Build Soil, Sustain Yields, and Slash Costs

How to minimize fertilizer dependency in crop production

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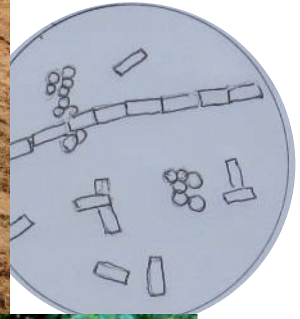
How did we get here ?

Nitrate and phosphate in streams and groundwater

Degraded, eroding soils

Depleted soil life

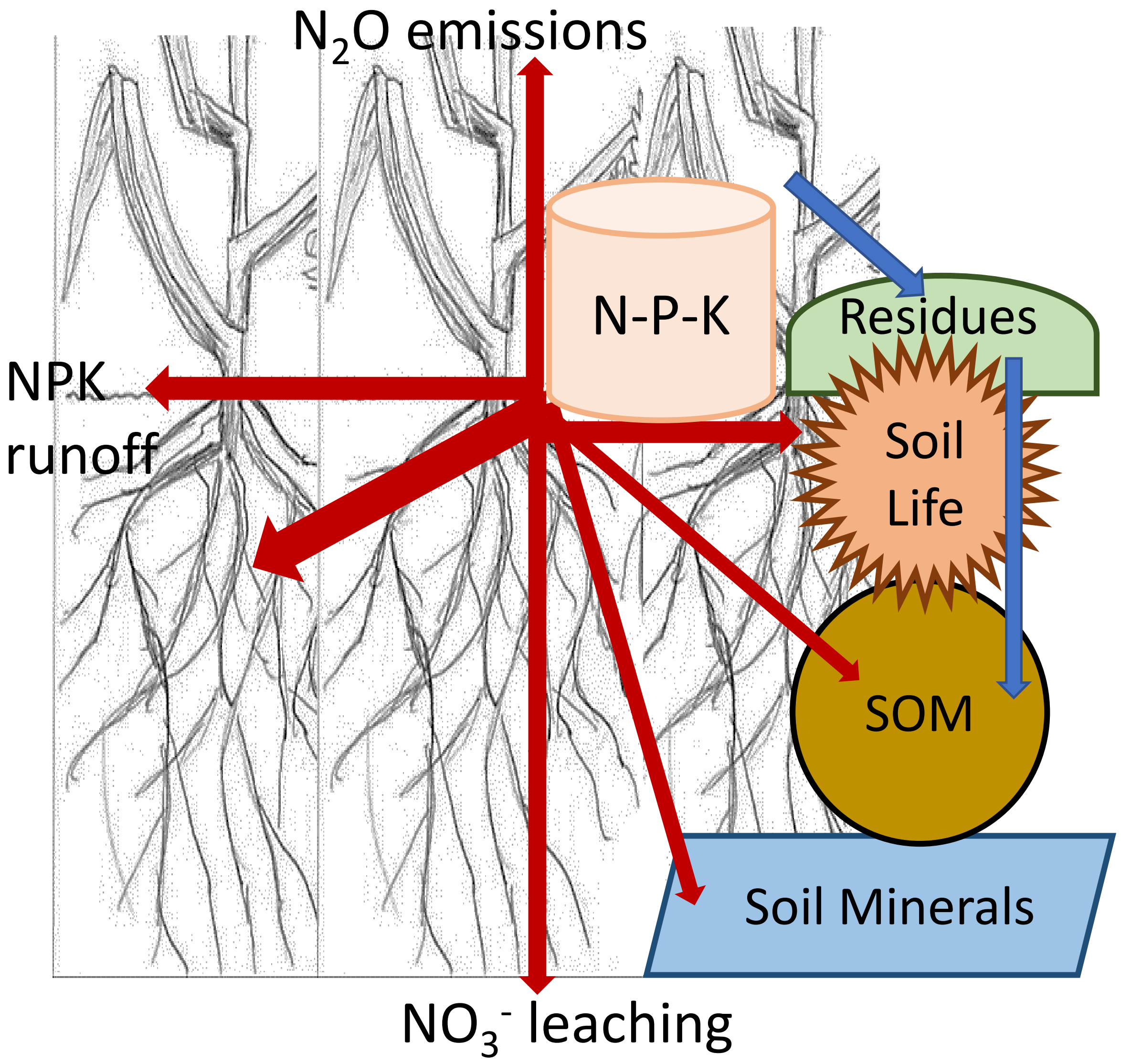


Nitrous oxide in the air

$teep fertilizer bill$

Hungry crops

20^{th} Century Nutrient Management



"Feed the Plant"

- Soluble nitrogen (N) phosphorus (P) and potassium (K) fertilizers
- Lime for acidic pH
- Other nutrients as needed

Soil life disregarded or seen as competitor for precious nutrients.

