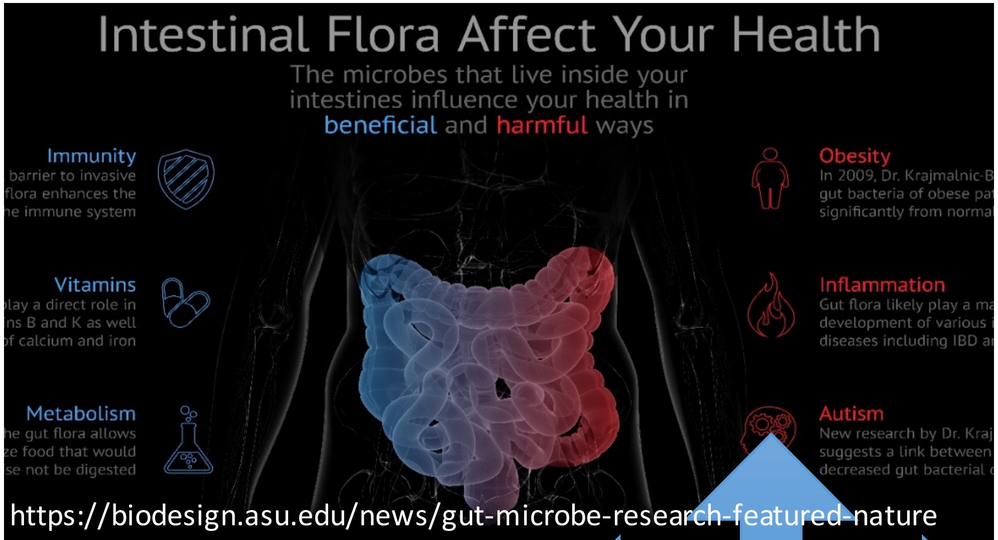
Aggregate Surfaces & Pores



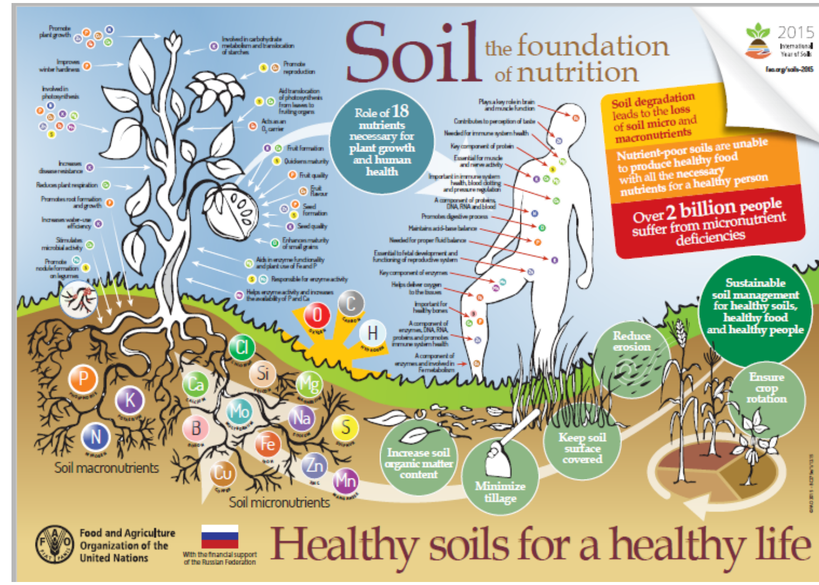
Earthworm & Root Channels



Healthy Soil is Foundation for Nutrition



https://biodesign.asu.edu/news/gut-microbe-research-featured-nature

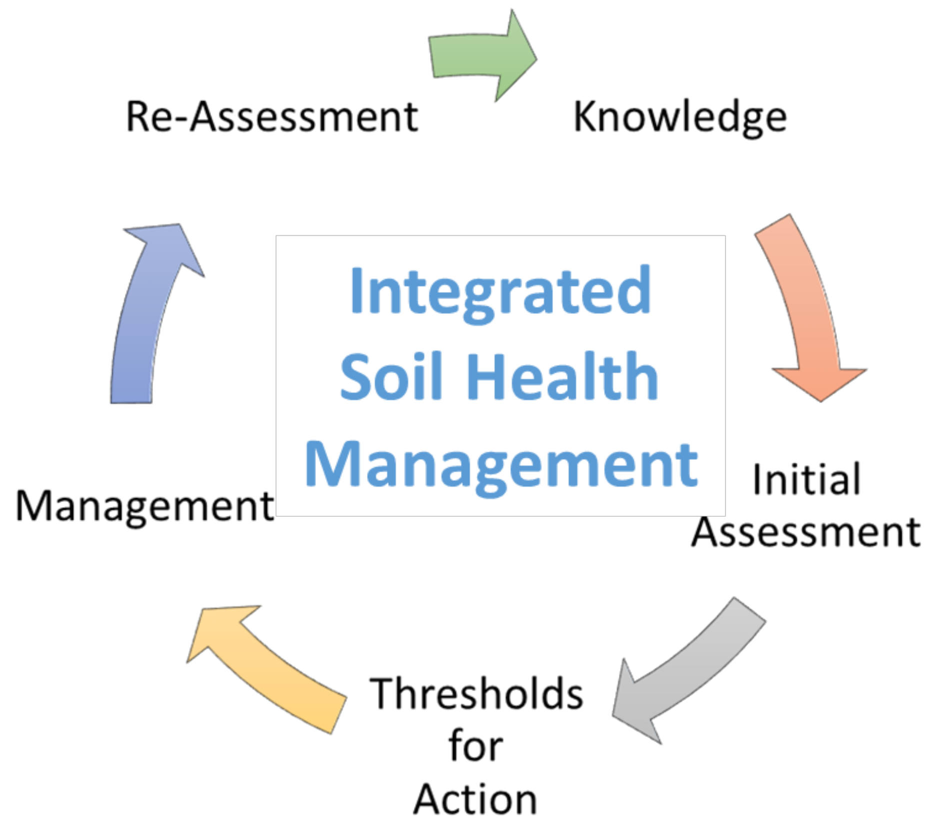


Links?


http://aem.asm.org/content/75/15/5111.full

Developing a Soil Health Management System To Optimize Soil Biological Functions

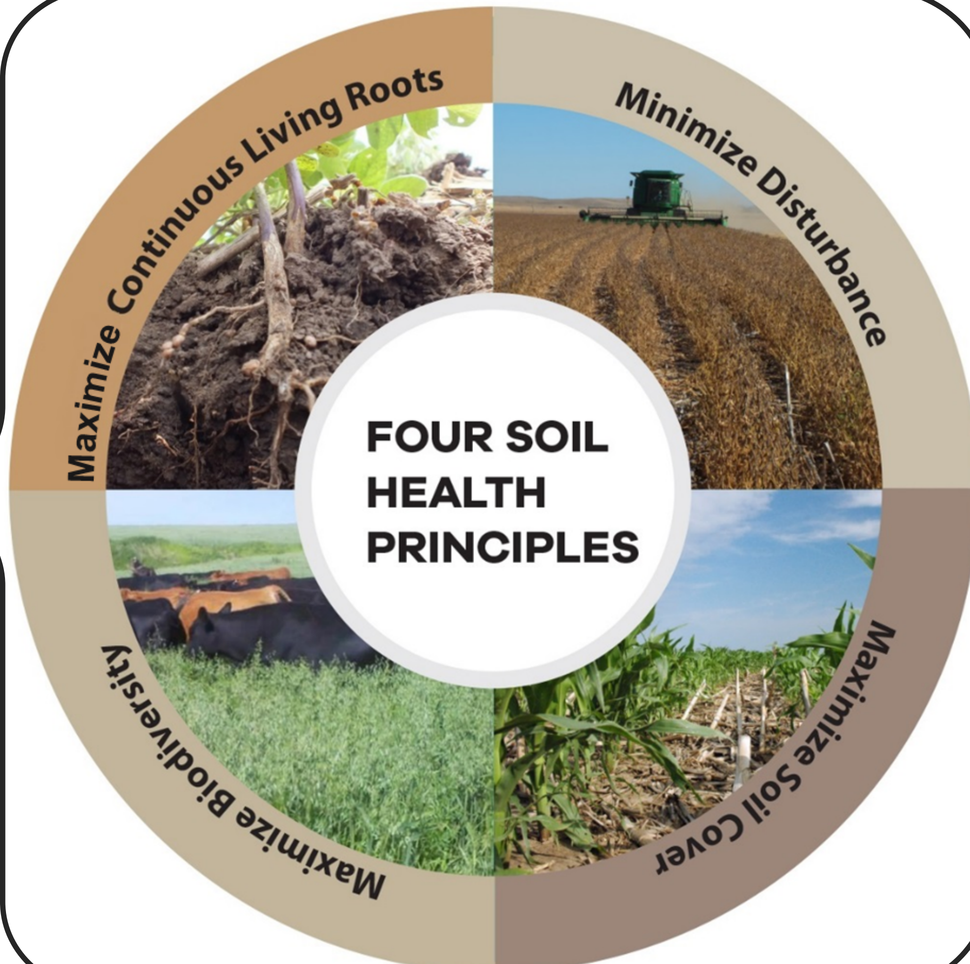
1. **Knowledge**
   a. Farm background & management history
   b. Identify problem(s)
2. **Initial Assessment**
   a. Field & laboratory
3. **Identify Thresholds for Action**
   a. Acceptable levels
4. **Identify Management Strategies**
   a. Short-term
   b. Long-term
5. **Re-assessment & Adaptation**



Adapted from: Manter, Delgado, & Moore-Kucera, 2018, In Press

Four Soil Health Principles With Universal Applications

Feed & Fuel
Soil Biology

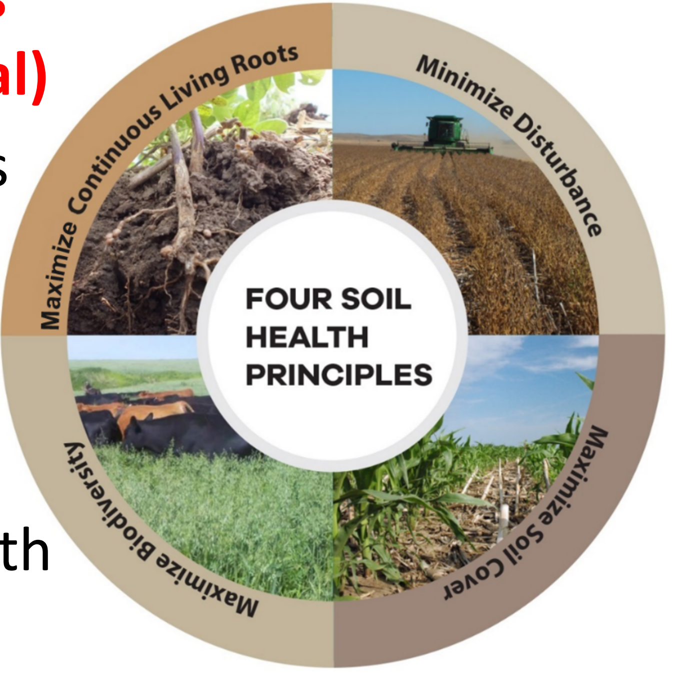


Protect Soil
Aggregates &
Organic Matter

Four Soil Health Principles With Universal Applications

Feed & Fuel Soil Biology with diverse C sources (plant, animal, microbial)

- Break disease cycles
- Stimulate microbial diversity
- Increase SOM and nutrient cycling
- Enhance plant growth
- Increase predator & pollinator populations



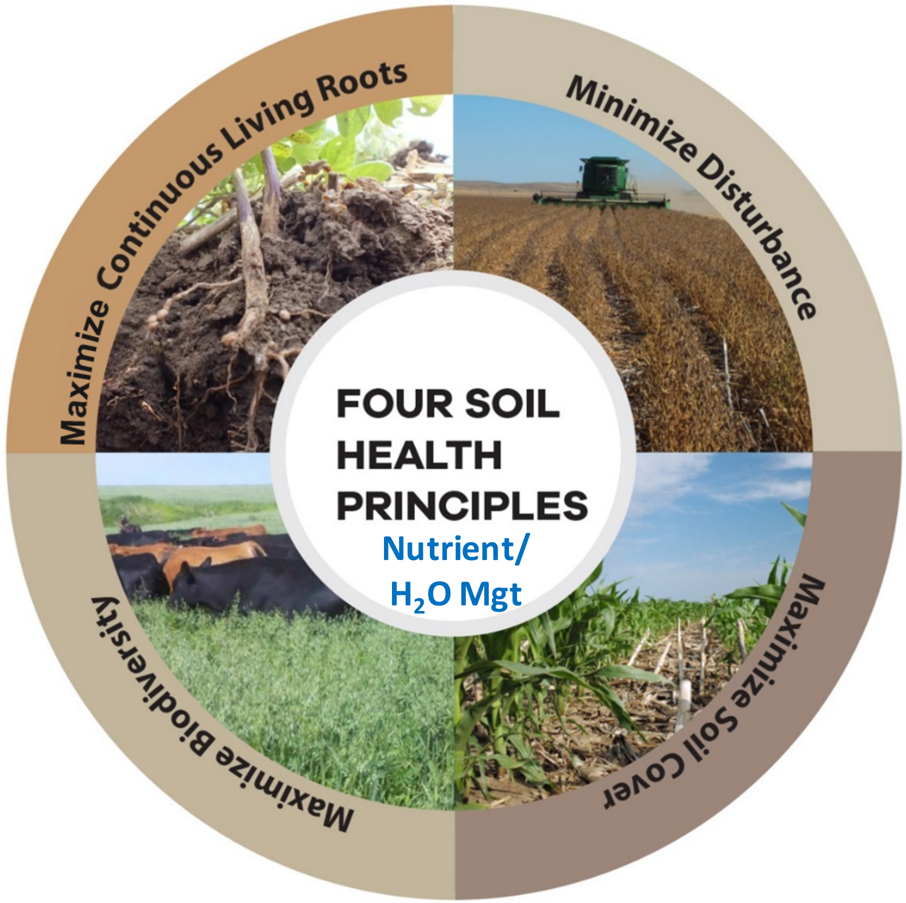
Protect microbial habitat

- Maintain SOM & aggregates
- Reduce erosion & runoff risk
- Buffer temperature
- Reduce evaporation

