Soil Biology and Nutrient Cycling on Yolo County Organic Farms

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Outline of my talk today:

- Basic aspects of soil biology and nutrient cycling
- How arbuscular mycorrhizae increase plant nutrient uptake and water use of organic roma tomatoes
- How soil carbon and microbial biomass improve plant-soil nitrogen cycling and plant nutrition in organic tomato production

Soil biology and nutrient cycling

- Increase the understanding of soil organisms: their functions, interactions and distributions
  - Soil communities and food webs
  - Interactions between soil organisms and roots

Greater plant yield (more litter)
Higher moisture & nutrient uptake
Improved rooting

More food for soil biota
Improved habitat for soil biota

Van Eekeren et al. 2007

Improved soil structure, nutrient cycling and water regulation

Soil biota

Photos from:

Global Soil Biodiversity Atlas

http://esdac.jrc.ec.europa.eu/content/global-soil-biodiversity-atlas

Orgiazzi et al. 2016

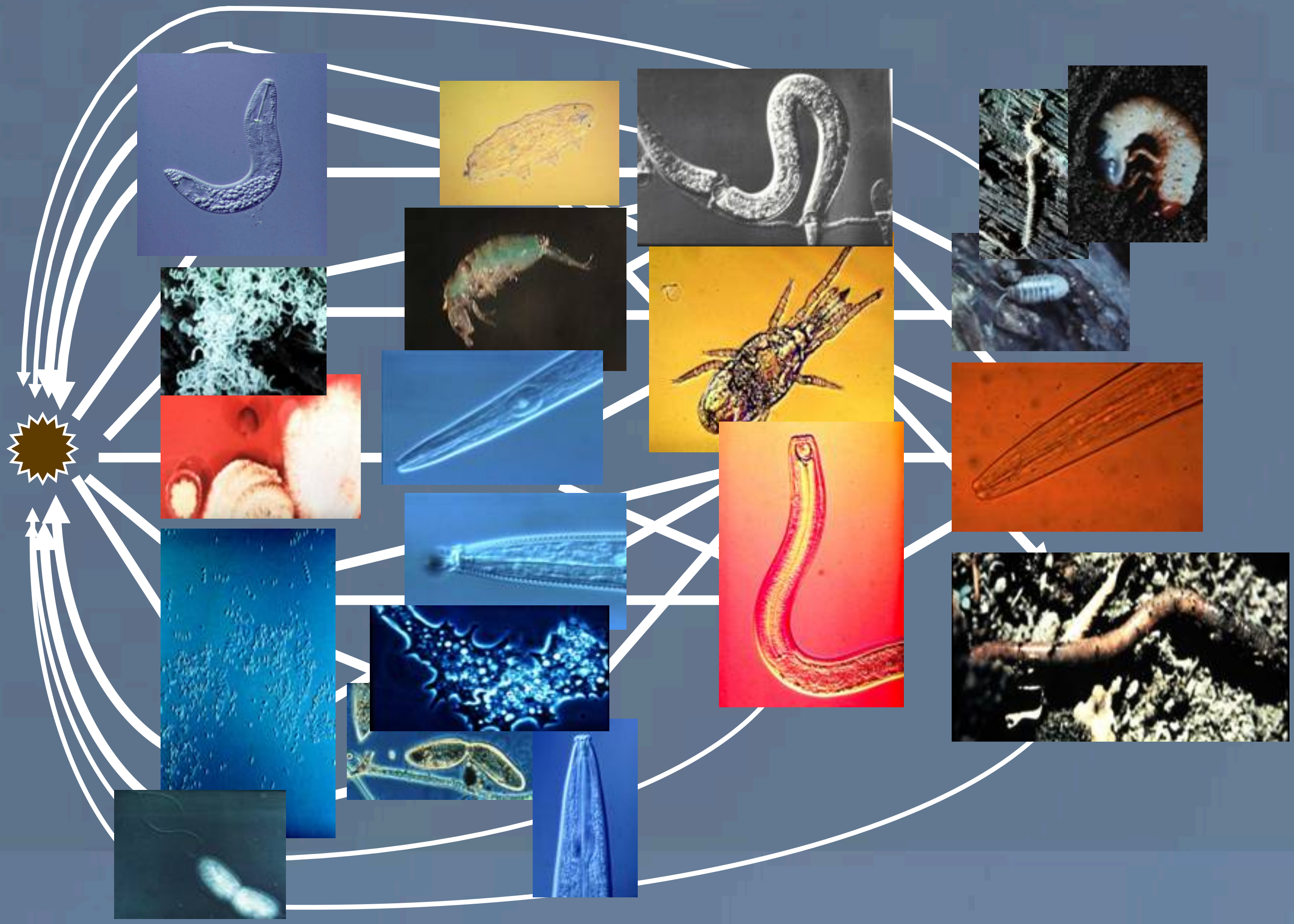
Past 10 years: much new evidence for close relationships among soil biota and plants

- Decomposer communities made better use of litter nutrients in their home than away (Schweitzer et al. 2012)
- Home soils doubled *Populus* survival and seedling survival was related to soil microbial biomass (Pregitzer et al. 2010)
- Defense compounds in foliage were affected by previous herbivory due to soil legacy effects (Kostenko et al. 2012)
- A complex rotation (mustard/sudangrass/rye) suppressed potato diseases, changed the soil microbial community, and increased yield (Larkin et al. 2016)
- Leaf infection (*Botrytis*) of tomato decreased when roots were inoculated with antifungal bacteria (Martinez-Hidalgo et al. 2015)

- Yet uncertainty…. if certain biota re-colonize slowly after organic transition there will be a lag in increasing desirable soil functions (Hedlund and Harris 2012)

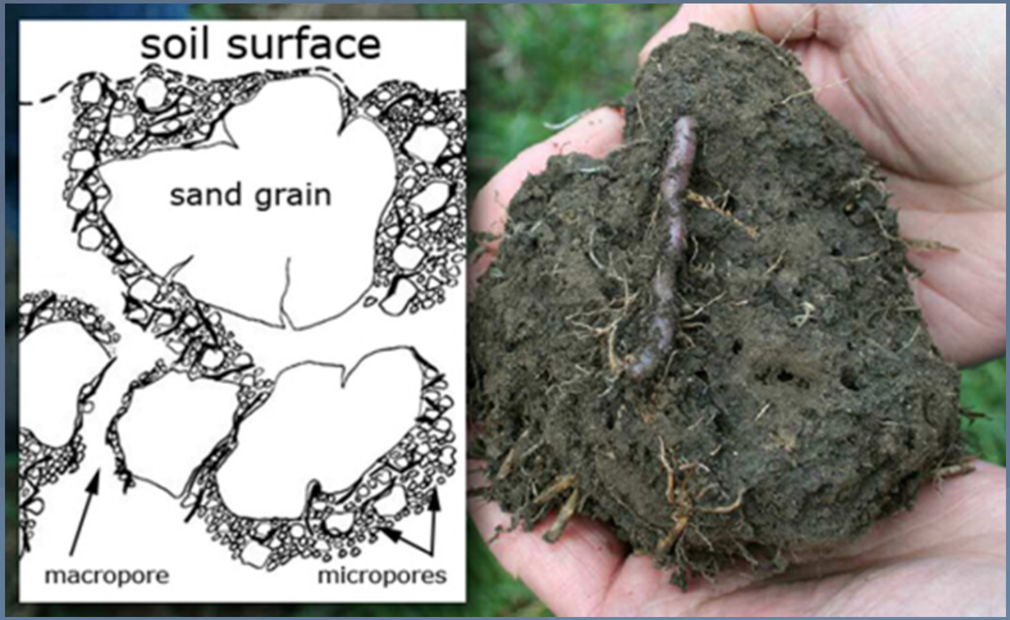
Soil food web and biodiversity

Soil organisms: their functions, interactions and distributions are typically associated with resource availability



Soil carbon

- Soil carbon is ≈50% of total soil organic matter (SOM)
- Improves soil structure by aggregating particles
  - More aeration and infiltration; less erosion
- Increases plant-available water (water holding capacity)
- Supplies food to soil microbes (<5% of total SOM)
- Promotes nutrient cycling



Soil management: National Organic Program

- The National Organic Program Rule, §205.203, Soil Fertility and Crop Nutrient Management Practice Standard

  Does not define specific land practices that producers must use, but identifies general soil management and environmental protection objectives
- Section 205.203(a)

  Select and implement tillage and cultivation practices that maintain or improve the physical, chemical, and biological condition of soil and minimize soil erosion
- Section 205.203(b)

  Manage crop nutrients and soil fertility through rotations, cover crops, and the application of plant and animal materials
- Section 205.203(c) and (d)