NPK recommendations based on:

- Expected crop uptake + estimated losses and tie-up.
- Yield trials in depleted soils.

Private service provider goals:

- Serve the farmer.
- Sell fertilizer.

The Morrow Plots at University of Illinois:

- Three crop rotations established 1901:

  Continuous Corn **Corn-Soy** **Corn-Oats-Alfalfa**

- **Synthetic NPK treatments** started in 1955 (medium) and 1967 (high).

"The use of science and technology has increased crop productivity over four-fold" Large sign at the Morrow Plot site

"Soil quality is a vital component of agricultural productivity. Crop rotation [helps prevent] depletion of soil quality." Wikipedia

Does soluble fertilizer also help soil quality?

Effects of 50 years' Synthetic NPK: the Morrow Plots

Soil sampled at 0-6, 6-12, and 12-18 inches in 1955 and 2005

Effects of synthetic NPK versus no fertilizer:

- Crop yield and residue return > doubled for both NPK rates.
- No increase in SOC (tons/acre) in fertilized plots.
- NPK decreased total and potentially mineralizable soil N.
- High NPK sharply reduced subsurface (6-18") SOC and total soil N.
- Exchangeable K increased as much or more in unfertilized plots.

Khan et al., 2007; Khan et al., 2009; Mulvaney et al., 2009.

Effects of Synthetic NPK: Other Trials

A global review of other field trials with synthetic NPK revealed:

- Downward trend in total SOC in 23 out of 25 long-term trials.
- Downward trend in total soil N in majority of 60 long term trials.
- Accelerated soil N mineralization in 19 out of 23 studies.
- No correlation between K fertilization and soil test (exchangeable) K.
- No crop yield response to K in 76% of 2,121 short-term trials.
- Negative effects of KCl on crop quality in 57% of 1,000 studies.

Khan et al., 2007; Khan et al., 2009; Mulvaney et al., 2009.

Lessons Learned from U Illinois Soil Health Studies

- Synthetic fertilizers do not build SOC.
- N rates above crop demand promote microbial consumption of SOC.
- Base N management on soil biological N mineralization:
  - Site-specific accounting for N provided by soil.
  - Synchronize supplemental N application with crop N demand.
- Most soils have vast reserves of non-exchangeable K that crops can access and return to topsoil in residues.
  - K recommendations are far too high; often none is needed.
  - KCl can harm crop quality; excess K reduces soil CEC and WHC.