Practices that Feed & Protect

Crop Rotation
Cover Crops
Relay Crops
Forage & Biomass Planting
Perennial Crops

Reduced Tillage
Controlled Traffic
Avoid Tillage When Wet
No-till
Fertility Mgmt
IPM

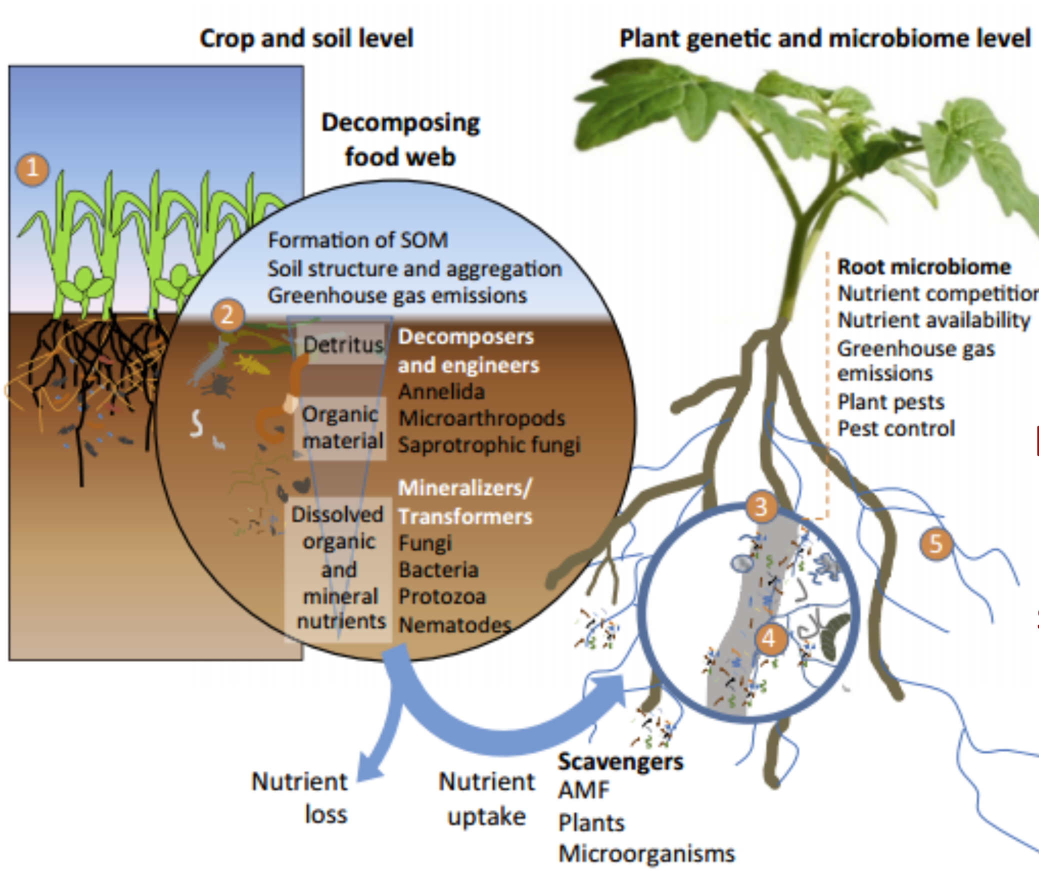


Cover Crop
Crop Rotation
Rotational Grazing
IPM
Pollinator Plantings
Organic Fertilizers
Amendments

Cover Crop
Mulching
Reduced Tillage
Forage & Biomass Planting
Residue Retention

Entry Points for Soil Health Management

Plant choice
Breeding
SH Management



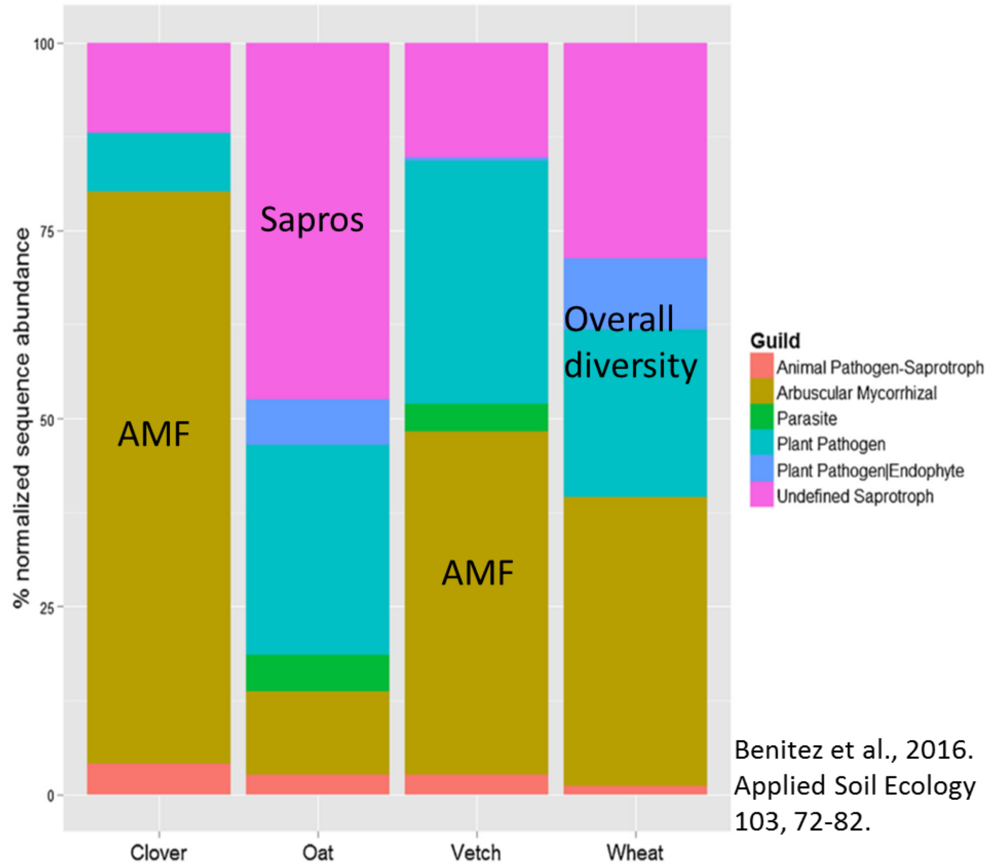
Disease suppression
Nitrification inhibition
Denitrification inhibition
Inoculation
Fostering disease-suppressive populations

Bender et al. 2016. An underground revolution: Biodiversity and soil ecological engineering for agricultural sustainability. Trends Ecol Evol.

Integrated Soil Health Management

Soil microbiomes and functions can be manipulated via:

- **Crop selection**
- Variety selection
- Fertilization
- Stress induction
- Amendments
- Plant developmental stage



Benitez et al., 2016. Applied Soil Ecology 103, 72-82.

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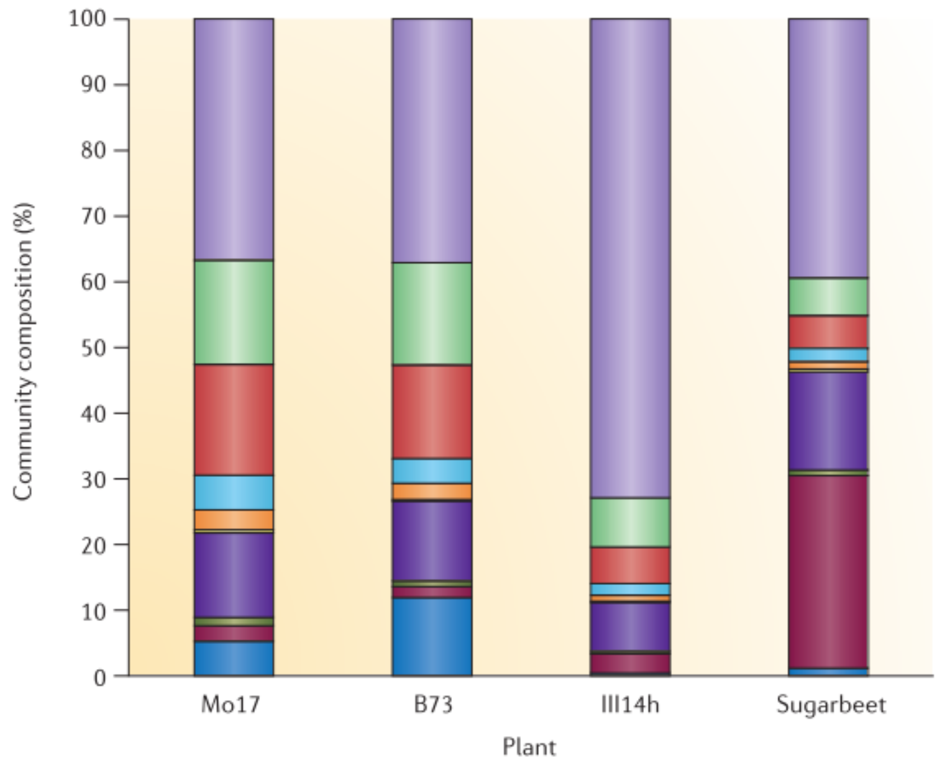
--3 Maize Varieties--



As shown in: Philippot et al., 2013. Nat Rev Microbiol 11, 789-799.

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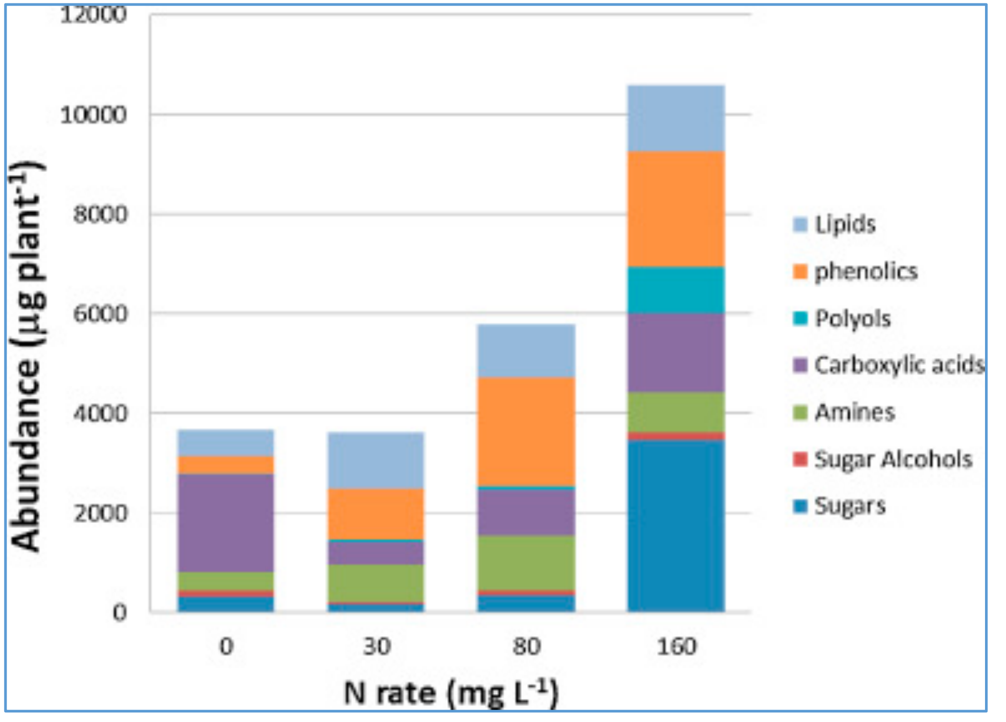

Zhu et al. 2016. Appl. Soil Ecol 107:324-333

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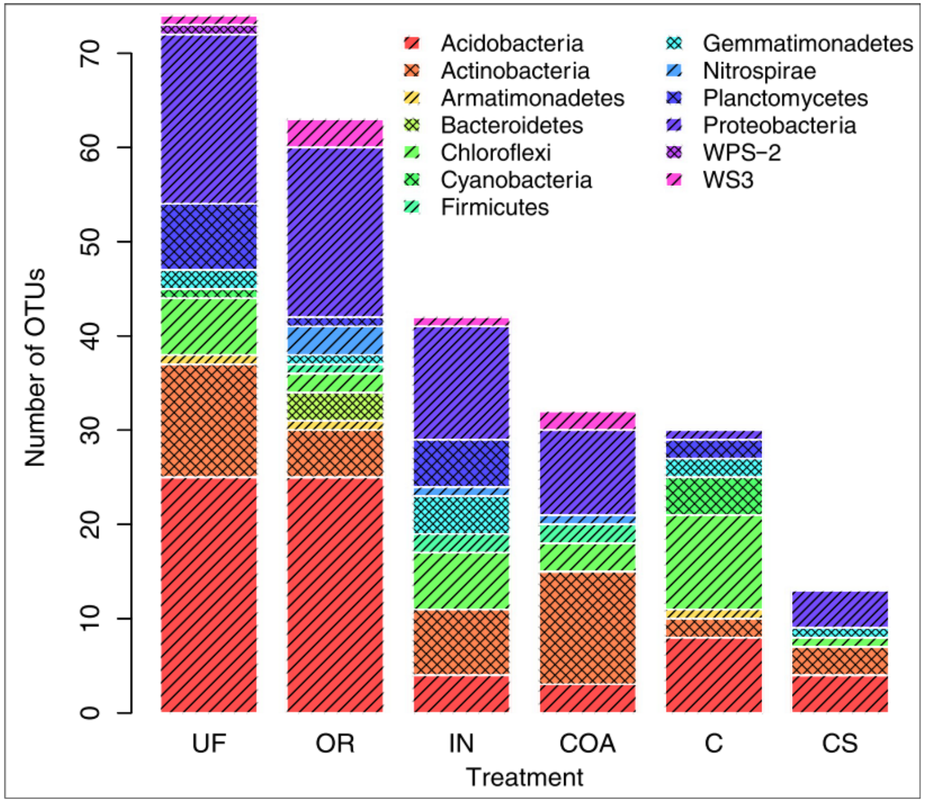

Soman et al., 2017. Plant and Soil 413, 145-159.