  Manage plant and animal materials to maintain or improve soil organic matter content in a manner that does not contribute to contamination of crops, soil, or water by plant nutrients, pathogenic organisms, heavy metals, or residues of prohibited substances

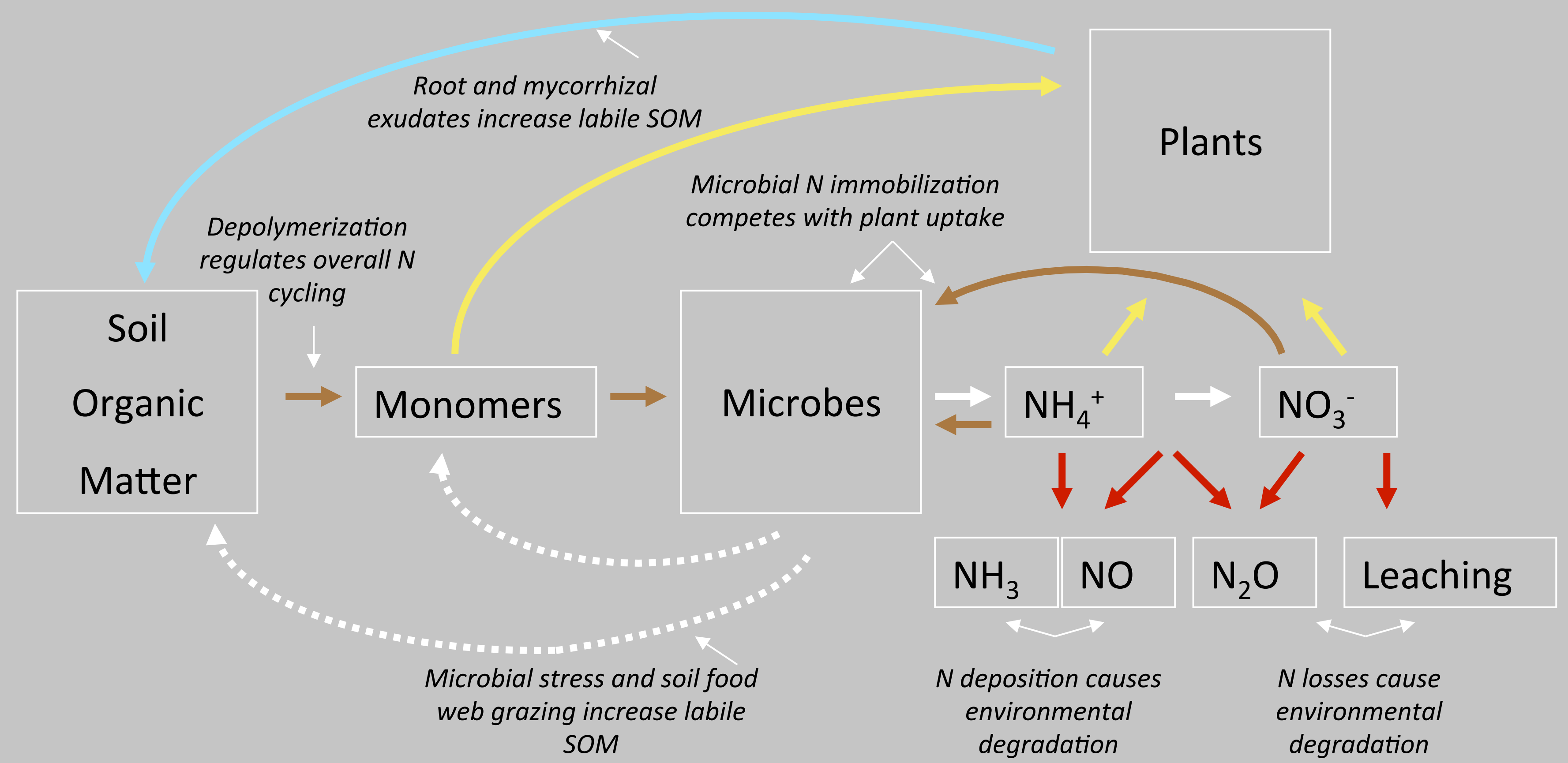

ATTRA

Soil Management:
National Organic Program Regulations

Section 205.203(a)

https://attra.ncat.org/attra-pub/summaries/summary.php?pub=180

Plant-soil-microbe nitrogen cycling



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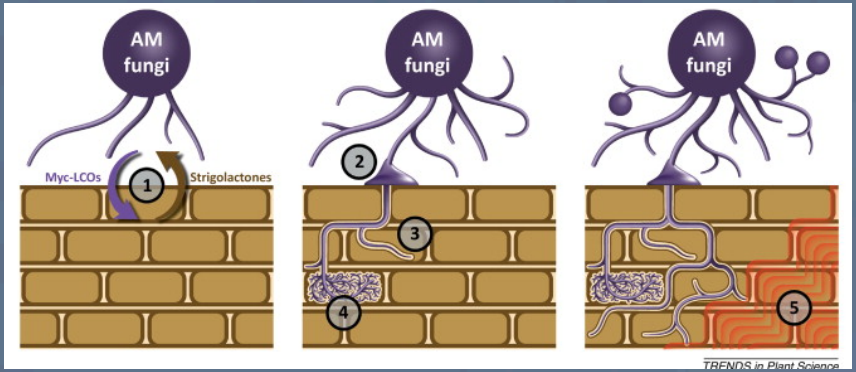
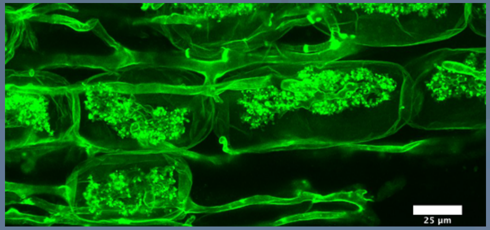
Tomato genotypes differing in the arbuscular mycorrhizal (AM) symbiosis

Arbuscular mycorrhizae: fungal-root symbiosis

- Plants regulate AM colonization
- Roots supply C to fungus; fungus supplies P and N to root
- Hyphae scavenge nutrients from a larger soil volume than roots alone