Khan et al., 2007; Khan et al., 2009; Mulvaney et al., 2009

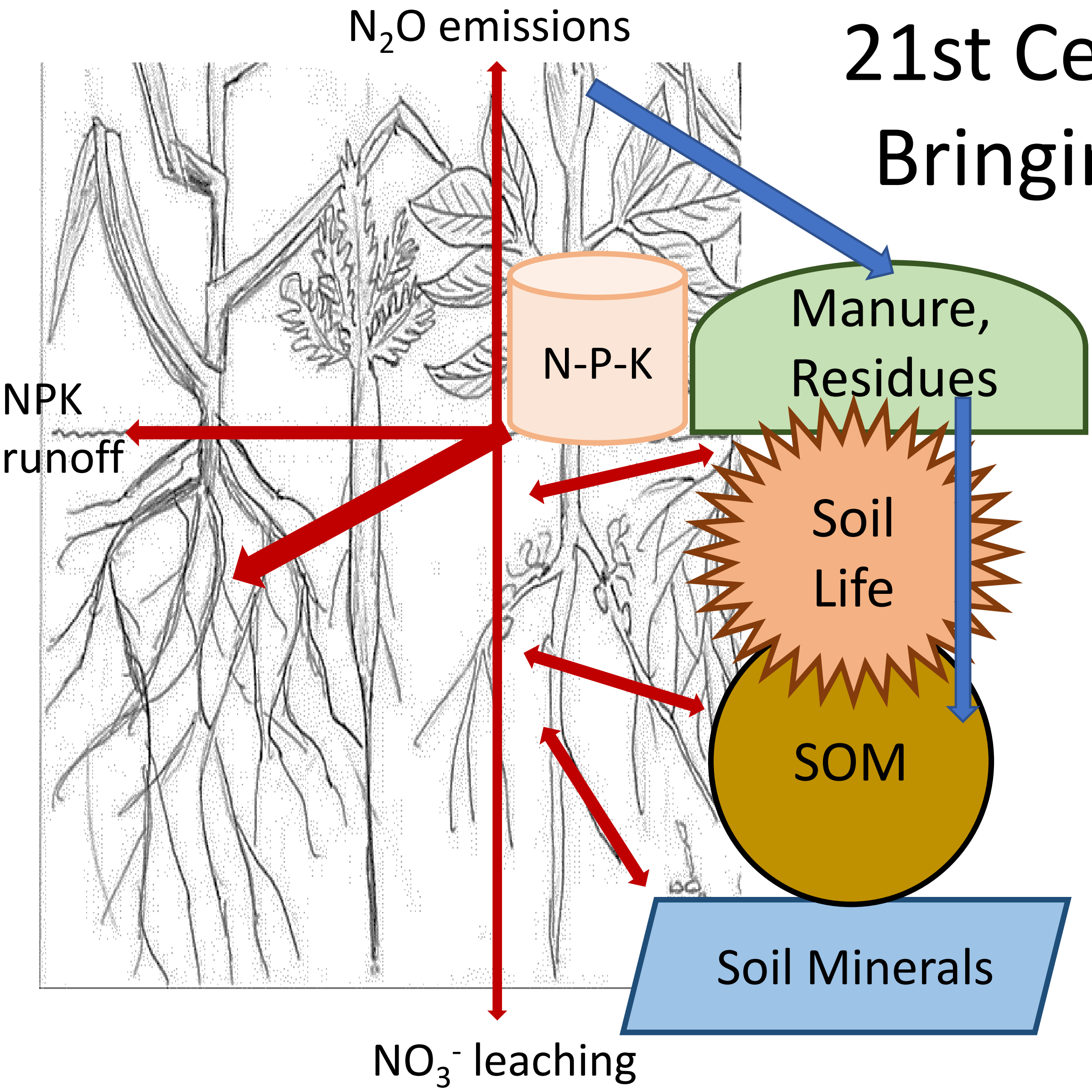
20^{th} Century Nutrient Management: the Organic Response

"Feed the Soil …"

- Return manure & residues to the soil.
- Use green manures.
- Integrate crops & livestock.
- Reduce off-farm inputs.
- Avoid synthetics.
- Attend to *all* nutrients, not just NPK.

"… and the soil will feed the crop."

21st Century Nutrient Management: Bringing Soil Microbes to the Table



"Feed the Crop *and* the Soil."

- Soluble fertilizers, manure, legumes
- Crop residues, cover crops

Soil life and SOM valued for soil health.

- Two-way nutrient exchange - may hold (tie-up) or release nutrients.

Recommendations include:

- Credits for legumes, manure, etc.
- Avoiding excesses to protect water.
- Crop rotation.

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21st Century Nutrient Management

NRCS 4Rs of Nutrient Management:

- Right Source
- Right Rate
- Right Timing
- Right Placement

Conservation Practice Standard 590 Nutrient Management

Soil Test Interpretation and Recommendations

Soil test P or K rating	Interpretation
Very low (VL)	Critically yield-limiting
Low (L)	Crop yield response likely (80%)
Medium (M)	50% chance of yield response
High (H) or Optimum	Yield response unlikely (10%)
Very high (VH)	Ample or excessive

- No N test unless pre-sidedress nitrate-N requested.
- Soil test K (exchangeable K) not reliable indicator of crop K status.

Soil Test Recommendations (lb/ac) for High Soil P and K compared with Crop Nutrient Removals

Source	Crop	N (based on crop)	P_2O_5 for H	K_2O for H	P_2O_5 for VH	K_2O for VH
LGU – Virginia Tech, 2018	Vegetables, various	90-200	50-100	50-100	0-50	0-50
Private lab soil test reports	Vegetables, various	100-150	40-80	40-80	30-40	0
Private lab soil test reports	Corn, 100 bu/ac	100	30-60	40	30	40

Crop and yield	Nutrient removals: N	P_2O_5	K_2O
Corn, 180 bu/ac	162	67	49
Wheat, 80 bu/ac	96	50	30
Grass hay, 5 tons/ac	170	52	250
Onions, 20 tons/ac	110	20	110
Spinach, 10 tons/ac	100	25	100
Tomatoes, 30 tons/ac	110	48	180