Integrated Soil Health Management

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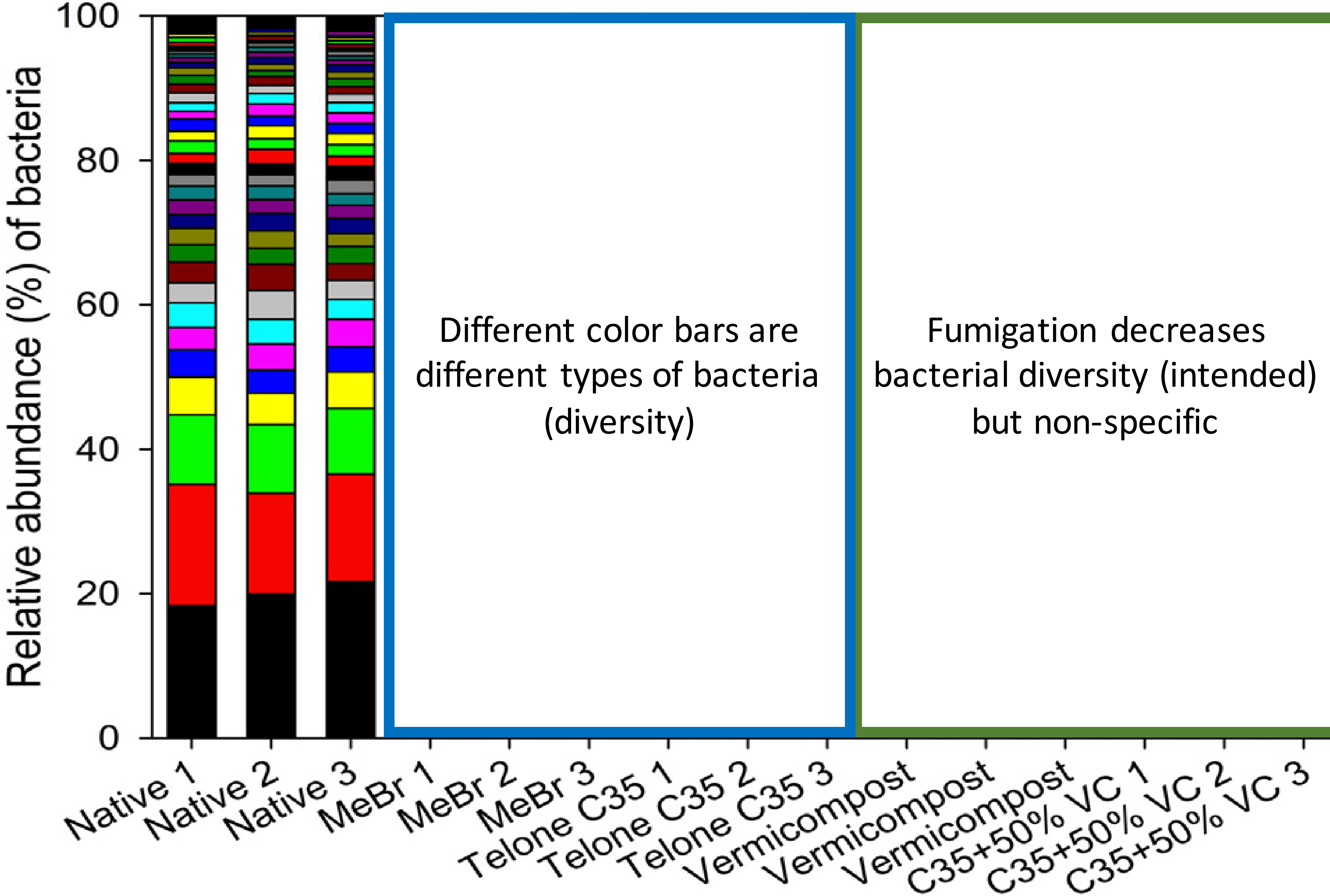
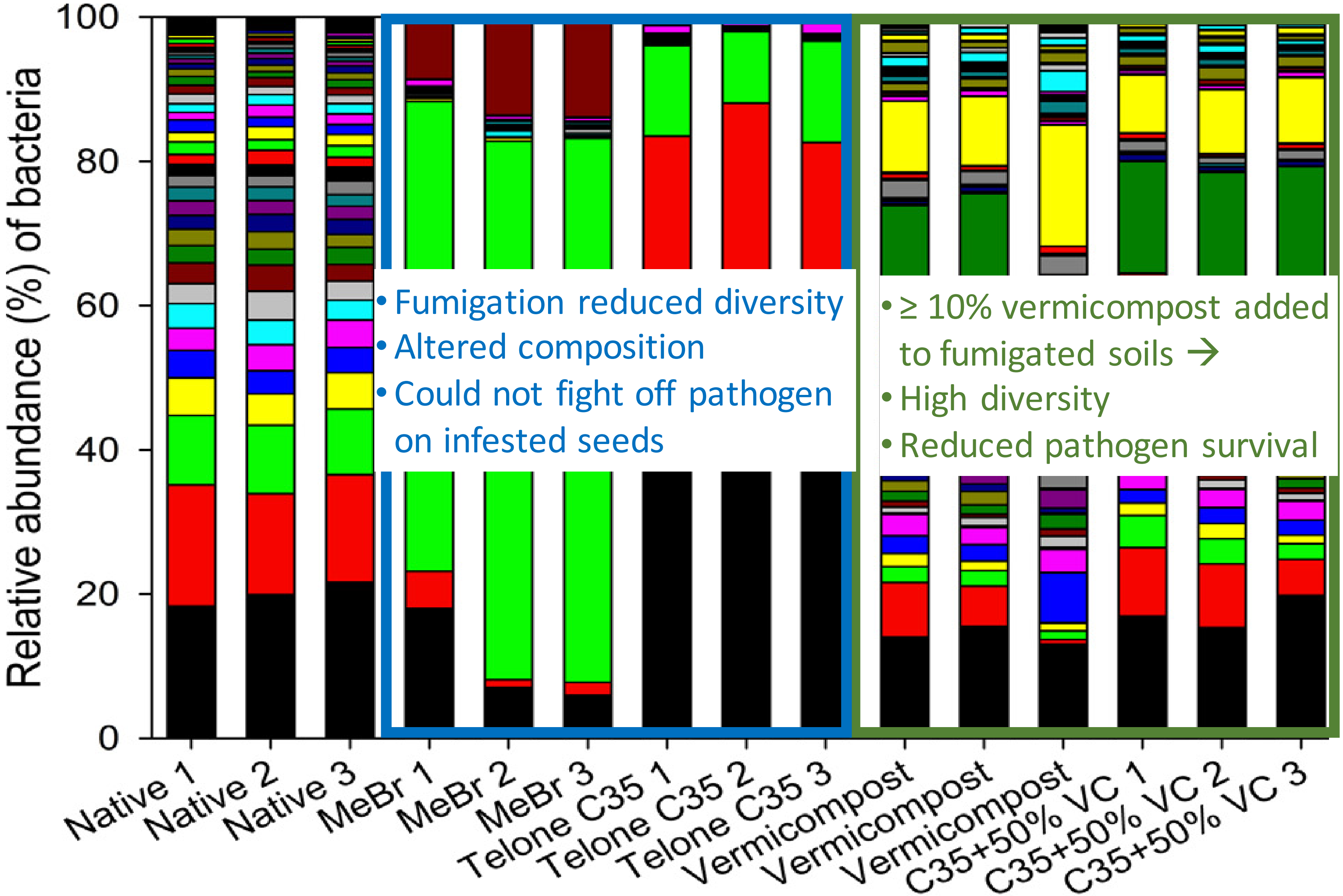
- Stress induction
- **Amendments**
- Plant developmental stage

Organic Amendments To Help Control Pathogens



Strauss, Stover, Kluepfel. 2015. Impact of biological amendments on *Agrobacterium tumefaciens* survival in soil.

Manipulation of Biota Through Organic Amendments to Control Pathogens



- Fumigation reduced diversity
- Altered composition
- Could not fight off pathogen on infested seeds

- ≥ 10% vermicompost added to fumigated soils →
- High diversity
- Reduced pathogen survival

Strauss, Stover, Kluepfel. 2015. Impact of biological amendments on *Agrobacterium tumefaciens* survival in soil.

Integrated Soil Health Management

Soil microbiomes and functions can be manipulated via:

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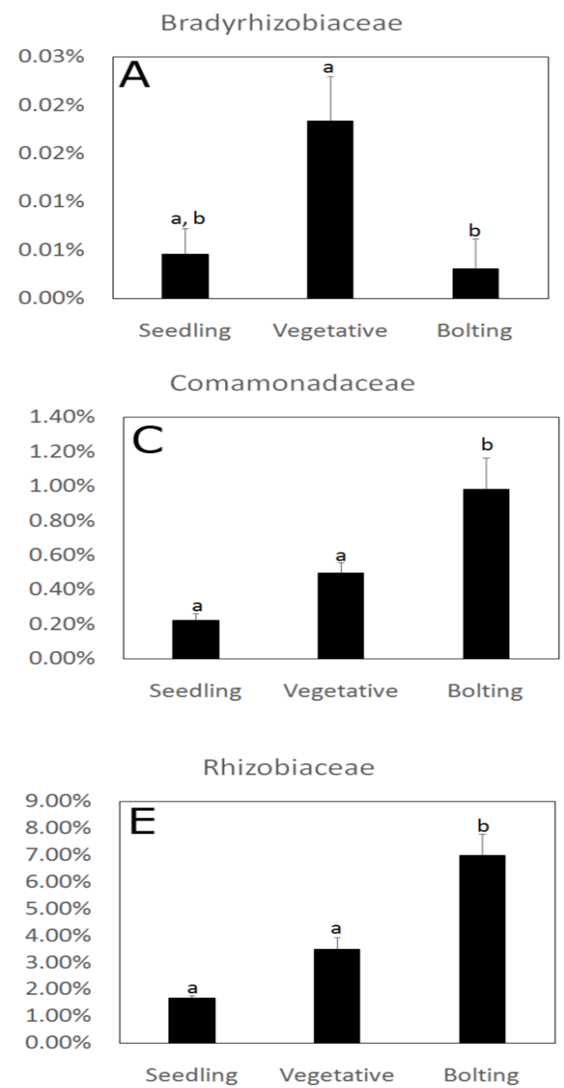
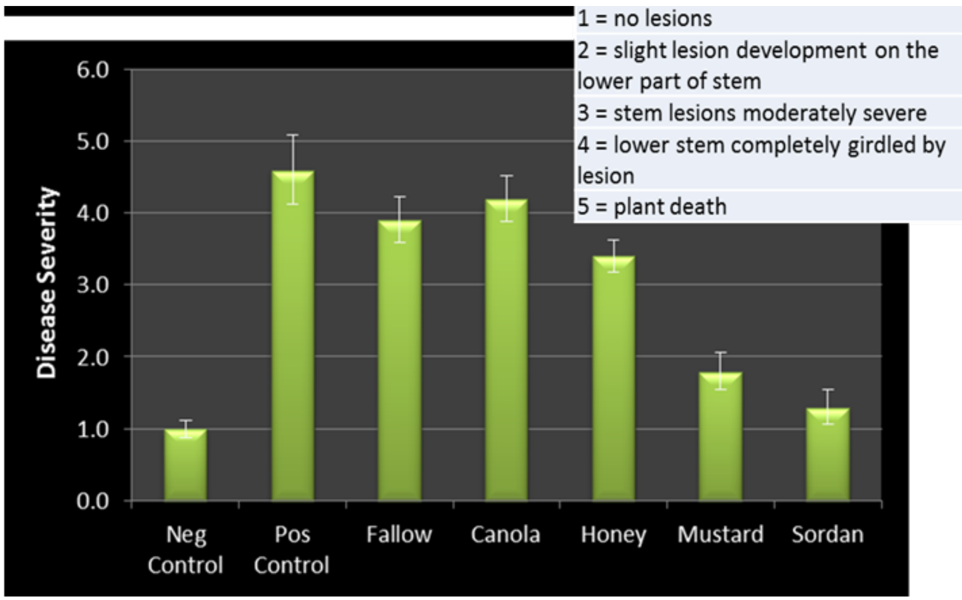
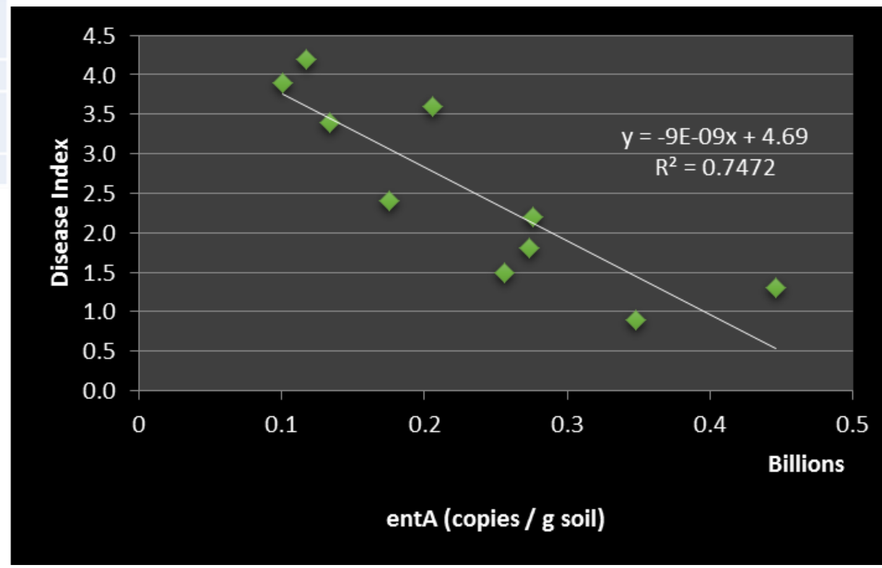