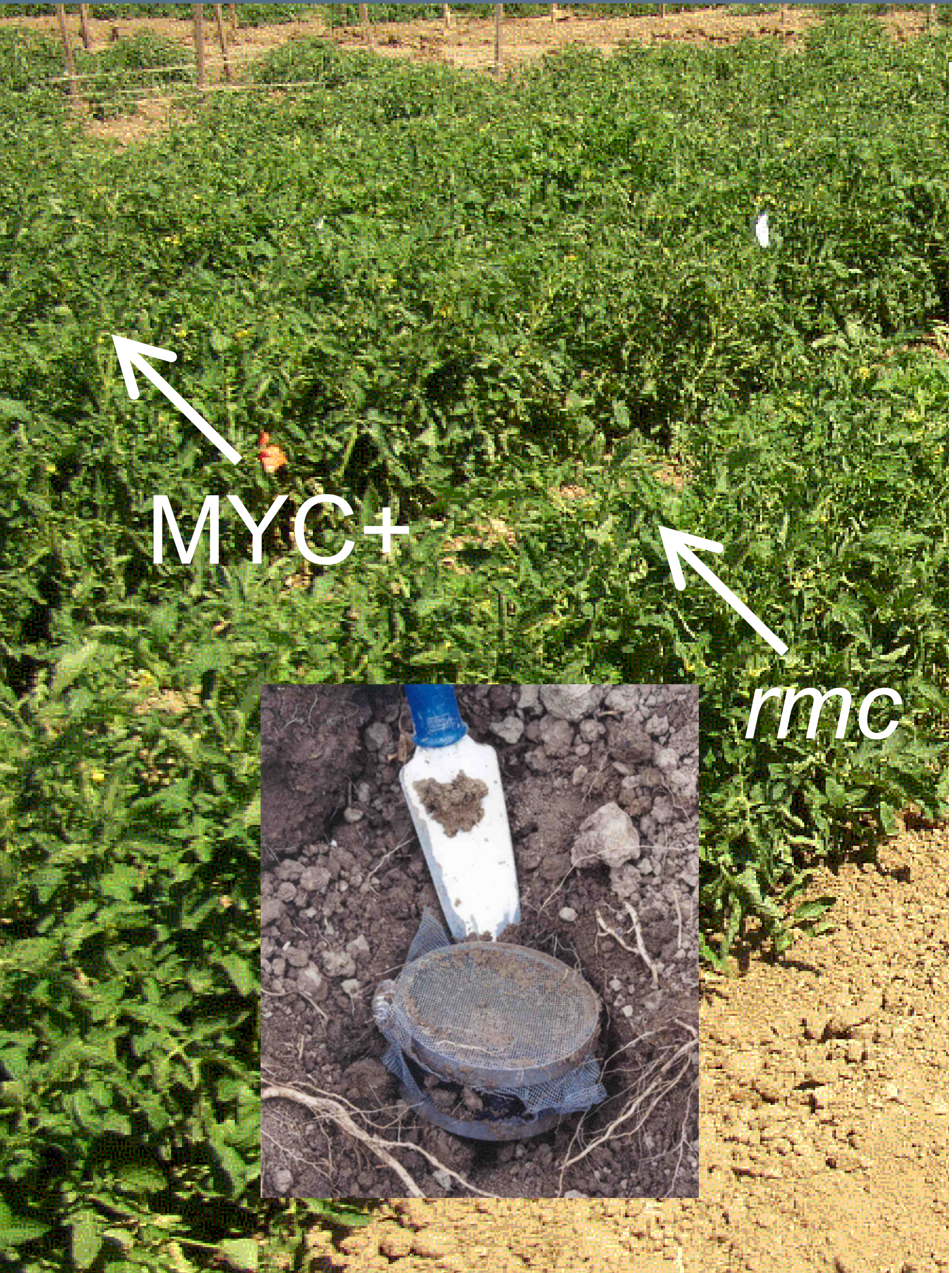




Tomato wild-type (MYC+) and mutant genotypes (*rmc*)

- MYC+ (AM mycorrhizae)
- *rmc* (AM mycorrhizae greatly reduced)
- Field and greenhouse studies (organic farm soil, no fungicides)
- Measured yields, AM colonization, plant nutrient uptake, root gene expression, plant photosynthesis, water use, and greenhouse gas emissions

Plant biomass



Shoot Biomass:
Vegetative biomass of the two genotypes was matched

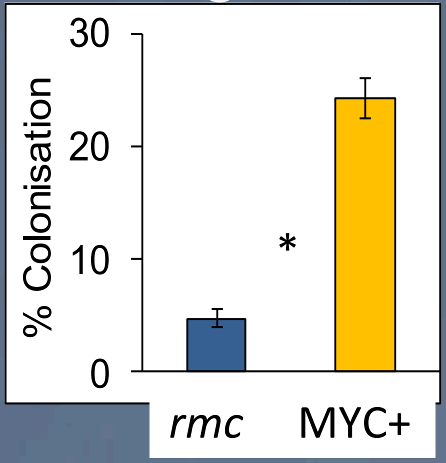
Fruit Yield:
Fruit biomass of the two genotypes was matched and was unaffected by both soil N and P microcosm addition treatments:

Fresh fruit weight (*rmc*):
565 ± 77 g/plant (mean ± SE)
Fresh fruit weight (MYC+):
571 ± 60 g/plant (mean ± SE)

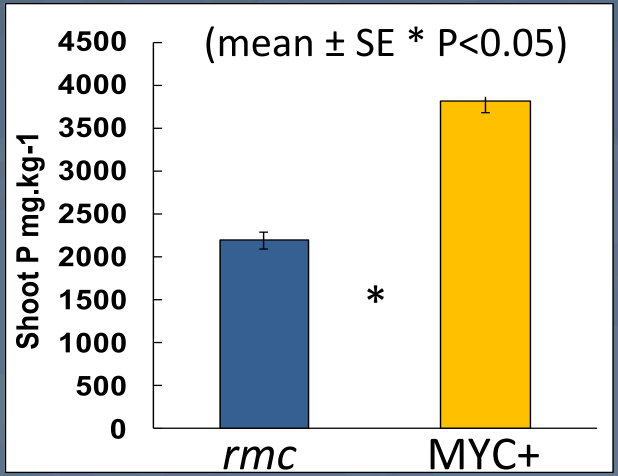
Cavagnaro et al. 2006

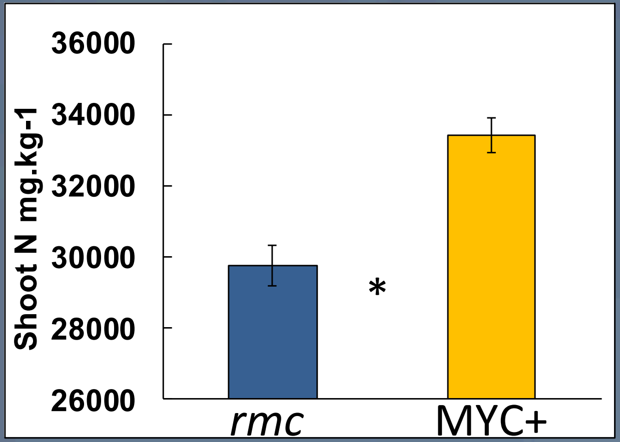
Tomato nutrient content

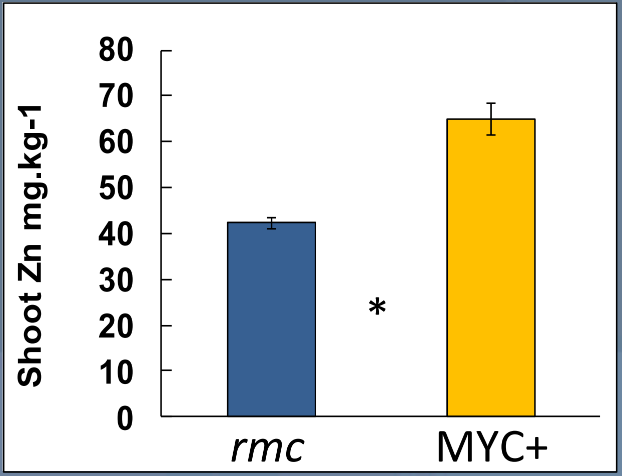
- Fungal colonization was much higher in MYC+ than *rmc* roots



- Shoot concentrations of N, P, Zn, S and Na were significantly higher in MYC+ than *rmc* plants
- Conversely, shoot Mg and Mn concentrations were significantly lower in the mycorrhizal plants
- Fruit followed similar nutritional trends as shoots
- Thus, tomato nutrition was strongly improved by the mycorrhizal symbiosis without an increase in yield





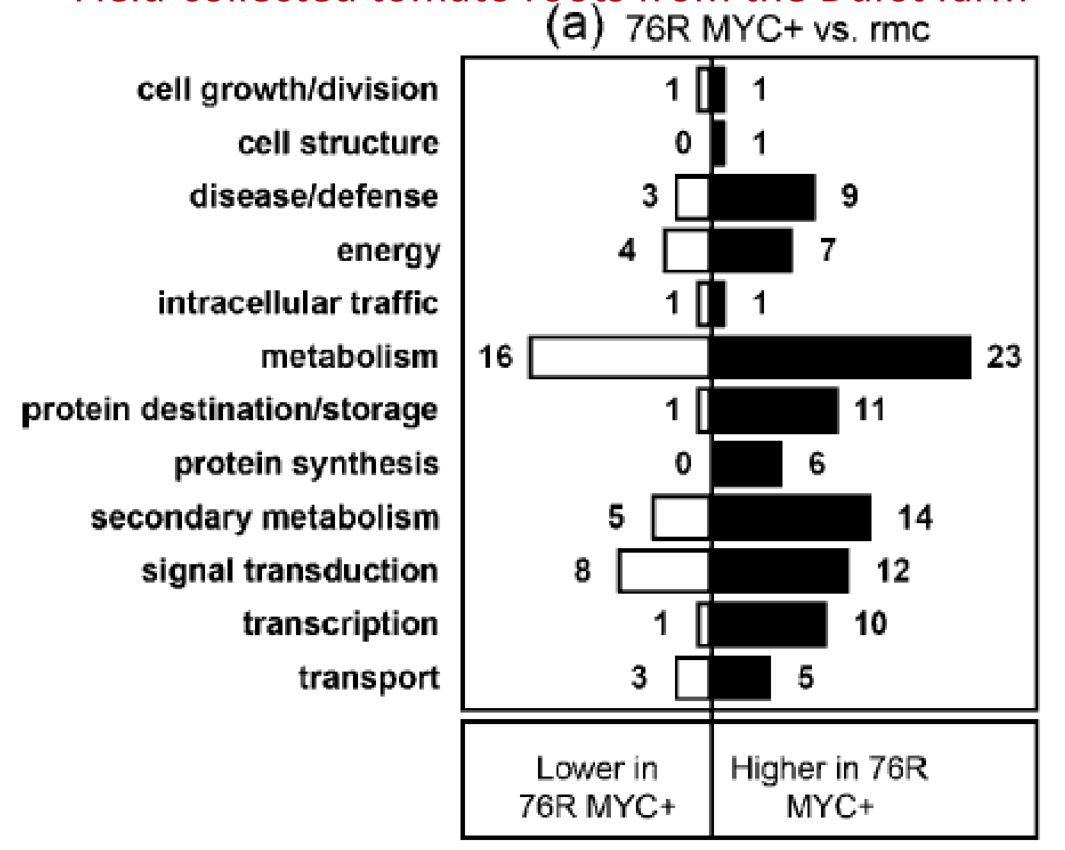


Cavagnaro et al. 2006

Gene expression in mycorrhizal roots

- Using Tomato Genome Array Chip (Affymetrix), expression of 174 of 9022 genes differed between MYC+ and *rmc* genotypes
- MYC+ roots up-regulated more genes than *rmc*
  - Expression of N, P, Cu and S genes for transport and metabolism higher in MYC+
- Root gene expression showed quick responses to addition of N fertilizer