Current LGU Recommendations for P and K

University	Soil P and K test optimum or "H"	Soil P and K test "VH"
U. Maine	Maintenance[1] or 0 and test soil regularly	0
Penn State	Maintenance[1] (H-) decreasing to 0 (H+)	0
Michigan State	0-30 lb/ac P_2O_5, 0 K2O	0
U. Georgia	0	0
Iowa State	Maintenance[1]	0
Oregon State	0	0

[1] Apply nutrient to replenish expected amount removed in harvest.

"Nearly all soils in Missouri require nitrogen for optimum production of crops … The soil test used to estimate the nitrogen-supplying power is the organic matter test."
N credits for soil range from 20 – 80 lb/ac based on soil texture and %SOM.

U. Missouri Soil Test Interpretation and Recommendations Handbook

Grain Crops may Need Little Fertilizer on Healthy Soils

Five-year Organic Systems Trials in South Carolina

- Organic corn-soy-wheat rotation with cover crops
- Coastal plain loamy sand, soil test P and K optimal.
- P and K zero or recommended rate
- H at 50% or 100% of recommended rate.

Results

- Organic system builds SOM 1.2% → 1.7%
- Full grain yields with 50% N rate and zero P and K.
- Little change in soil P or K.
- 13 trials in NC, OH, IL, and ND gave similar results.

Standard soil tests & recommendations:

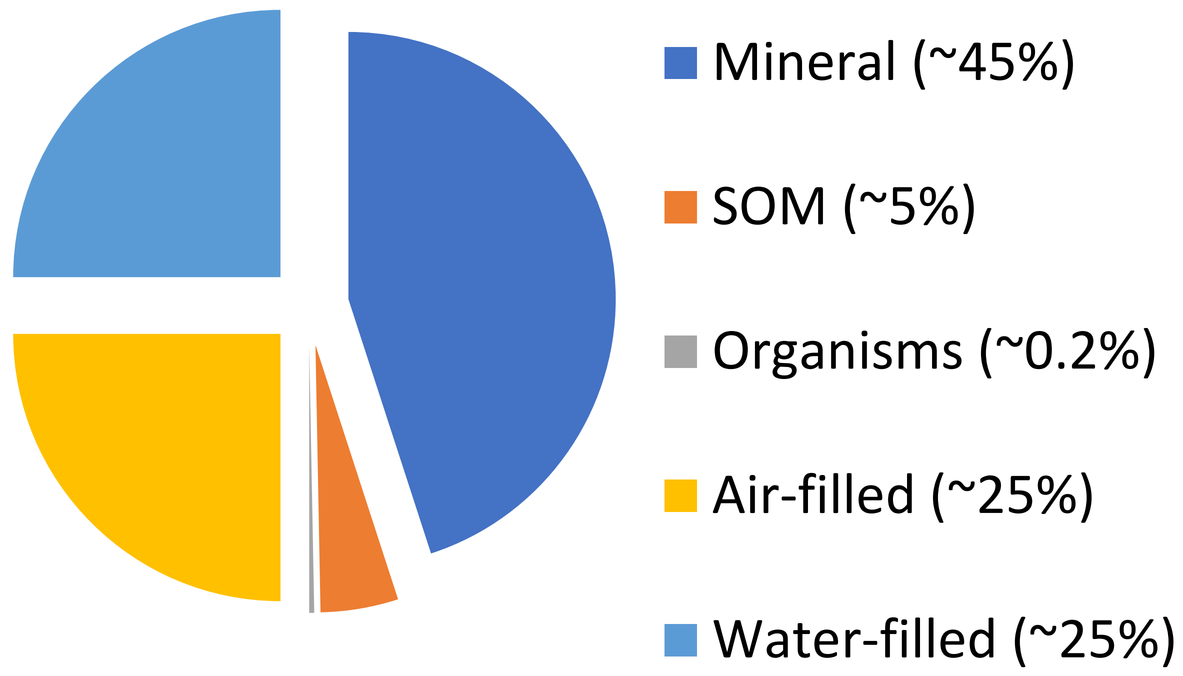
- Measure top 6 inches only.
- Ignore soil biology.
- Assume soil is "leaky".
- Overlook nutrient recovery by cover crops.