Yuan Jun et al. 2015. Soil Biol Biochem 89:206-206

Crop Selection for Specific Functions (e.g., Disease Suppression)





Unpublished data courtesy Dr. Dan Manter, USDA-ARS

Cracking the Microbial Molecular Code for Soil Health

Function	Microbial indicators
SOM/ C cycling & decomposition	• Total microbial biomass • Specific taxa or genes encoding for C mineralization • Root growth genes
Aggregation	• Arbuscular mycorrhizal fungi • Actinobacteria, • Bacillus and other EPS producers
Nutrient cycling	• Microbial biomass • N fixers, nitrifiers, denitrifiers, N decomp genes • P-solubilizing bacteria, P and S decomp genes
Disease suppression	• Genes for siderophore production • Antibiotics • Induced systemic resistance; Systemic Acquired Resistance
Stress Resiliency	• Gene involved in ethylene degradation (ACC deaminase) • Hormone producing (e.g. auxin, cytokinin) bacteria

Tools Needed

- Soil health is driven by the actions of soil microbes and biota
- Sampling and methodological advances should focus on the living soil component
- Appropriate databases needed
- National living soil archive needed
- On-line public forum/ discussion groups needed

PNAS

Why we need a National Living Soil Repository

Daniel K. Manter[a], Jorge A. Delgado[a,1], Harvey D. Blackburn[b], Daren Harmel[c], Adalberto A. Pérez de León[d,e], and C. Wayne Honeycutt[f]

Soils are the keystone of healthy and vibrant ecosystems, providing physical, chemical, and biological substrates and functions necessary to support life. In particular, it's the extensive and elaborate matrix of soil microorganisms and other life forms that contributes to soil health and utility.

But soils are under constant threat from heavy use, changing climate, and in some cases poor management (1, 2). In view of soil's key role and threatened status, we believe that there is a need for the scientific community to undertake coordinated research and development efforts that will lead to a unique asset: a National Living Soil Repository (Fig. 1).

Already local and national soil archives have been shown to be of great utility for studying, analyzing, and documenting long-term environmental and ecological trends. For example, the historical soil archive at Hubbard Brook helped researchers discover the link between fossil fuels and acidification of rain and snow (3); the Rothamsted Sample Archive in the United Kingdom has shown a steady increase in dioxins during the last century (4). And yet, a soil repository/archive

Manter et al., 2017. Proc Natl Acad Sci 114, 13587-13590.

Thank You!

"Whether you think you can,
or you think you can't
you're right."
–Henry Ford

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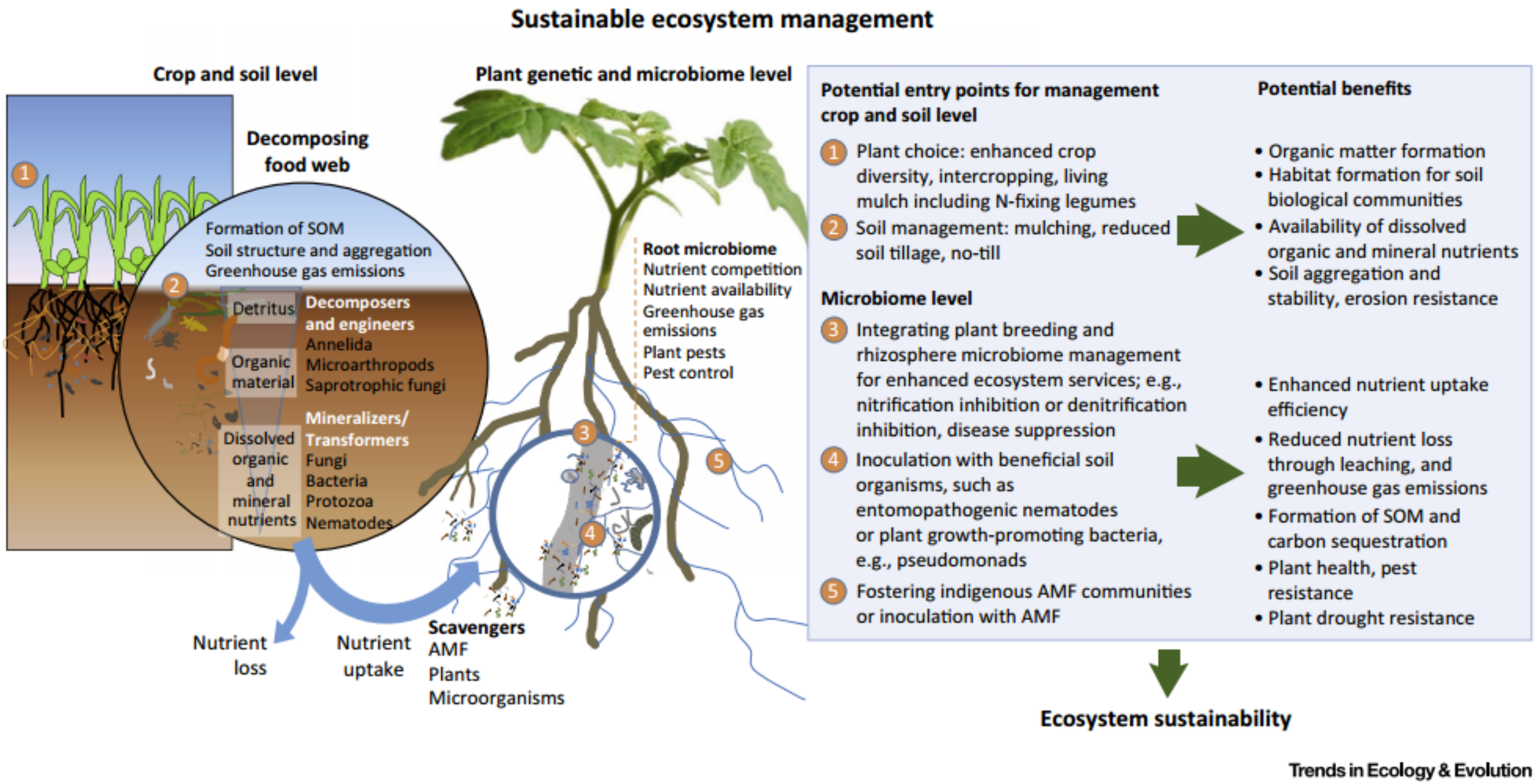
503-320-8286



Bender et al. 2016. An underground revolution: Biodiversity and soil ecological engineering for agricultural sustainability. Trends Ecol Evol.

Siderophore synthesis genes

Index is significantly correlated with direct measurement of siderophore activity

And was correlated with disease suppressivity

Unpublished data courtesy Dr. Dan Manter, USDA-ARS

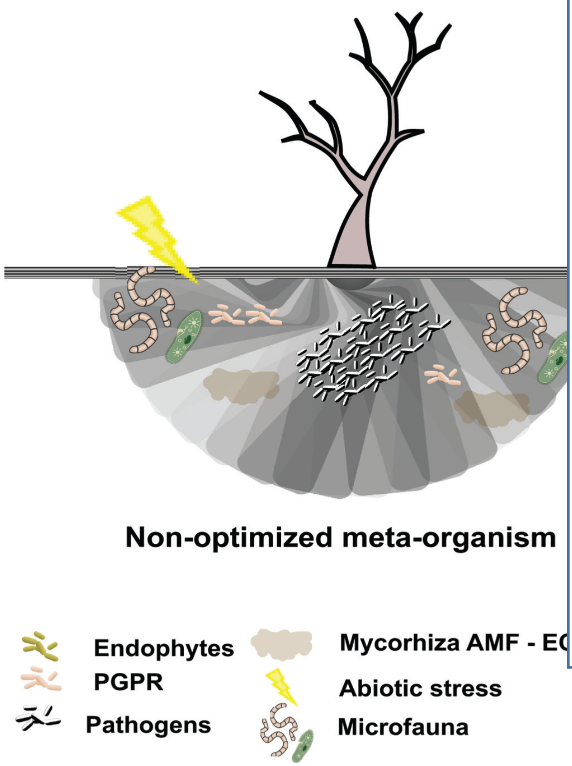
Important Considerations When Developing a SHMS

- Starting point
- History
- Abiotic factors
- Goals
- Thresholds
- Tools used for assessment
- Flexibility and adaptation plan

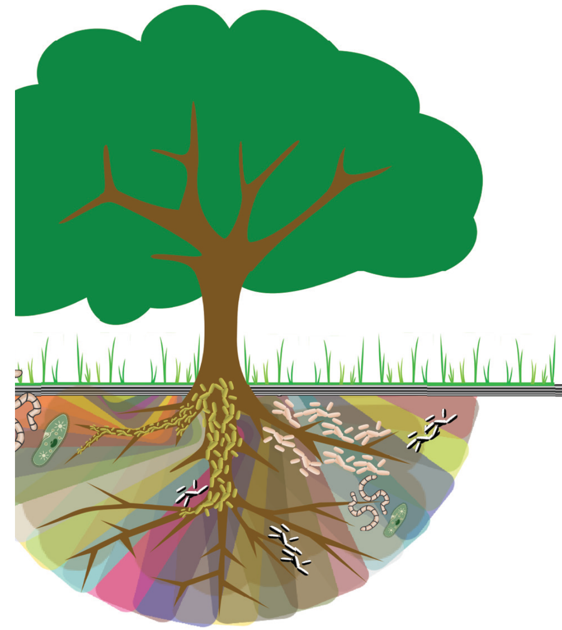
Questions needed?

- Which combinations of crop rotations and cover crop mixes support desired community composition?
  - Can populations be manipulated via management of crop rotations and cover crop mixes to optimize certain functions? "Designer systems"
  - Is more always better? Microbial competition for plant nutrients and timing must be better understood to be controlled
- Irrigation, nutrient, and pest management must be included in management decisions
- Biological hot spots should be maximized
- Plant protection and resiliency are channels of maximum return but receive less focus in research programs

Manipulation Through Management



- No-till/ conservation tillage; IPM
- Crop rotations; livestock incorporation
- Cover crops; relay crops; crop residue retention
- Perennial crops
- Organic fertilizers
- Weed control by mulching, shading, competition

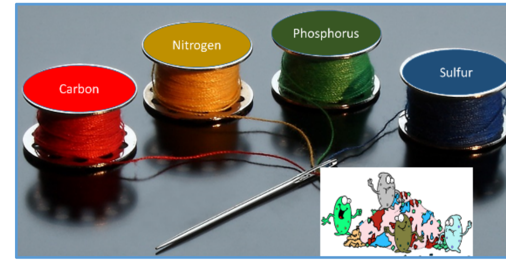


Optimized meta-organism

Enhanced N and P availability and higher levels of nutrients cycling
Improved growth
Enhanced disease supressiveness
Higher resistance to abiotic stress
Niche saturation

Quiza, L., et al. (2015) Frontiers in Plant Science 6, Article 507; Lehman, R. M., et al. (2015). Journal of Soil and Water Conservation 70(1): 12a-18a; Lehman, R. M., et al. (2015) Sustainability 7(1): 988-1027; Bender et al. 2016. Trends Ecol Evol.