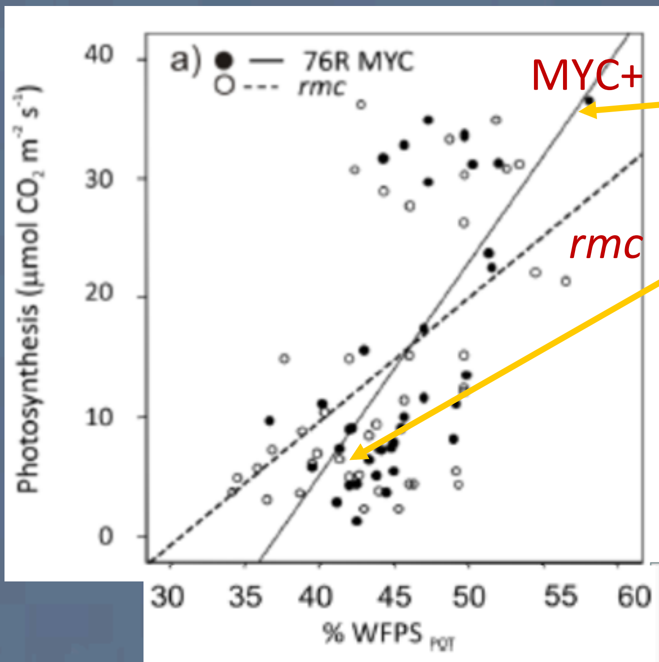
Field-collected tomato roots from the Durst farm



- Deep sequencing metatranscriptomics (454) of the same root samples showed mycorrhizal-specific gene sequences for N and P transport and metabolism, and for aquaporins

Ruzicka et al. 2010, 2012, 2013

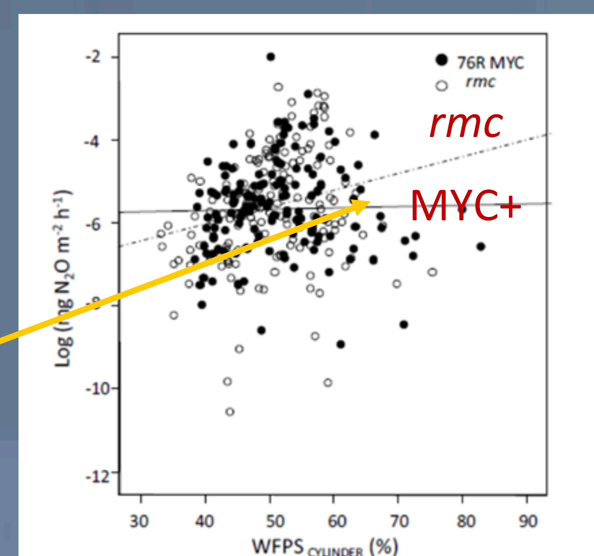
Water: Tomato genotypes in a pot study



- High soil moisture: Higher photosynthetic rate in mycorrhizal genotype (MYC+ > *rmc*)
- Low soil moisture: Lower photosynthetic rate in mycorrhizal genotype (MYC+ < *rmc*)
- MYC+ improves water use efficiency (WUE) (except when soil moisture is very high)

Lazcano et al. 2014

The soils in pots with MYC+ plants emitted less nitrous oxide (N_2O), a potent greenhouse gas produced by soil microbes in wet conditions



WFPS: Water-filled pore space

Water: Tomato genotypes in a field study

At 12.8 and 7.4 acre-inches of irrigation:

- Total marketable yield (TMY) was 25% higher in mycorrhizal plants (MYC+ > *rmc*)
- Water use efficiency (WUE) was 30% higher in mycorrhizal plants (MYC+ > *rmc*)
- Lower culls in occurred in mycorrhizal plants (MYC+ < *rmc*)

UCD Farm Roma Yield and Water Use Efficiency							UCD Farm Culls			
		Water	Total yield	TMY	Total yield AWUE	TMY AWUE	Percentage of Total Yield			
Treatment	Variety	acre-in	lbs per acre	lbs per acre	lbs per in water	lbs per in water	Green	End rot	Rotten	Total Cull
Control	MYC+	12.8	75284	69829	5882	5455	26.9	2.5	0.6	29.9
Control	rmc	12.8	56721	52611	4431	4110	36.9	3.0	1.1	41.1
Deficit	MYC+	7.4	69239	60996	9357	8243	21.7	3.2	0.6	25.6
Deficit	rmc	7.4	54635	48131	7383	6504	28.3	2.6	0.7	31.6

Bowles et al. 2016

Outline of my talk today:

- Basic aspects of soil biology and nutrient cycling
- Arbuscular mycorrhizae in organic roma tomatoes increase 1) nutrient uptake; and 2) yield under water deficit
- How soil carbon and microbial biomass improve plant-soil nitrogen cycling and plant nutrition in organic tomato production

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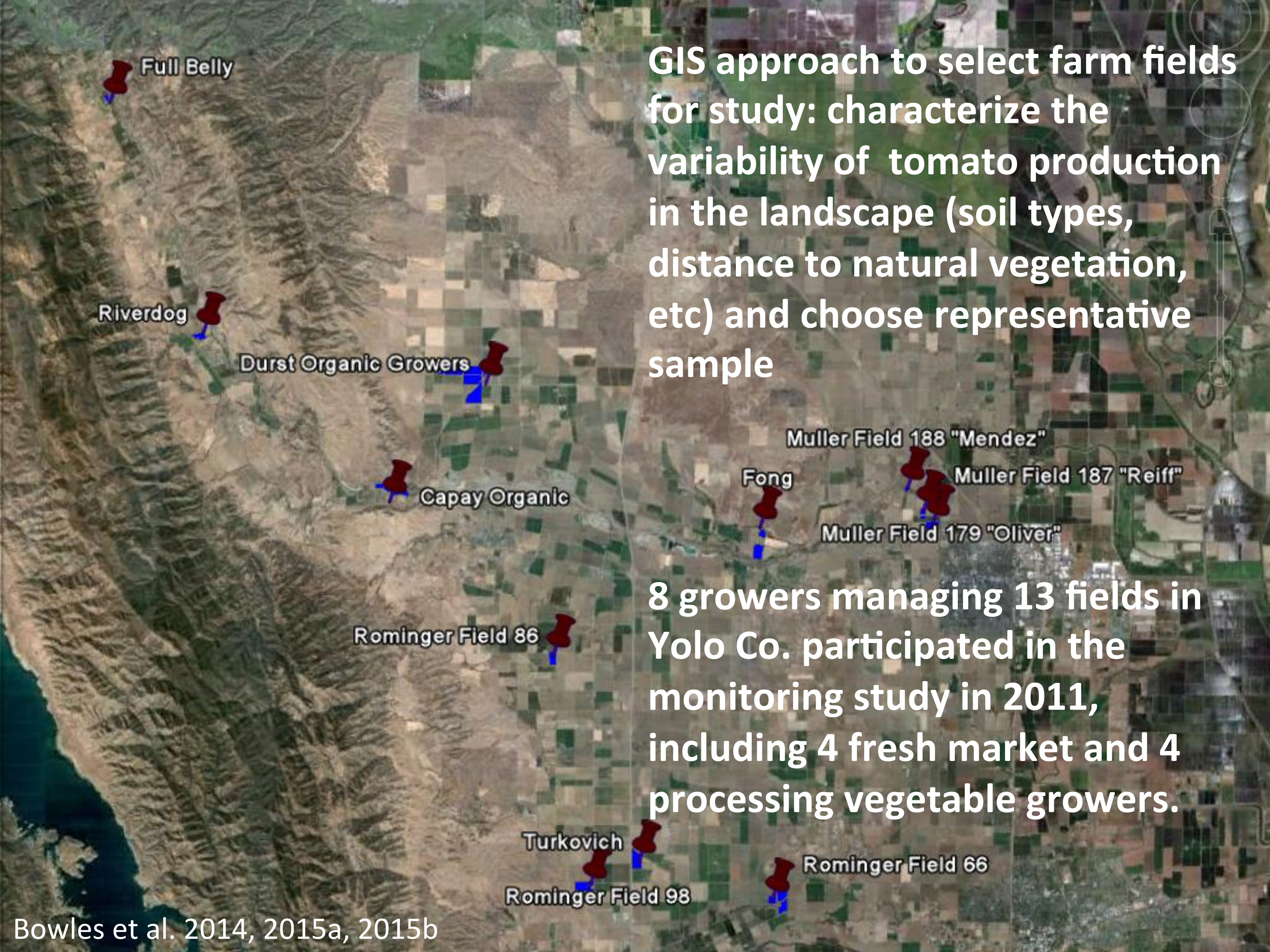
Survey of 13 Yolo Co. organic tomato fields