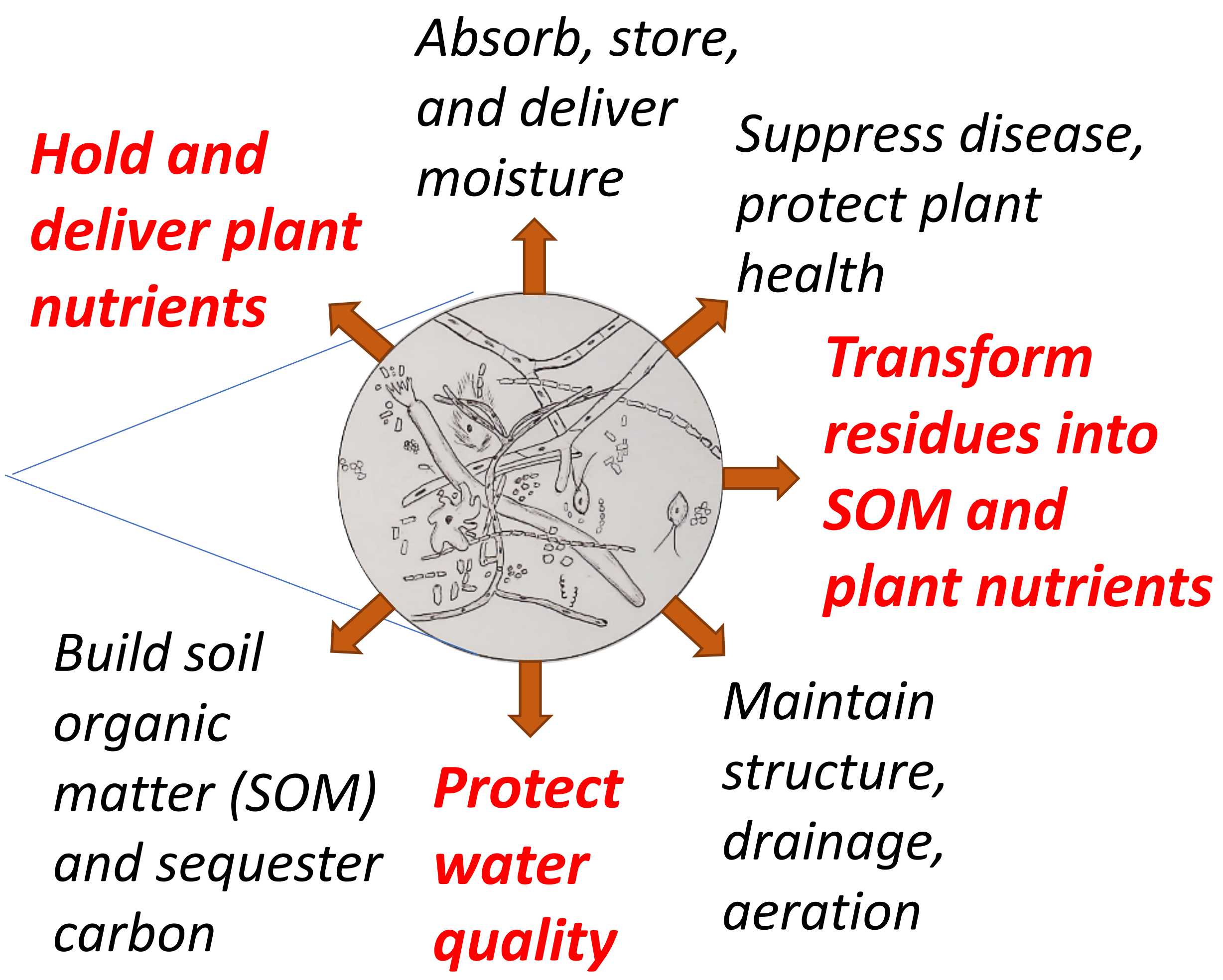
"Living soil changes everything"

Kloot, 2017.