Soil Microbes: Eye of 'Nutrient Needle'

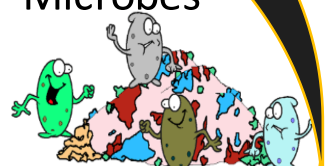


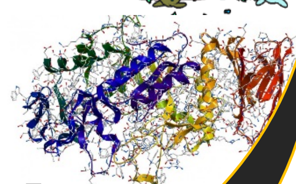
Organic Compounds
Proteins
Amino acids
Nucleic acids

Photo courtesy of USDA-NRCS

Mineralization

Microbes





Enzymes

Plant-available Inorganic Compounds
Ammonium (NH_4^+)
Sulfate (SO_4^{2-})
Phosphate (PO_4^{3-})

Impact

Potential for reduced fertilizer inputs Or increased NUE

Soil microbial biomass accounts for:

- 1-5% of total organic C
- 2-6% of total organic N
- ~3% of total organic P in arable soils
- 5-24% of total organic P in grassland soils

(Paul, 1984, Plant and Soil 76:275-285)

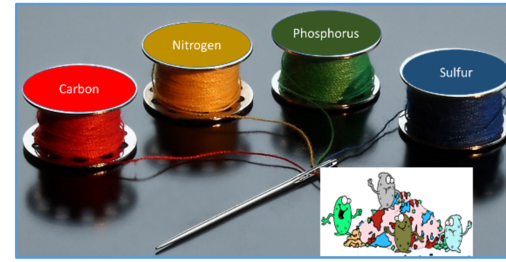
What we know

- Soil organisms release enzymes and convert organic compounds into plant-available forms (after they get what they need)
- Symbiotic relationships between NFB and plant roots help plants acquire N from atmosphere
- Symbiotic relationships between AMF and plant roots help plants gain access to broader nutrient pool and additional enzymes help extract mineral-bound nutrients
- Fungi and bacteria possess biochemical compounds that can mine phosphorus bound to minerals and release in plant available forms
- Plant-microbe communications via biochemical signaling can help plants resist stress such as drought and pathogens
- Soil organisms especially earthworms, fungi, and bacteria help soil particles form stable aggregates important to resist erosion
- Soil organisms can be ‘self-regulating’ in that competition keeps populations in check over the long-term

How do we manage for biology?

- Different varieties of same crop stimulates different microbial populations
- Different cover crops support different communities
- Fertilization can influence root exudation and microbial populations
- Herbicides can shift populations
- Tillage disrupts microbial habitat and populations
- Single species crops can support pathogen populations in higher concentrations than desired

Soil Microbes: Eye of 'Nutrient Needle'



Organic Compounds

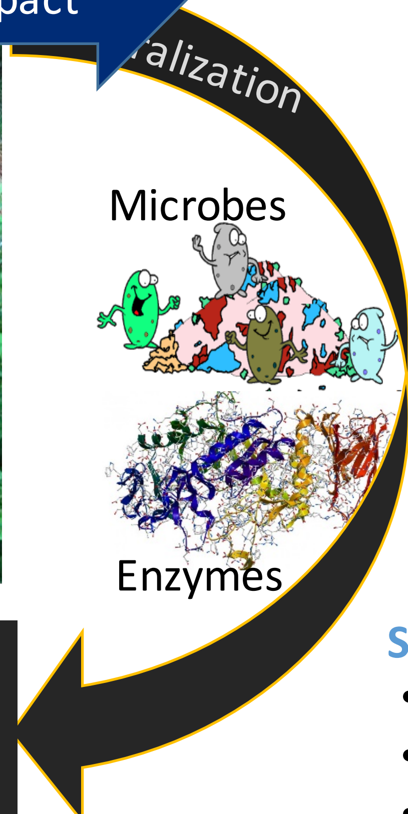
Proteins

Amino acids

Nucleic acids

Photo courtesy of USDA-NRCS

Impact



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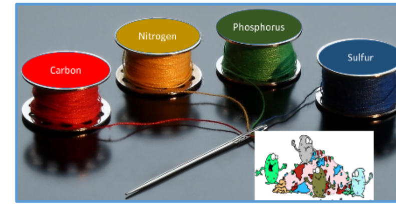
Soil Microbes for Nutrients

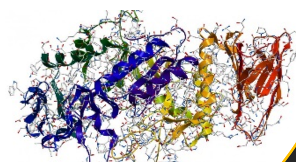


Photosynthesis → releases sugars for bacteria

Fava Bean; Moore-Kucera, 2016

N fixation

Rhizobia



Enzymes

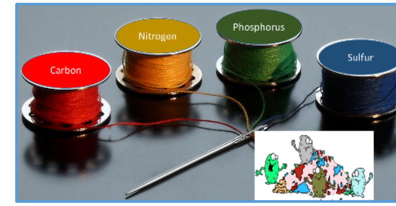
Specialized bacteria convert N from atmosphere → NH_3

Impact

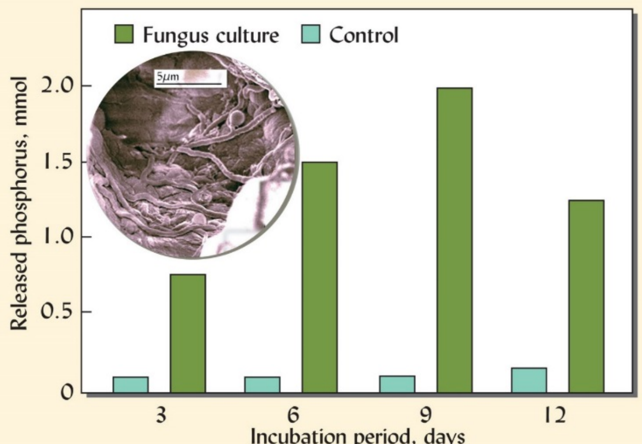
Potential for reduced fertilizer inputs Or increased NUE

Barrios, 2007. Soil biota, ecosystem services and land productivity. Ecological Economics, 2:269-285.

Soil Microbes for Nutrients

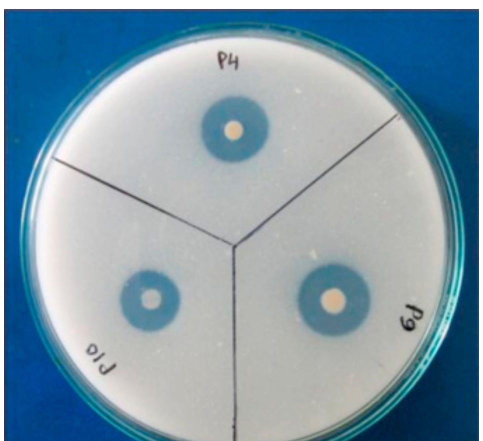


P-solubilizing fungi



The Nature and Properties of Soils, 15e, Weil and Brady

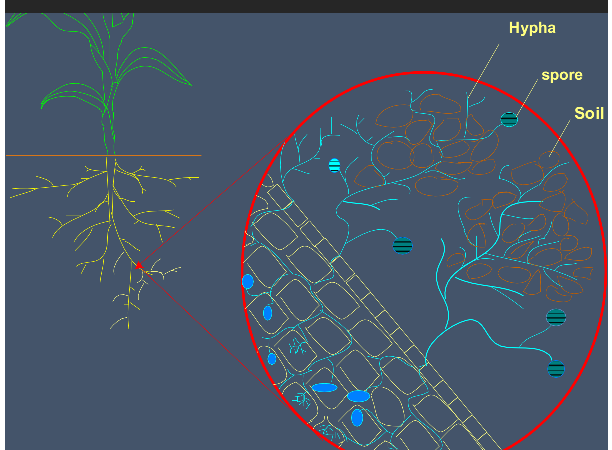
Impact → Potential for reduced fertilizer inputs Or increased NUE



Ghosh et al., 2016. Microbiol. Res. 183: 80-91.

Solubilization of insoluble phosphate by bacteria

AMF Extend Root Surface Area



Increase Nutrient Uptake

- Release specialized enzymes to extract P from minerals
- Release acids to lower pH to make P more soluble
- Increased surface area increases nutrient absorptive area

Soil Biota for Aggregate Formation

Physical Enmeshment (Fungal Hyphae & Plant Roots)

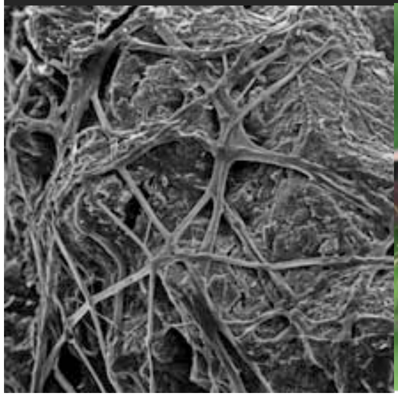
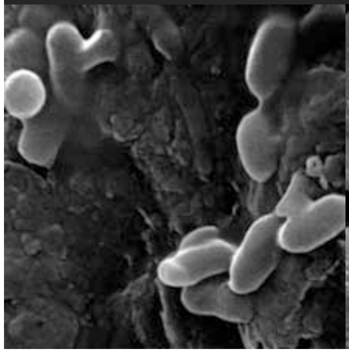
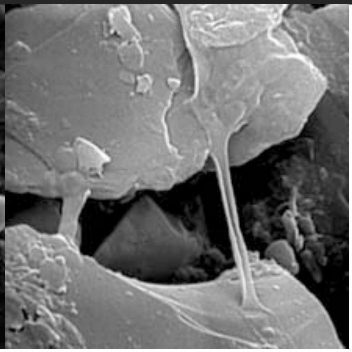
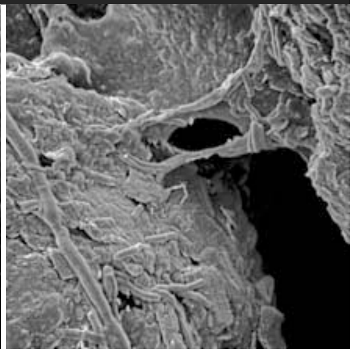


Image source: Aaron Roth, NRCS-OR

Biochemical Glues From Bacteria and Fungi







Impact

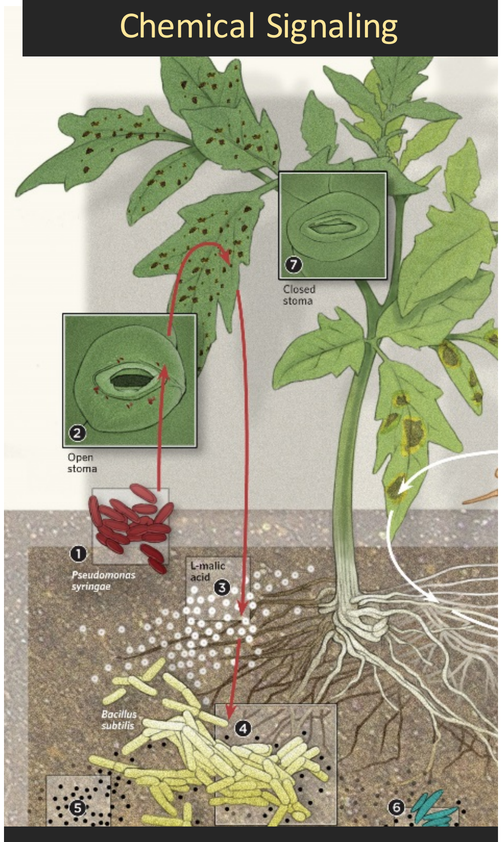
Photo: J Moore Kucera, NRCS-SHD; Soil Health Training, Pullman, WA, 2017

Aggregate Stability
Increased Water and Air Flow
Increased WUE
Reduced Erosion Risk
Increased Microbial Habitat

SEM photos used with permission from eickh@uni-bremen.de (http://www.microped.uni-bremen.de/SEM_index.htm)

Soil Microbes for Plant Protection

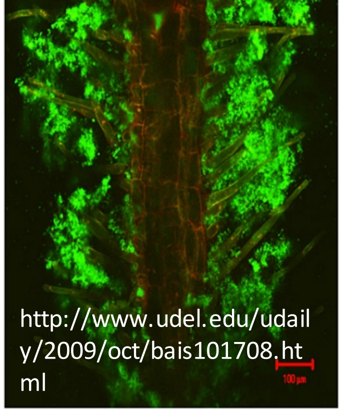
Plant-Microbe Chemical Signaling



Bacteria released abscisic acid (close plants stomata)

http://www.the-scientist.com/?articles.view/articleNo/34209/title/The-Soil-Microbiome/

Biofilm of beneficial bacteria protecting against *P. syringae*



http://www.udel.edu/udaily/2009/oct/bais101708.html

Predation

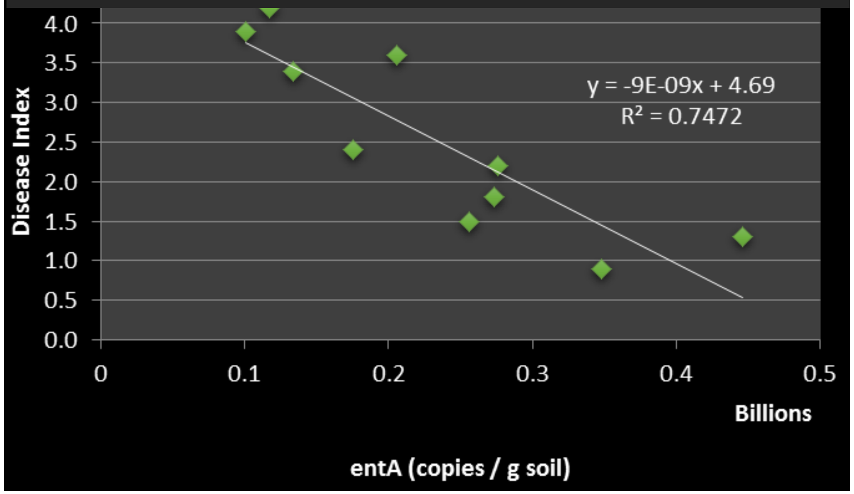
SCN parasitized by a fungus

http://www.extension.umn.edu/agriculture/soybean/soybean-cyst-nematode/chemical-biological-potential.html