- Silt loam soils
- Differences in soil and water management among 13 fields
- Measurements
  - Indicators of soil N availability
    - Soil NH_4^+ and NO_3^-
    - Soil potentially mineralizable N (PMN)
    - Soil organic matter (SOM): total C & N, dissolved organic C (DOC), permanganate oxidizable C (POCx)
    - Tomato yield and N
  - Soil microbial activity
    - Soil microbial biomass
    - Potential enzyme activity (C, N, P, & S cycling)
  - Plant root activity
    - Expression of N metabolism genes in roots
    - ^{15}N tracer experiments
- Analysis
  - First, examine measurements individually on each farm
  - Then use multivariate statistical technique to help visualize all the variables and farms together

Bowles et al. 2014, 2015a, 2015b



GIS approach to select farm fields for study: characterize the variability of tomato production in the landscape (soil types, distance to natural vegetation, etc) and choose representative sample

8 growers managing 13 fields in Yolo Co. participated in the monitoring study in 2011, including 4 fresh market and 4 processing vegetable growers.

Bowles et al. 2014, 2015a, 2015b

Management practices used for organic Roma-type tomato production

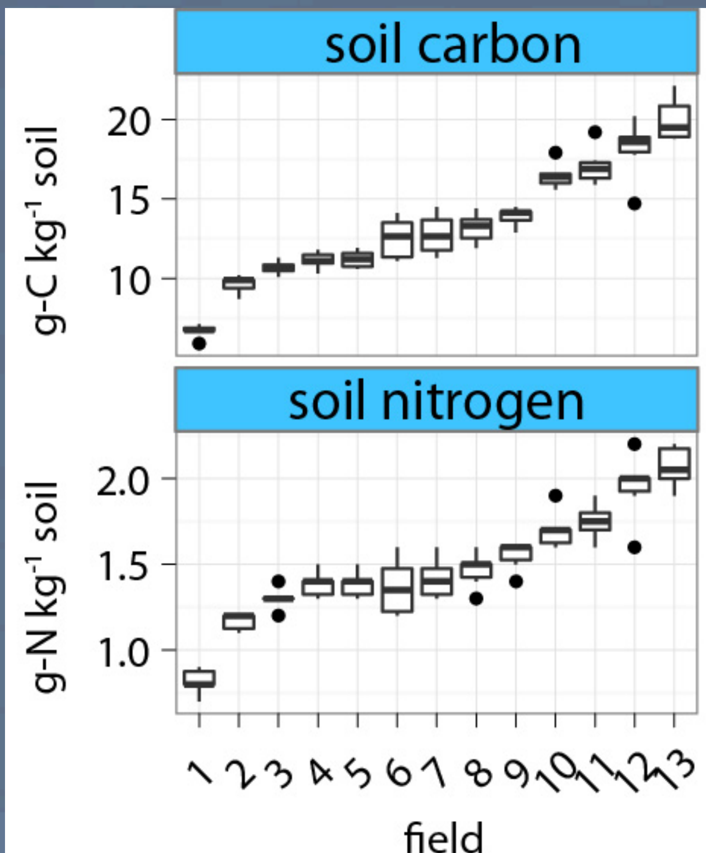
Farm	Fields	Certified	Market	Primary organic inputs	Secondary inputs	Irrigation
A	1,2,3	Mixed	Processing	poultry/cow manure (fall)	none	Furrow
B	4	All	Fresh	vetch winter cover crop	guano, soluble	Drip
C	5	Mixed	Processing	poultry manure (spring)	none	Drip
D	6, 9	All	Processing	poultry litter (fall), vetch winter cover crop	guano	Furrow
E	7	All	Fresh	composted green waste (fall), vetch winter cover crop	pellets, soluble	Drip
F	8	All	Fresh	composted green waste (fall)	pellets, soluble	Drip
G	10,11,13	Mixed	Processing	composted green waste (fall)	Chilean nitrate	Furrow
H	12	All	Fresh	composted green waste (fall)	soluble	Drip

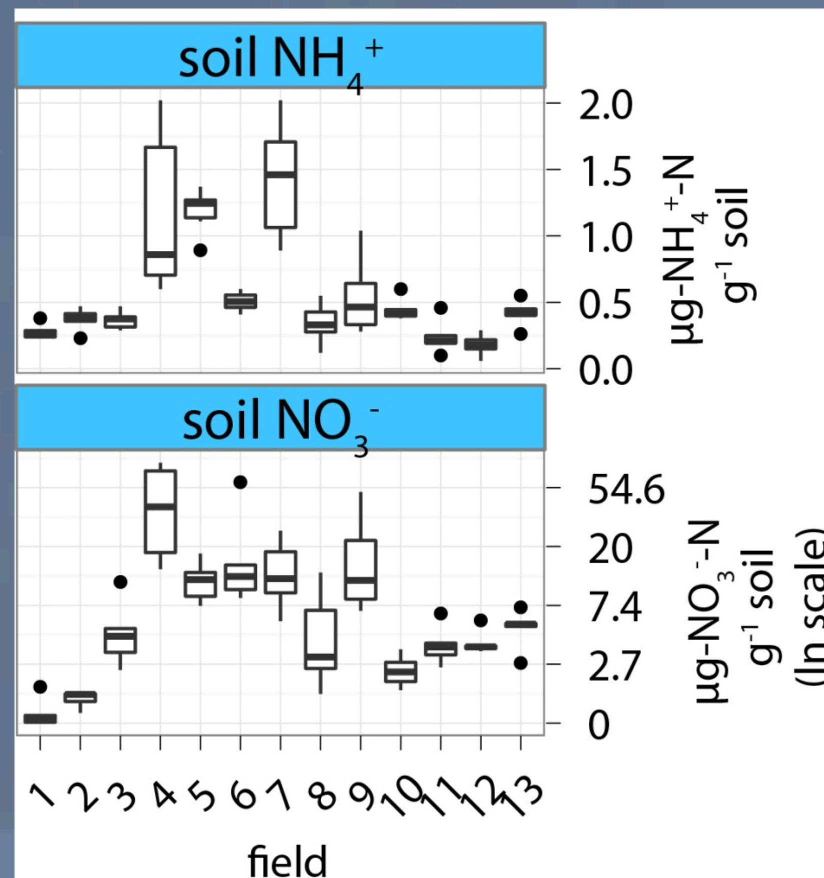
Bowles et al. 2014, 2015a, 2015b

SOM and inorganic N across the farms

Soil data shown for the top 0-6 inch layer at mid-season

- 3-fold range of total soil C (0.67 – 2.0 %) and N (0.08 – 0.21 %)
- Soil NH_4^+ low, but large variability in soil NO_3^- (0.19 – 44.9 µg-N g^{-1} soil)