Tiny but Mighty: Soil Life Drives All Soil Functions

Soil Components by Volume





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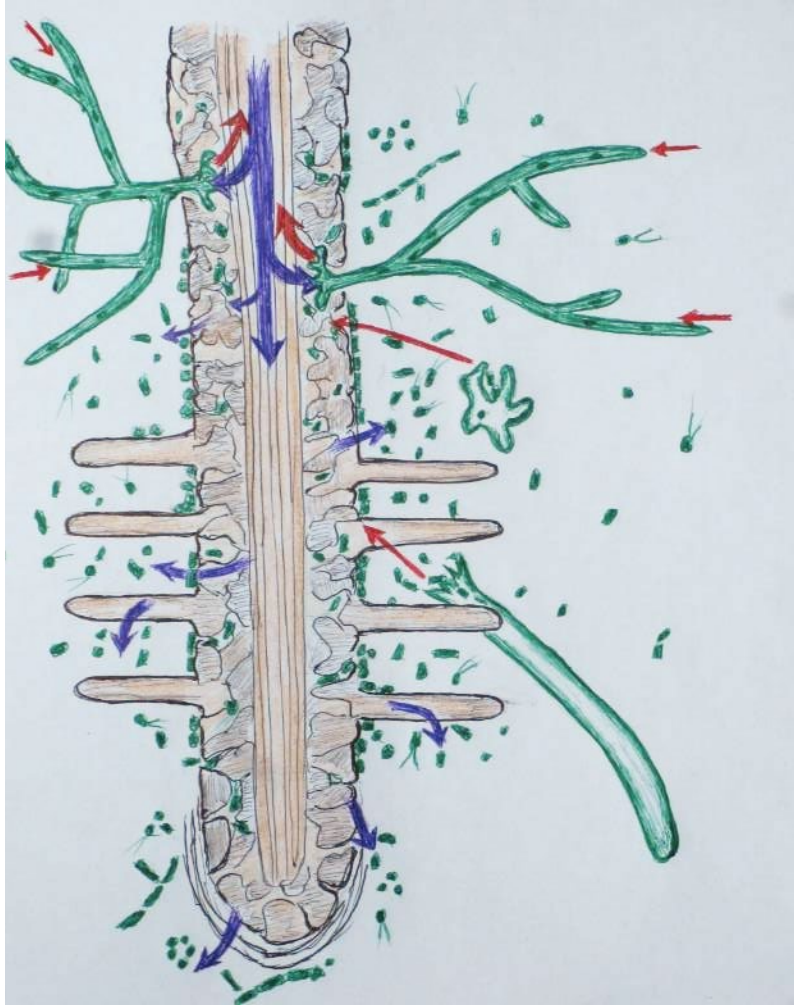
Nutrients for Carbon: an Ancient Partnership

- Plants provides organic carbon (*blue arrows*) to:
    - Mycorrhizal fungi.
    - Endophytic (within root tissue) bacteria.
    - Rhizosphere (near-root) microbes.
- These microbial partners (*green*) deliver nutrients (*red arrows*) directly to plant roots.
- Microbial grazers – nematodes and protozoa, release additional nutrients.
- Plant enzymes and chemical signals regulate these processes to match crop nutrient needs.
- *Land plants co-evolved with mycorrhizal fungi 450 million years ago to build the word's first living soils*.