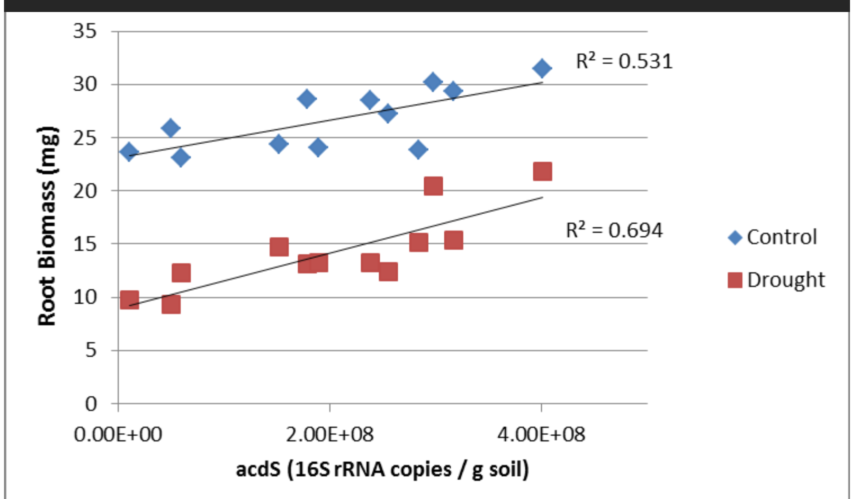
Impact → **Enhanced Plant Growth**
Reduced Pesticides

Soil Microbes for Plant Protection

Gene production for nutrient uptake & disease suppression



Gene production for enhanced root growth under drought



Impact →

Enhanced Plant Growth
Reduced Pesticides
Increased Resiliency

Unpublished data courtesy Dr. Dan Manter, USDA-ARS

Manipulation of Biota Through Organic Amendments

Mustard Seed Meal

Replant soil (M. Mazzola) **'Virgin' soil**

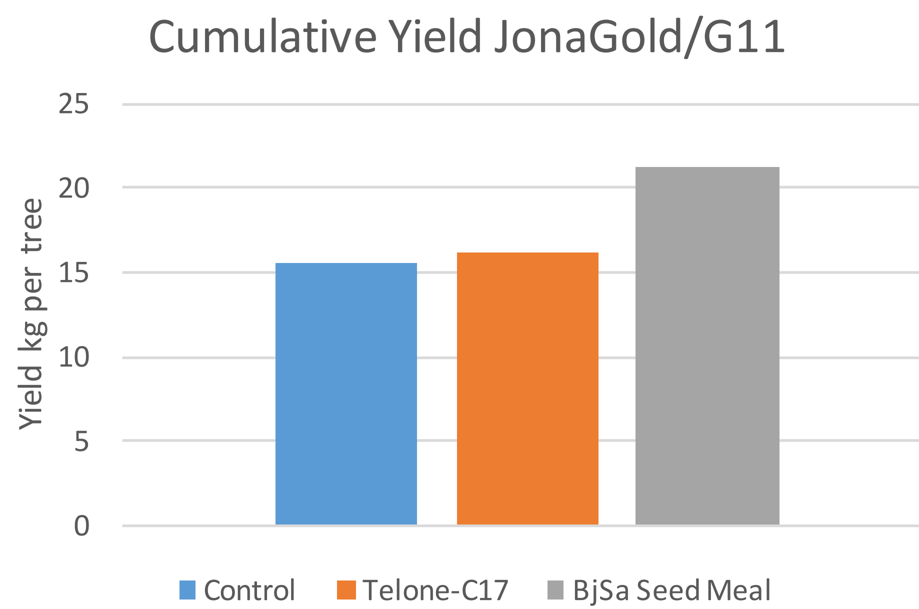
Effect of Apple Replant Disease
Gala/M26, Moxee, WA

Mazzola and Strauss, 2013; Mazzola et al. 2014.

Compared to Control & Fumigation:
Mustard seed meal altered types & numbers of fungal community but not diversity

TABLE 4. Density (number of g^{-1} root) of *Pratylenchus penetrans* recovered from roots of JonaGold/G11 apple as influenced by soil treatment at the SMR commercial organic orchard, Chelan, WA[y]

Soil treatment[z]	2010	2011	2012
Control	164 b	287 a	246 b
Telone-C17	80 ab	881 b	398 c
BjSa-Sp	9 a	163 a	52 a

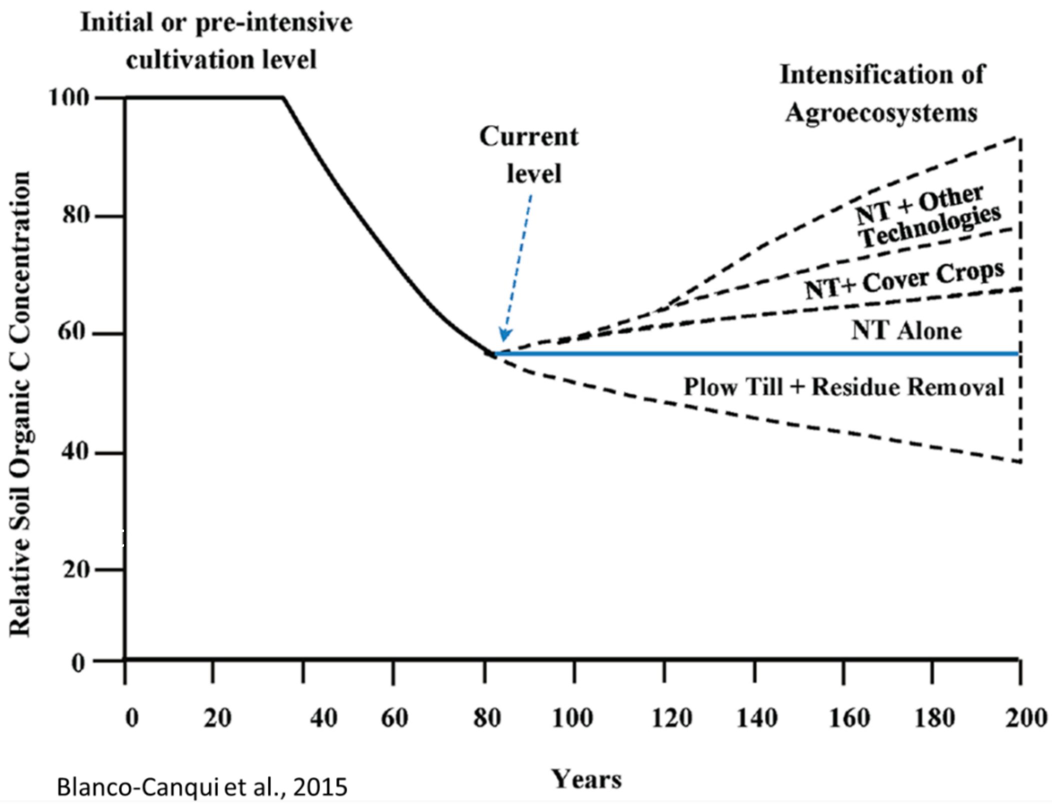


Manipulate Microbes via Biological Amendments

- Great promise and potential
- Success dependent upon delivery system, soil, environmental, plant compatibility, and biological competition factors
- Limited regulation and testing of products once released (e.g., product quality and consistency)

**random products pulled from internet search for biological inoculants to illustrate extensive options; not comprehensive and no endorsement or evaluation implied

Managing for Microbes: System Synergies



Blanco-Canqui et al., 2015

- Reduced Tillage

- Cover Crops

Central Indiana in the summer of 2011

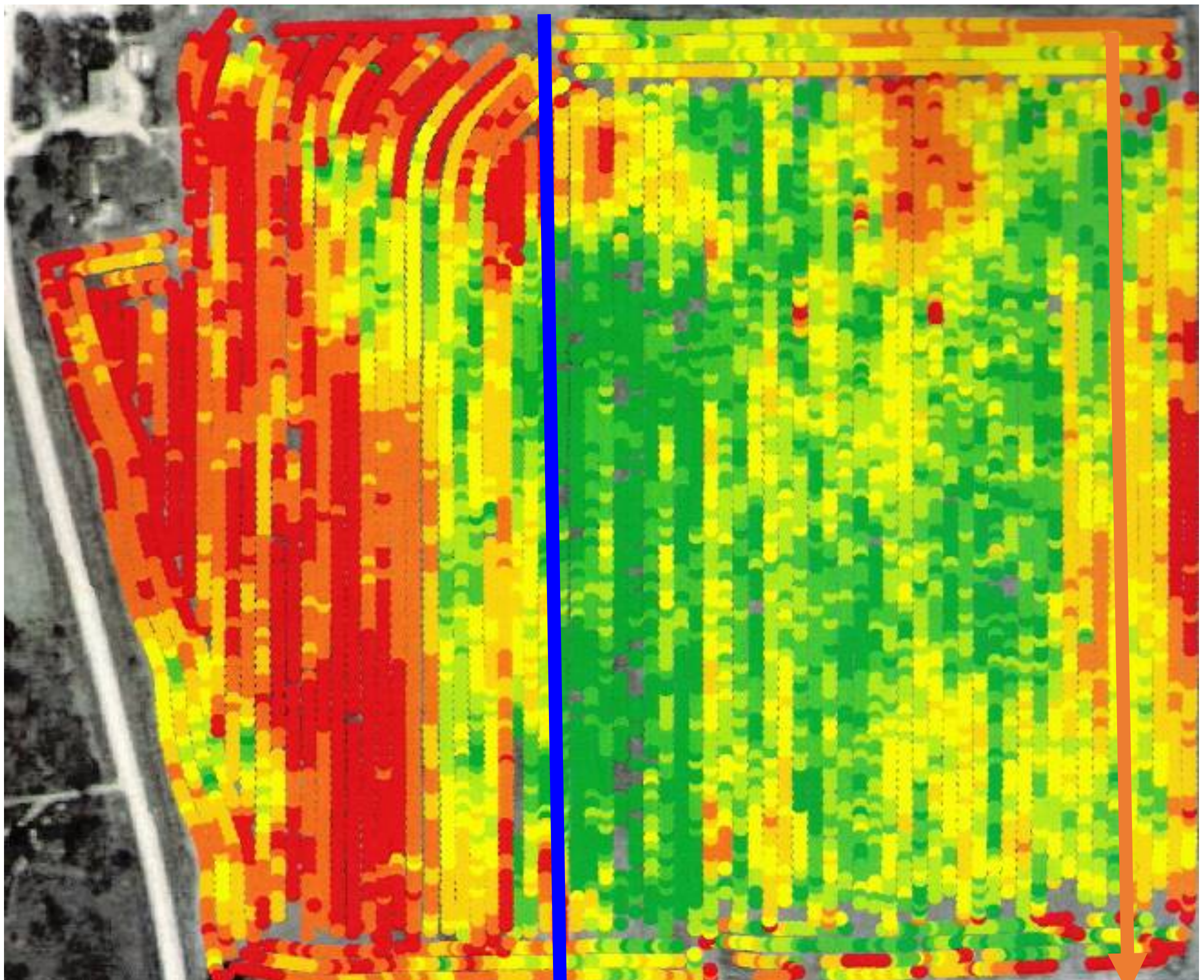
Farm on left uses cover crops and no-till. Farm on the right is in traditional chisel/disk.

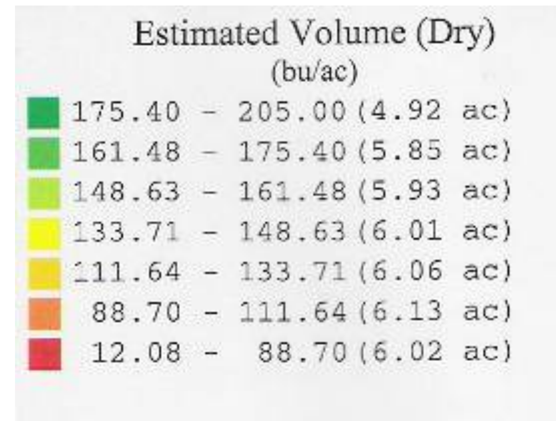
J. Maloney, 2011

Cover Crop Yield Effects (IL example)

No Cover Crop
80+/- bu/ac

6 years CC
160+/- bu/ac





Mike Plummer's long-term no till with ryegrass cover crops on heavy clay soil.