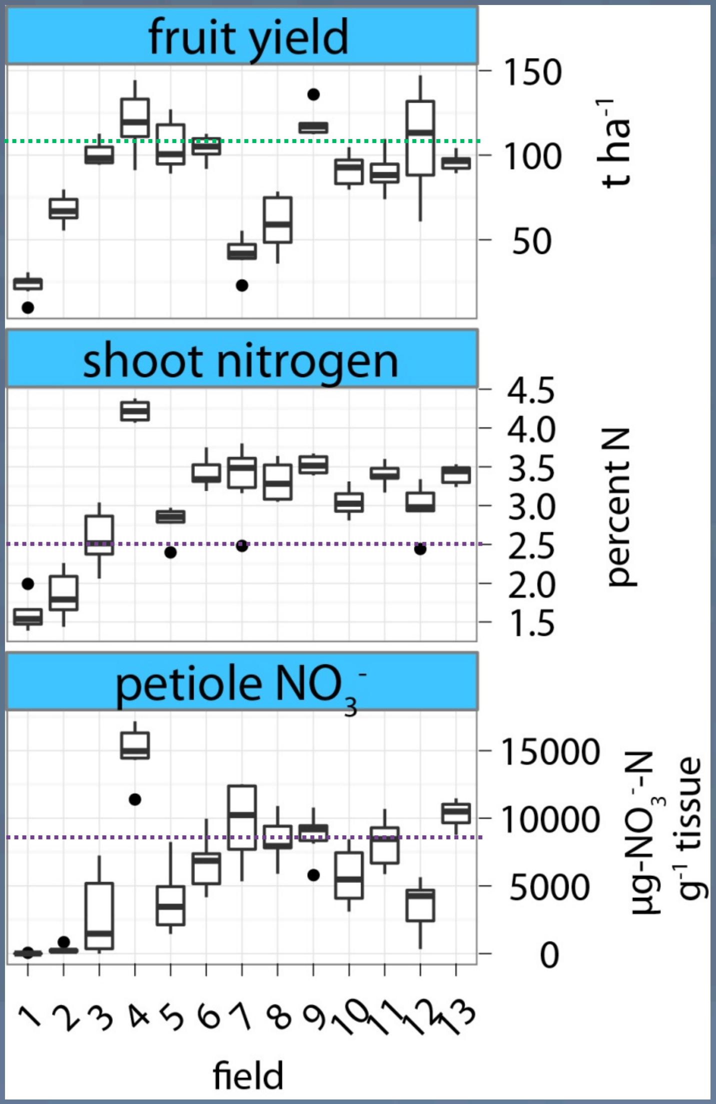
Bowles et al. 2014, 2015a, 2015b

Crop productivity and N

Average 2011 CA production: 107 t/ha 48 t/acre (conventional processing tomatoes)

N deficient (<2.5% N)

N deficient (<8000 ppm)



- 9/13 fields close to overall CA average for processing tomatoes
- 11/13 fields above critical shoot N level
- But 8/13 fields show N deficiency based on petiole NO_3^-
- Poor relationship between petiole NO_3^- and fruit yield
- Thus, the study showed generally good yields, and adequate N, but petiole NO_3^- is not a valuable indicator on these organic farms

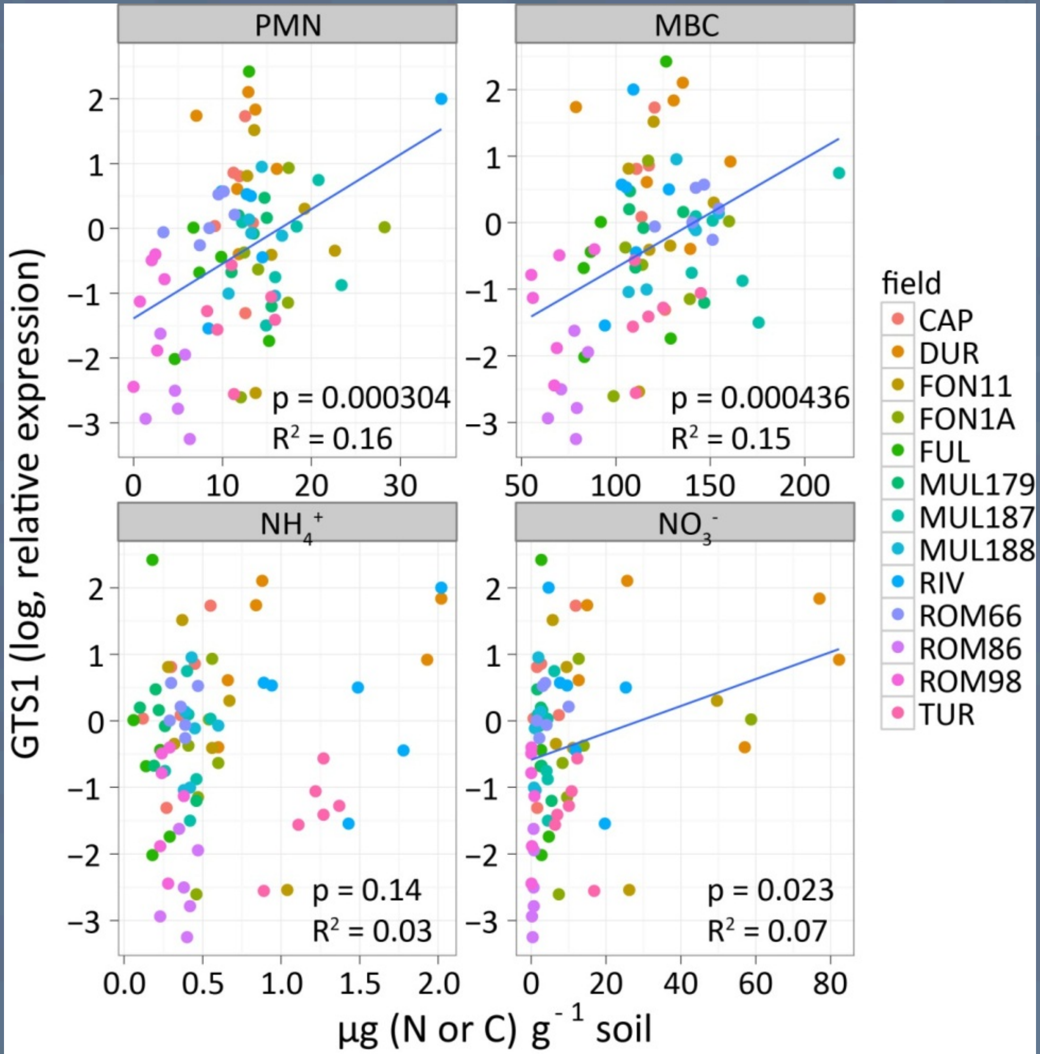
Bowles et al. 2014, 2015a, 2015b

Three fields as examples

Farm	Field	Certified	Market	Primary organic inputs	Secondary inputs	Irrigation
A	1	Mixed	Processing	poultry/cow manure (fall)	none	Furrow
Nitrogen deficient	• Soil: lowest total soil C and N; lowest soil nitrate • Plants: low N and low yields					
B	4	All	Fresh	vetch winter cover crop	guano, soluble	Drip
Nitrogen saturated	• Soil: low total soil C and N; high soil nitrate • Plants: very high plant N and high yields					
H	12	All	Fresh	composted green waste (fall)	soluble	Drip
Tightly-coupled soil nitrogen cycling	• Soil: higher total soil C and N; low soil nitrate • Plants: moderate plant N and high yields					

Bowles et al. 2014, 2015a, 2015b

A plant's eye view of soil N cycling



- qPCR of root gene expression
  - Root enzyme encoded by GTS1* is involved in incorporation of soil NH_4^+ and NO_3^- into plant biomass
- GTS1 expression better associated with soil microbial biomass and activity than with soil NH_4^+ and NO_3^- pools
- Plant roots may be taking up NH_4^+ and NO_3^- at the very moment when these nutrients are released by soil microbes

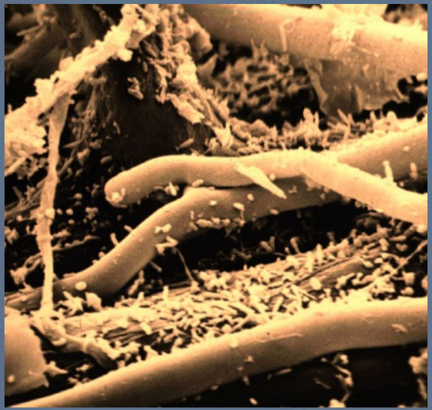
Bowles et al. 2014, 2015a, 2015b

*GTS1 = glutamine synthetase (cytosolic)

Putting it all together

Plant & soil measurements revealed three scenarios on working farms:

- N deficient
- N saturated
- Tightly-coupled plant-soil N cycling

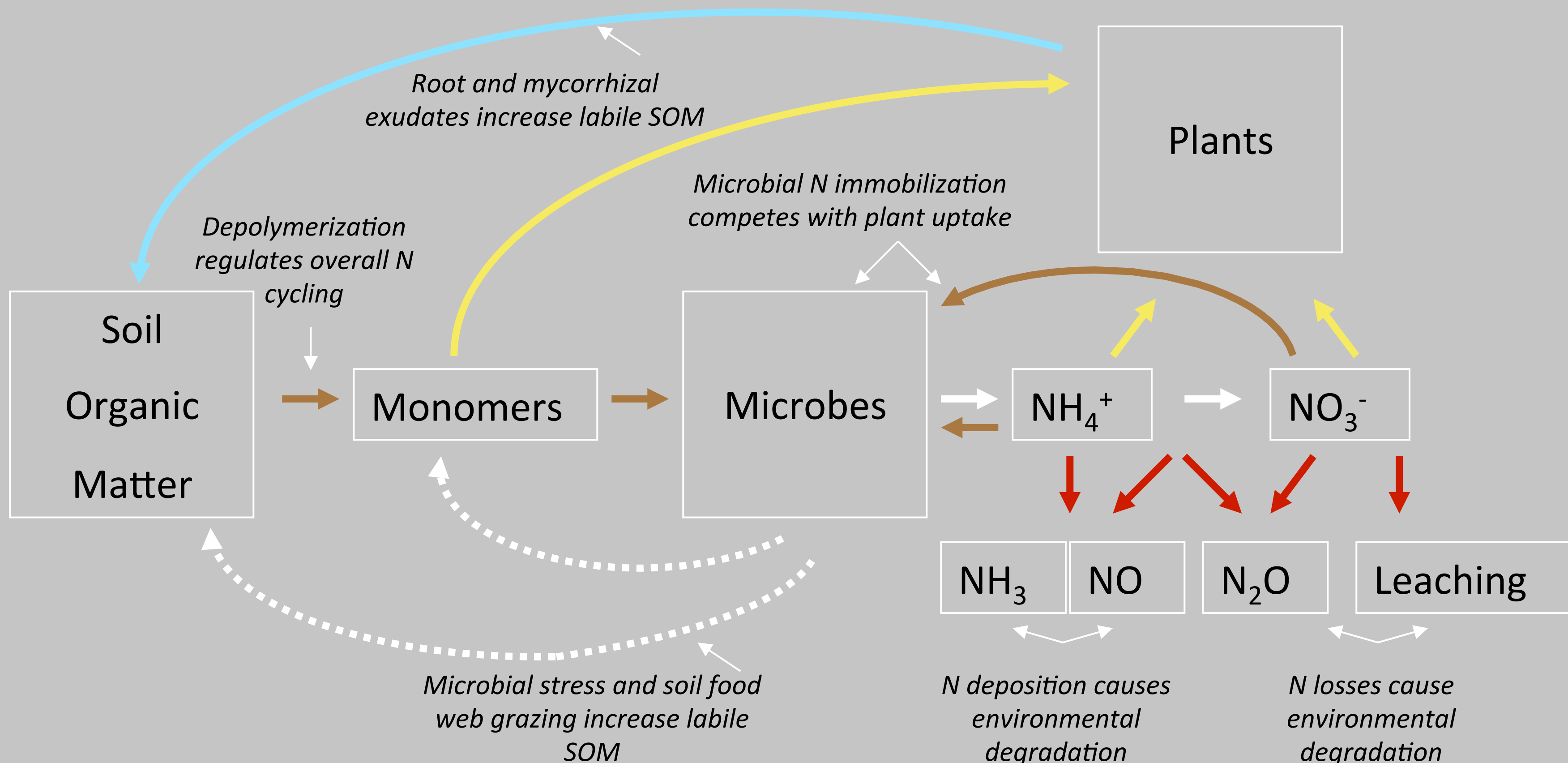


Tightly-coupled plant-soil N cycling occurred with higher soil C contents, active microbial biomass, and activity of soil enzymes that release N

Root N uptake was supported by tightly-coupled N cycling (^{15}N expts). Root N metabolism genes showed a more positive response to soil microbial bioassays than to soil inorganic N.

Bowles et al. 2014, 2015a, 2015b

Plant-soil-microbe nitrogen cycling



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- Basic aspects of soil biology and nutrient cycling
- How arbuscular mycorrhizae increase plant nutrient uptake and water use of organic roma tomatoes
- Higher soil carbon supports higher soil microbial biomass, soil enzyme activity, and release of plant available N (NH_4^+ and NO_3^-). Roots rapidly assimilate the released N to meet plant N demand. This tightly-coupled plant-soil N cycling reduces the potential for N losses to the environment.

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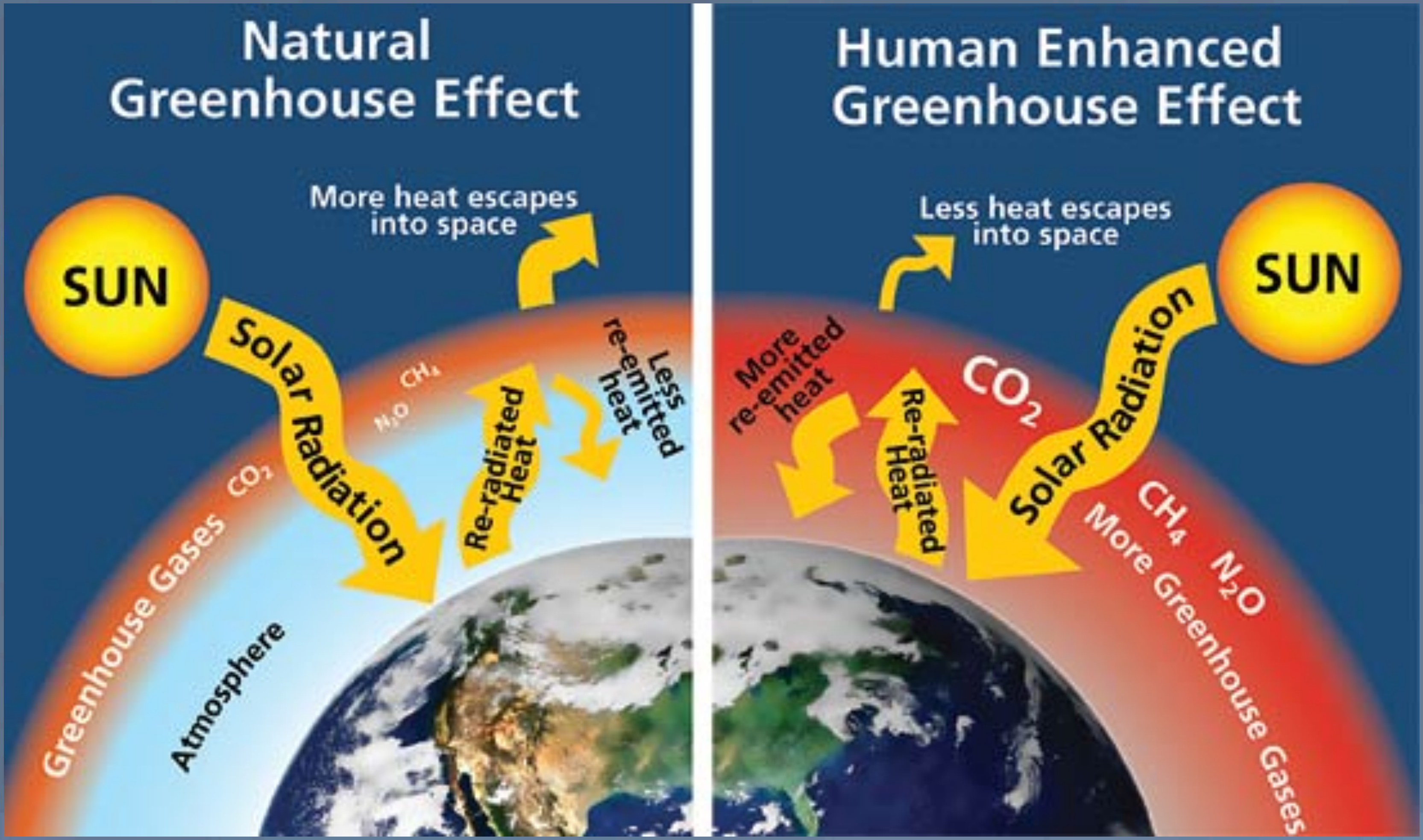
Thank you to Yolo County farmers for providing the field laboratories that have allowed us to study soil and root ecology as it relates to actual crop production.

Thanks to many postdocs and graduate students for their work over the years!