Based on a diagram by Ray R. Weil

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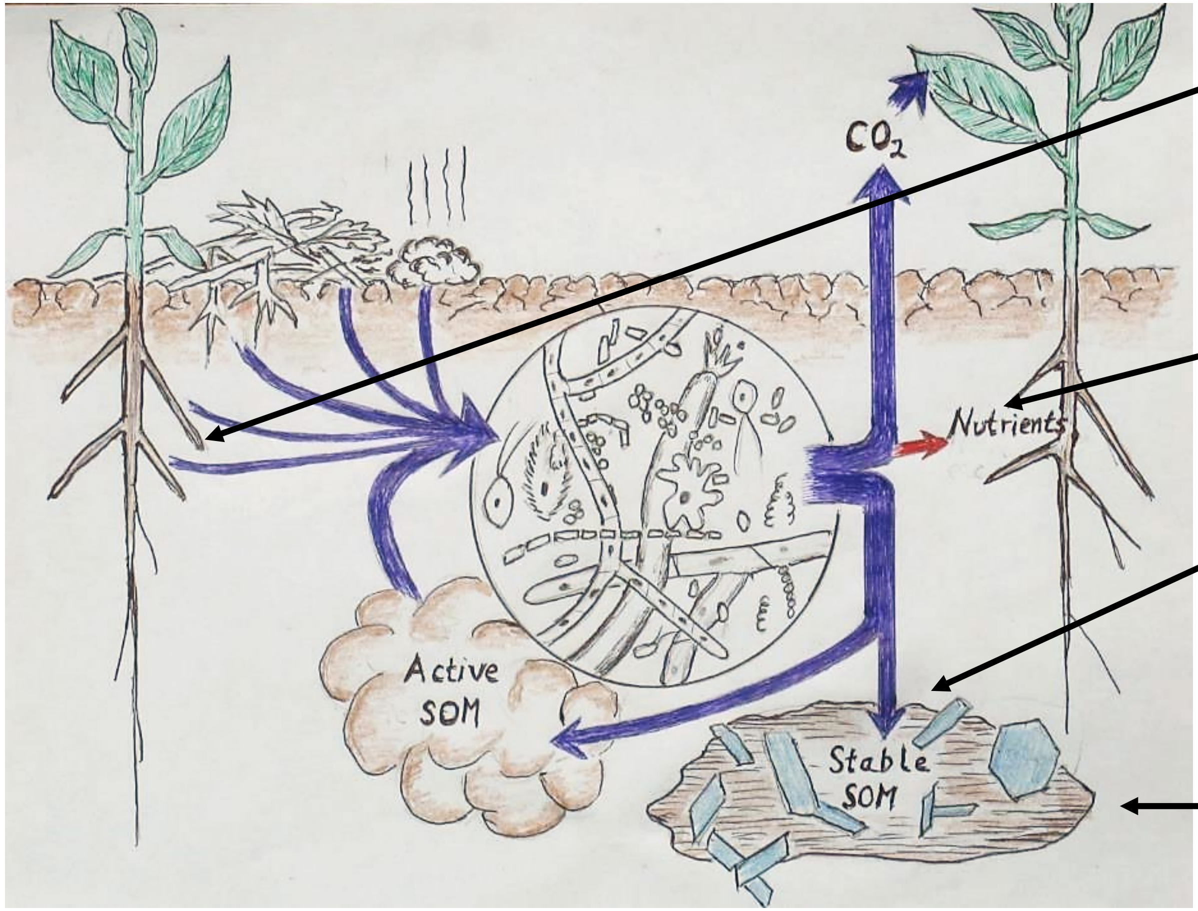
How Soil Microbes Feed Crops while Sequestering Carbon



Plant root exudates provide the "daily bread" for soil microbes

Microbial mineralization of residues and active SOM releases N and other nutrients, thereby supporting plant growth

SOM stabilization occurs when microbial remains and byproducts form *mineral-associated organic matter* (MAOM).

Deep roots and leaching soluble SOM become **subsoil MAOM**.

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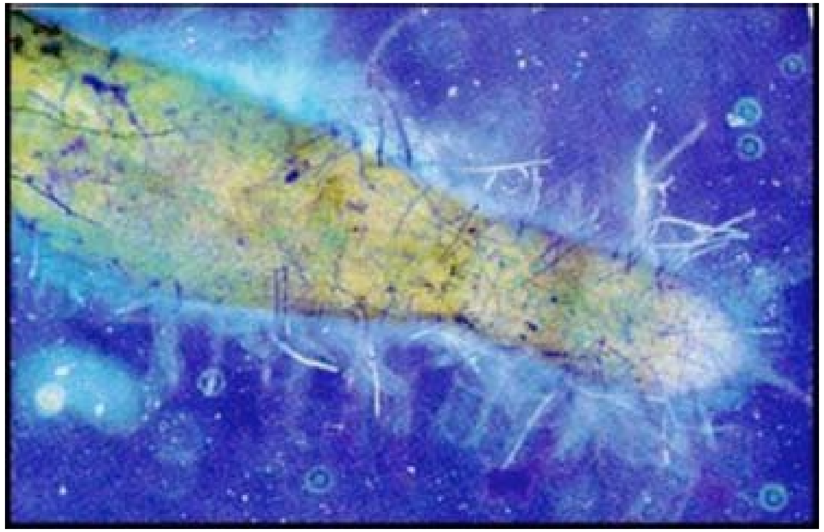
How to Enhance the Soil's Capacity to Sequester Carbon and Feed Crops

- Maximize year-round living root.
- Promote root growth and root exudate production:
  - Avoid N and P excesses. Keep N and P rates *slightly below optimum for top growth.*
  - Include legumes in crop rotation and pasture.
  - Graze rotational pasture late in rapid growth phase.
- Use shallow (3-4") non-inversion tillage – speed disk, rotary harrow, rototiller on low PTO speed. This doubles microbial biomass compared to:
  - Moldboard plow (buries soil life).
  - Continuous no-till (restricted aeration, herbicides).