Cover Crop Chart

GROWTH CYCLE
- A = Annual
- B = Biennial
- P = Perennial

RELATIVE WATER USE
- = Low
- = Medium
- = High

PLANT ARCHITECTURE
- = Upright
- = Upright-Spreading
- = Prostrate

Cool Season

Grass

Crop	Growth cycle	Water use	Architecture
Barley	A	Low	Upright
Oat	A	Medium	Upright
Ryegrass	A/P	Medium	Upright
Wheat	A	Medium	Upright
Cereal rye	A	High	Upright
Triticale	A	High	Upright
Annual fescue	A		Upright

Broadleaf

Crop	Growth cycle	Water use	Architecture
Phacelia	A	Low	Upright
Flax	A	Medium	Upright
Spinach	A	Medium	Upright-Spreading
Kale	A	Medium	Upright-Spreading
Canola	A/B	Medium	Upright-Spreading
Mustard	A/P	High	Upright-Spreading
Turnip	B	High	Upright-Spreading
Radish	A	High	Upright-Spreading
Beet	B	High	Upright-Spreading
Carrot	A/B	High	Upright-Spreading

Legumes

Crop	Growth cycle	Water use	Architecture
Field pea	A	Low	Upright
Lentil	A	Low	Upright-Spreading
Lupin	A	Low	Upright
Vetch	A/B	Medium	Prostrate
Berseem clover	A	Low	Upright
Red clover	B/P	Low	Upright
White clover	P	Low	Upright
Sweetclover	A/B	Medium	Upright
Medic	A/P	Low	Upright-Spreading
Birdsfoot trefoil	P	Medium	Prostrate
Sainfoin	P	High	Upright
Alfalfa	P	High	Upright
Chickpea	A	Low	Upright-Spreading
Cowpea	A	Low	Upright-Spreading
Soybean	A	Medium	Upright-Spreading
Mung bean	A	Medium	Upright-Spreading

Warm Season

Broadleaf

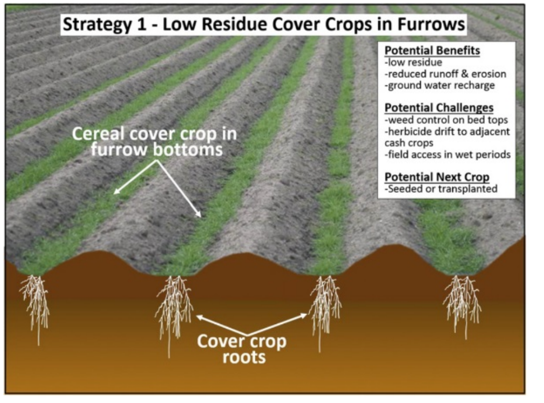
Crop	Growth cycle	Water use	Architecture
Amaranth	A	Low	Upright
Buckwheat	A	Medium	Upright
Sunflower	A	High	Upright
Safflower	A	High	Upright
Squash	A	Medium	Prostrate
Chicory	P	Medium	Upright-Spreading

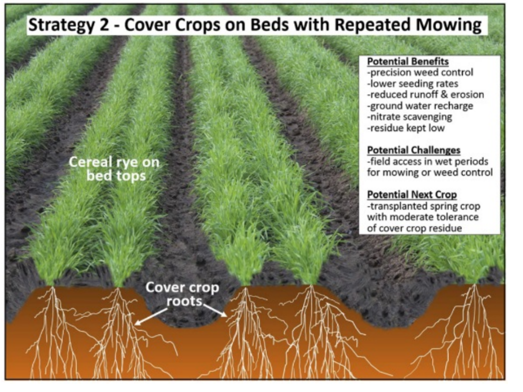
Grass

Crop	Growth cycle	Water use	Architecture
Pearl millet	A	Low	Upright
Foxtail millet	A	Low	Upright
Proso millet	A	Medium	Upright
Sudan grass	A	Medium	Upright
Teff	A	Medium	Upright
Grain sorghum	A	Medium	Upright
Corn	A	High	Upright

Manage for Soil Biology with Cover Crops for Improved Yield

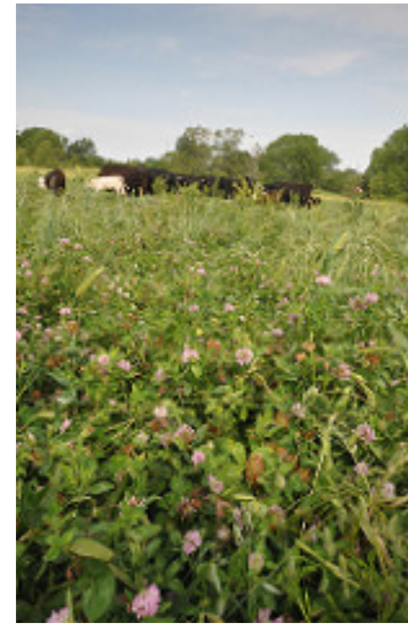
- **Frequent cover cropping** improved soil food web more than compost
- Vegetable yields were greater in frequently cover cropped systems compared to those infrequently cover cropped regardless of compost inputs



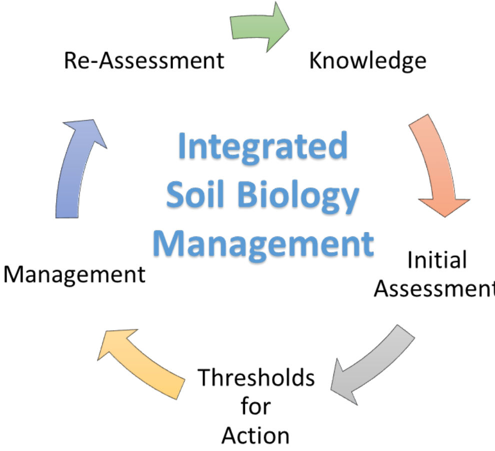


Brennan & Acosta-Martinez. 2017. Soil Biol Biochem 109:188-204; Brennan, E.B. 2017. HortTechnology 27:151-161

Manage For Biology

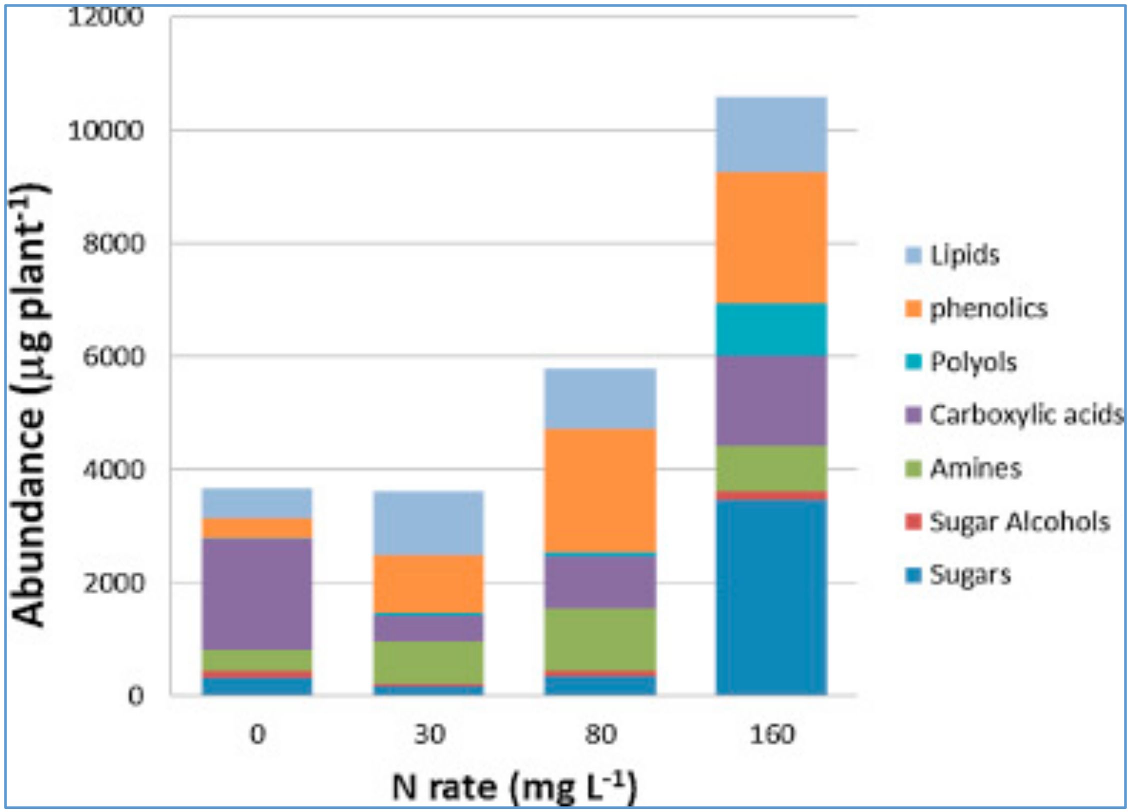


Summary



- Soil health functions are driven by soil microbe-plant actions and interactions
- Develop SHMS that aim to maximize synergistic impacts to address problem and site-specific issues
- Keep expectations in check
- Managing for soil microbes for specific functions is possible but much more research is needed
  - Manage through amendments
  - Manage through practices

Manipulate Microbes Through Fertilization?



- N rate changed amount & composition of root exudates
- Increased microbial biomass and competition
- NUE decreased
- Fertilizer lost to microbes

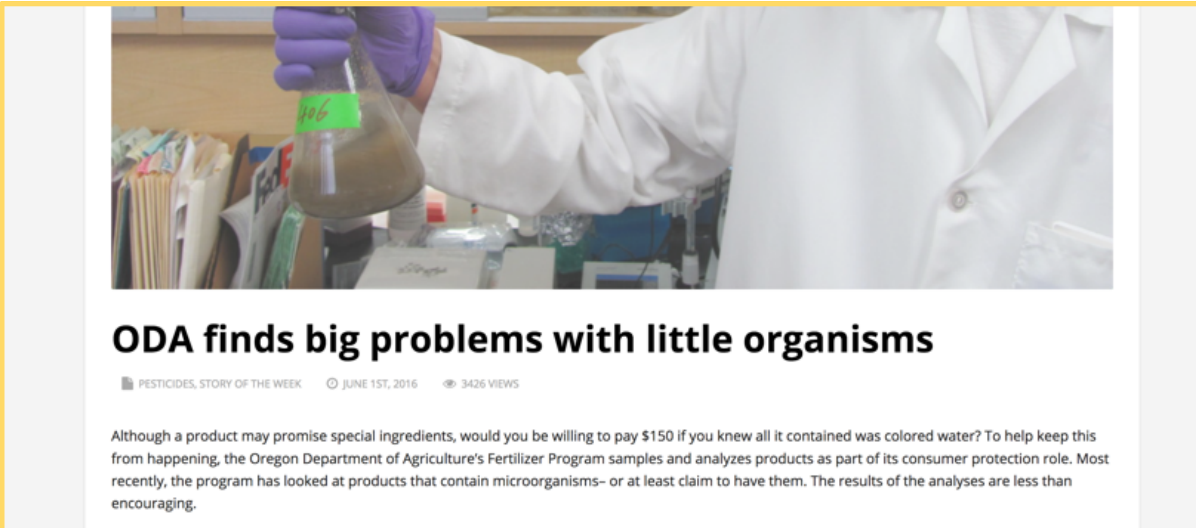
Zhu et al. 2016. Appl. Soil Ecol 107:324-333

Managing for Biology

- Most ag soils are carbon depleted
- Disturbances destroys habitat and hyphal networks
- Bare, fallow fields provide little protection, no C
- Many fertilizer concentrations too high for symbiosis
- Agrichemicals have mixed effects

- ➢ Manage for hot spots
- ➢ Support biology to build aggregates and create pore space
- ➢ Protect the habitat
- ➢ Feed the soil so it can feed us
- ➢ Optimize biological nutrient cycling
- ➢ Optimize plant-microbe interactions for plant defense optimization

Manipulate Microbial Population (Targeted Group) Through Biological Amendments?

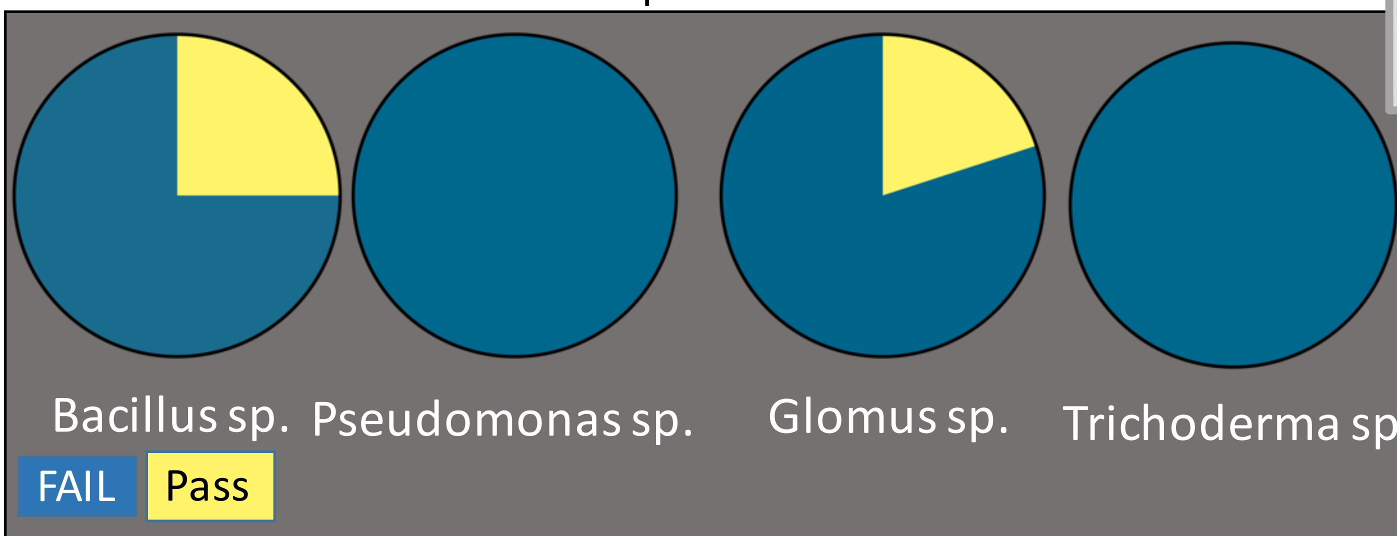


ODA finds big problems with little organisms

PESTICIDES, STORY OF THE WEEK · JUNE 1ST, 2016 · 3426 VIEWS

Although a product may promise special ingredients, would you be willing to pay $150 if you knew all it contained was colored water? To help keep this from happening, the Oregon Department of Agriculture's Fertilizer Program samples and analyzes products as part of its consumer protection role. Most recently, the program has looked at products that contain microorganisms– or at least claim to have them. The results of the analyses are less than encouraging.

Does the content meet specifications on the label?