Greenhouse effect

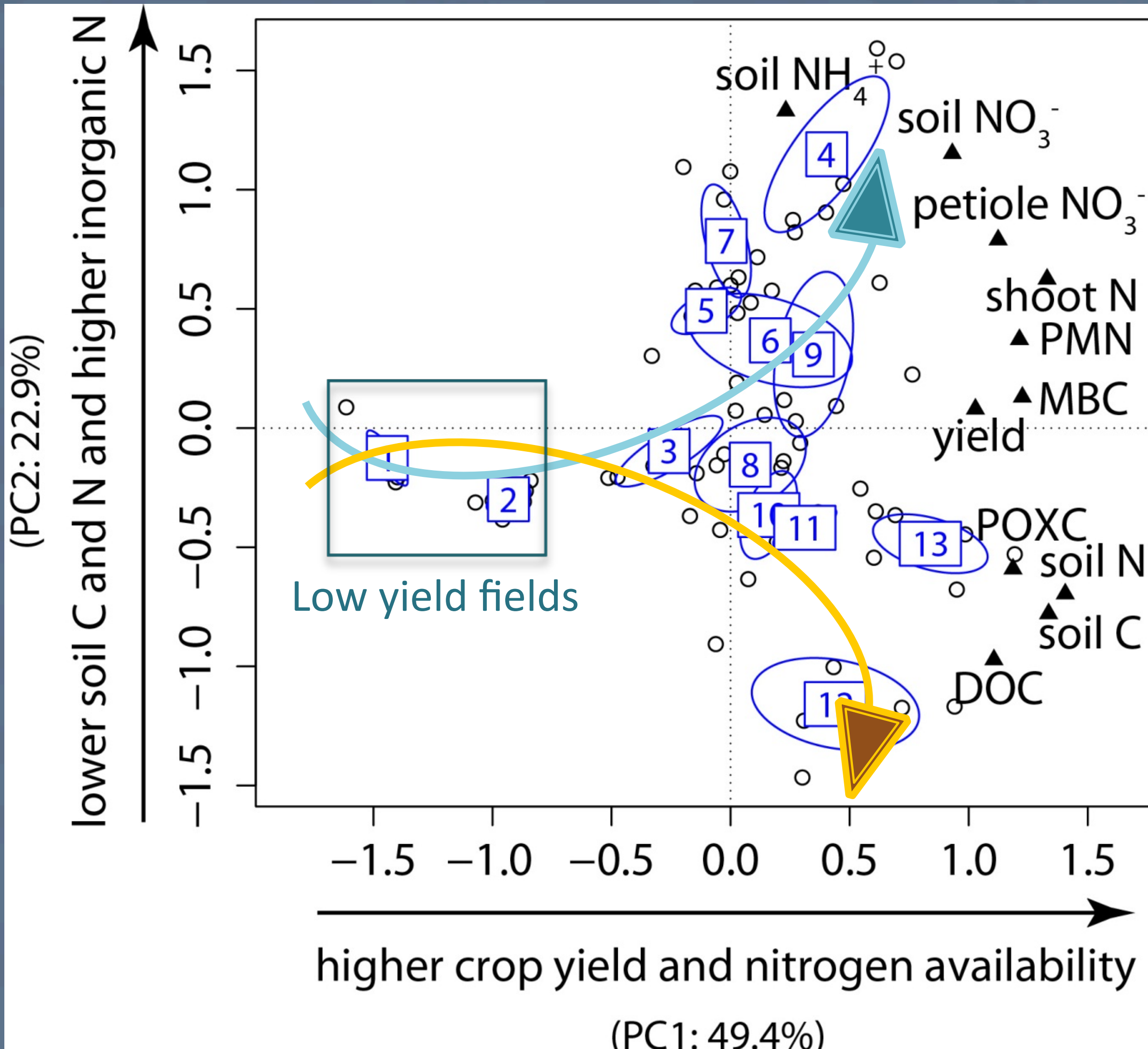


Soil characteristics across the farms

Field	Mapped soil series	Measured texture	pH
1	Tehama loam	Loam	6.67
2	Tehama loam	Silt loam	6.82
3	Capay silty clay	Silt loam	6.70
4	Tehama loam	Silt loam	6.55
5	Capay silty clay	Silt loam	6.33
6	Brentwood silty clay loam	Silt loam	6.34
7	Yolo silt loam	Silt loam	7.19
8	Yolo silt loam	Loam	6.79
9	Yolo silt loam	Silt loam	6.36
10	Yolo silt loam	Silt loam	6.62
11	Yolo silt loam	Silt loam	6.88
12	Yolo silt loam	Loam	6.78
13	Yolo silt loam	Silt loam	6.53

- Similar soil types
- Relatively little variation in texture and pH

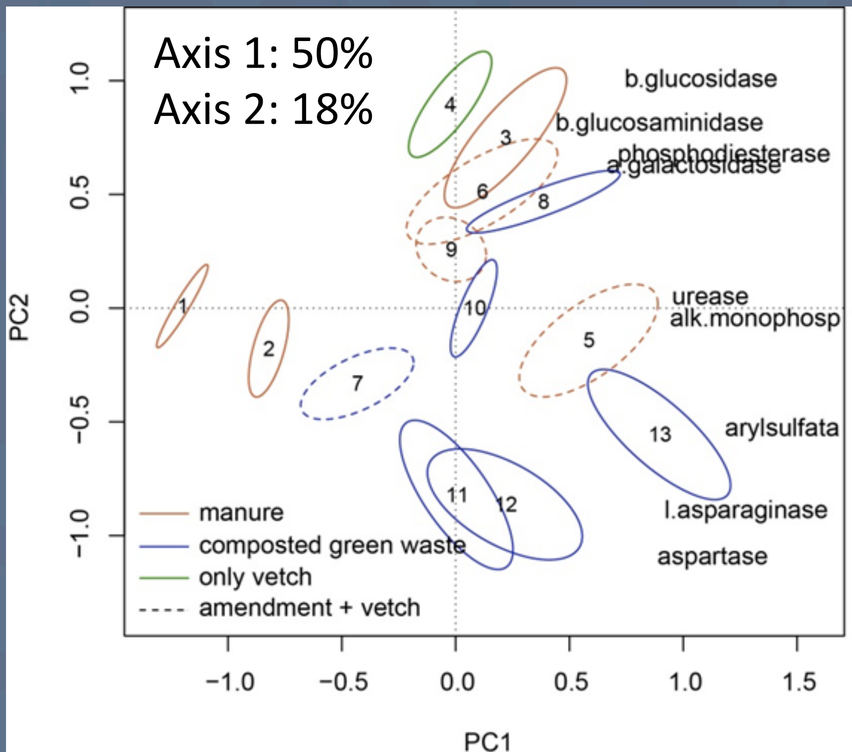
Soil and crop PCA of 13 organic farm fields

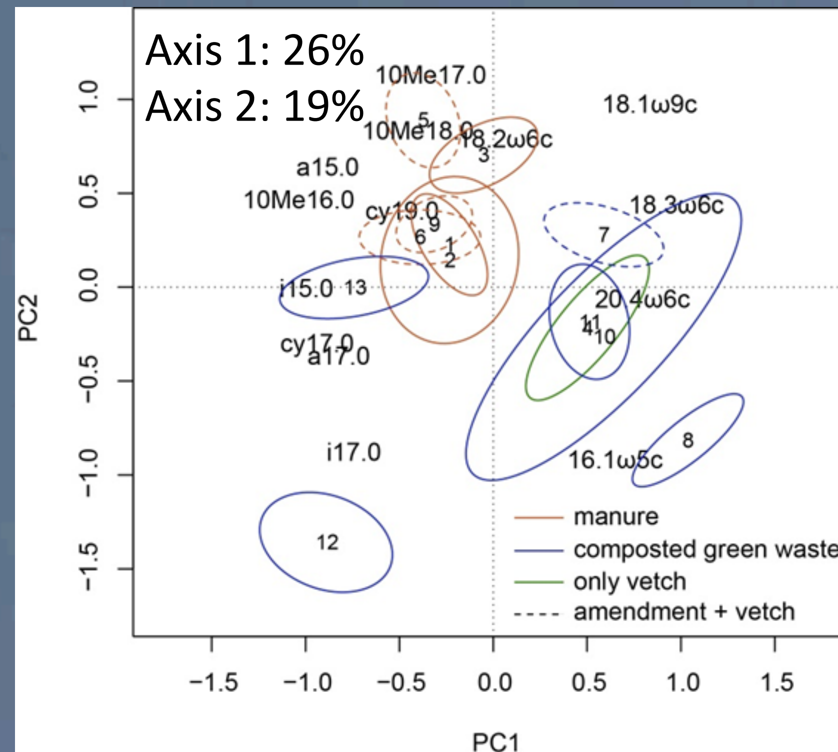


- Two pathways toward higher yields and N availability
  - Blue arrow: higher inorganic N availability
  - Yellow arrow: higher soil C availability
- What causes more tightly-coupled C & N cycling and good/ high yields (yellow arrow)?

Bowles, Soil Biol Biochem subm.

Soil potential enzyme activity and FAME PCAs of 13 organic farm fields





- C and N cycling soil enzymes show opposite trends:
  - N cycling enzymes: greater activity in fields with higher C availability
  - C cycling enzymes: greater activity in fields with higher inorganic N pools
- Soil enzymatic N release and turnover means plants can acquire N even when NH_4^+ and NO_3^- pools are small

Arbuscular mycorrhizae decrease roots