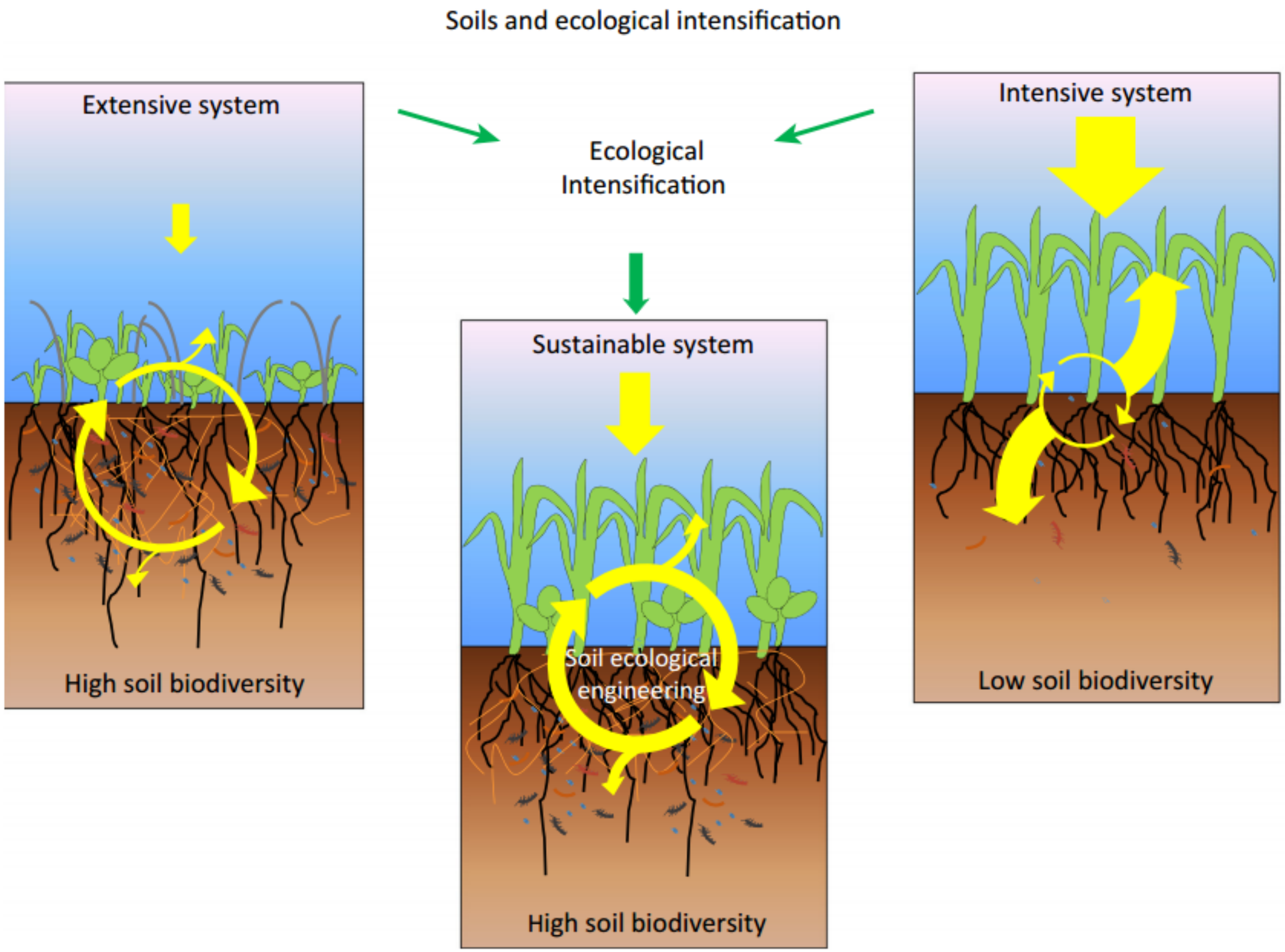


Slide Courtesy Dr. Trippe, USDA-ARS Corvallis

Manage for Biology: Manage Soil Temperature

- Impact of High Temps:
  - High temps = higher water loss
  - Loss of functional soil organisms (think solarization)
  - Increases rates of oxidation
- Lower temperature under residue

Importance of Soil Biology: Plant Productivity, Ecosystem Resiliency and Self Sufficiency



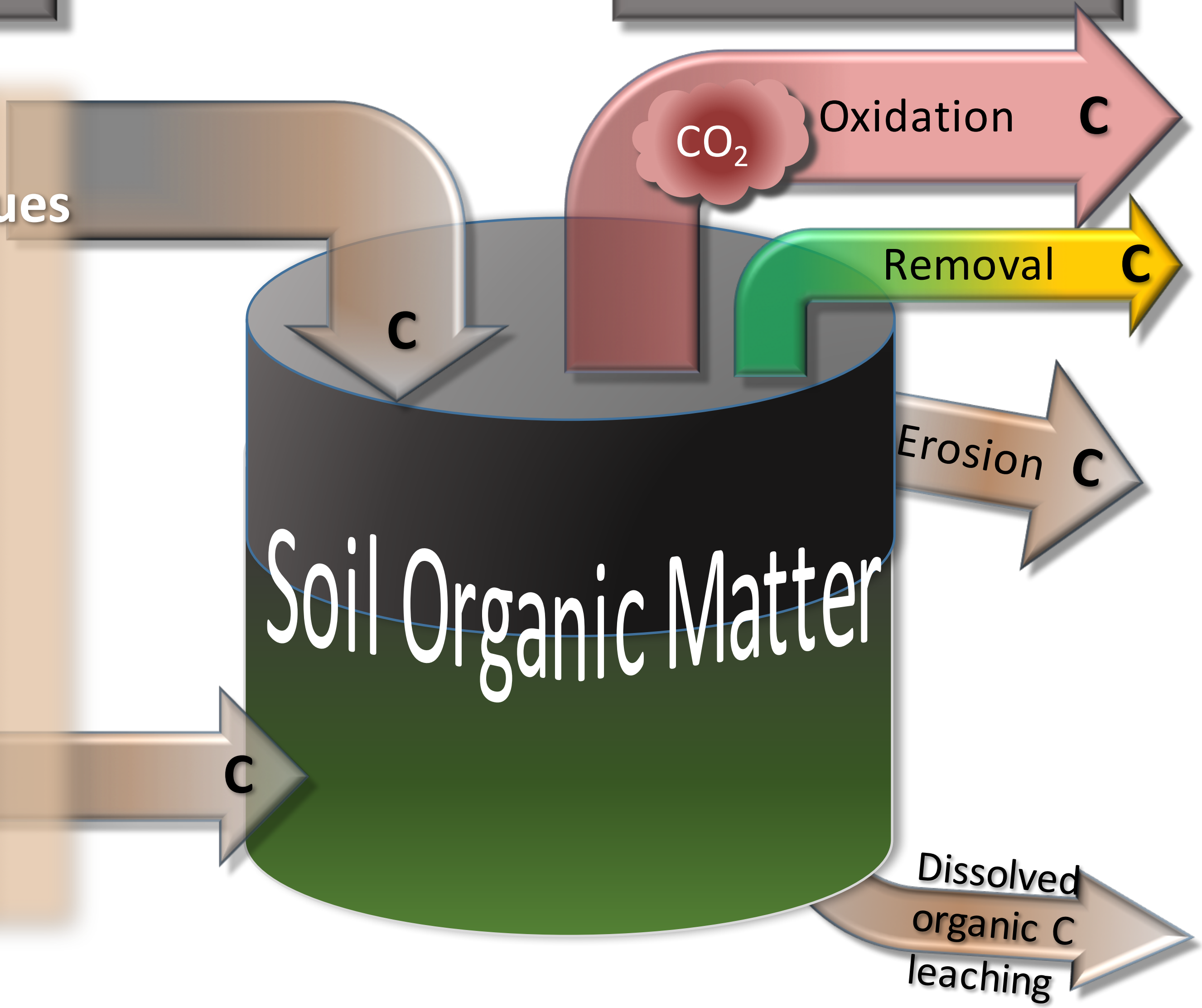
Bender et al. 2016. An underground revolution: Biodiversity and soil ecological engineering for agricultural sustainability. Trends Ecol Evol.

Managing for Biology: Manage for C

Carbon In

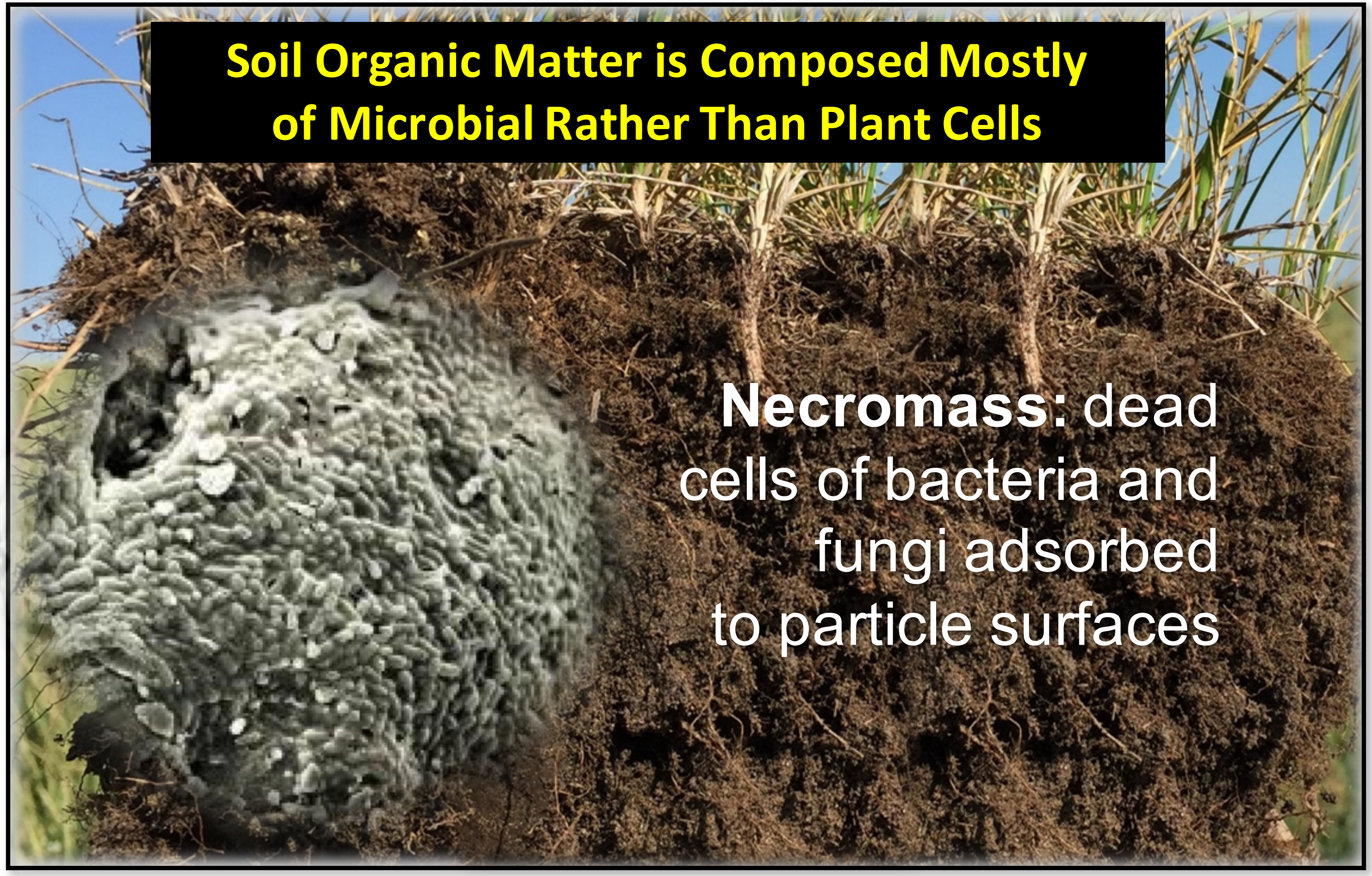
- Plant litter /residues
- Animal wastes
- Imported bio-products
- Rhizodeposition
- Root residues

Carbon Out



The Nature and Properties of Soils, 15e, Weil and Brady

Soil Microbes for SOM Formation and Stabilization



Benefits of Soil Organic Matter

Food & habitat for soil organisms

Increased microbial activity, decomposition, mineralization

Increased microbial biomass, competition & antagonism against plant pests

Increased infiltration and water-holding capacity

Protect surface from solar energy and raindrops

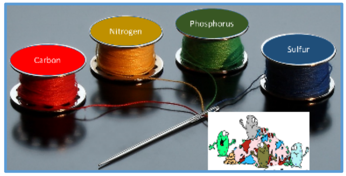
Increased CEC & adsorption of organic compounds

Buffers temperature extremes

Increased supply of micro- and macro-nutrients

Increased aggregate stability, macroporosity

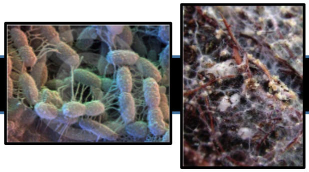
Microbes, Predators & N Mineralization



For every 1000 lb of residues.....

450 lb C
23 lb N
C:N = 20:1

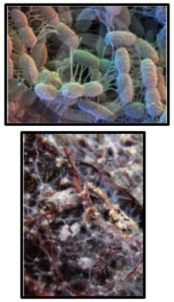
292 lb C lost as CO_2 (65%)



158 lb (35%) C and 20 lb N (87%) incorporated into microbial biomass

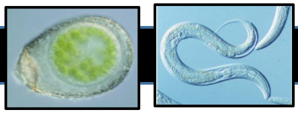
23-20 lb = 3 lb N NH_4^+ (13%) mineralized (released) to soil from decomposition

Microbes now become prey



158 lb C
20 lb N
C:N = 8:1

95 lb C lost as CO_2 (60%)



63 lb (40%) C and 6.3 lb N (32%) incorporated into faunal biomass

13.7 lb NH_4^+ released to soil from predation

73% of the original N was released (16.7 lb NH_4^+) to soil (mineralized)