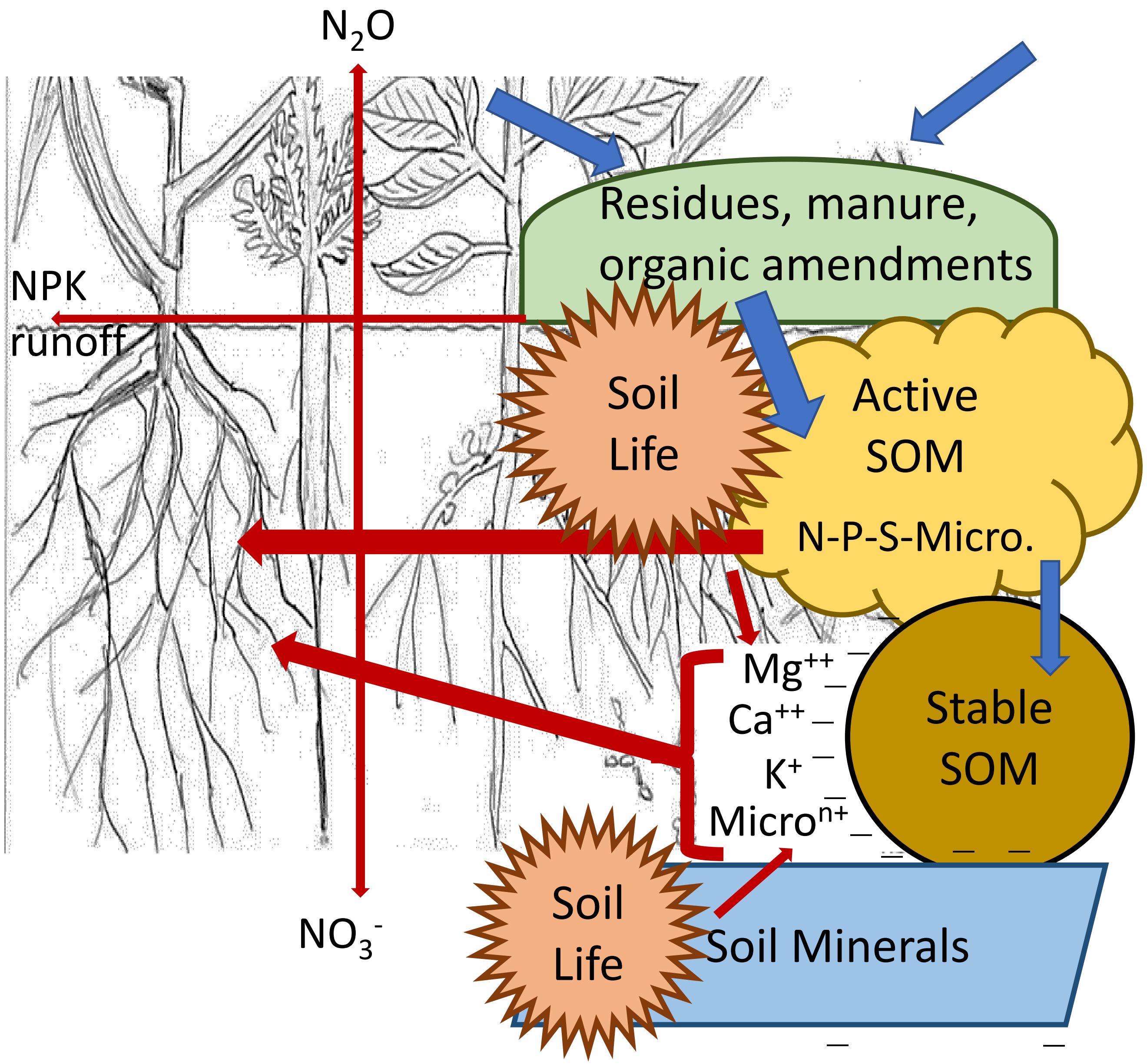
Soil bacteria proliferate near an actively growing plant root. Protozoa release nutrients to roots as they feed on bacteria.

Biologically Based Nutrient Management

Organic farming relies on soil life to:

- Process residues into active SOM.
- Retain nutrients.
- Provide timely, season-long crop nutrition.
- Form stable SOM which expands the soil's cation exchange capacity (CEC).
- Mobilize P, cations, and micronutrients from soil minerals.

NOP-allowed concentrated fertilizers are used judiciously when needed.



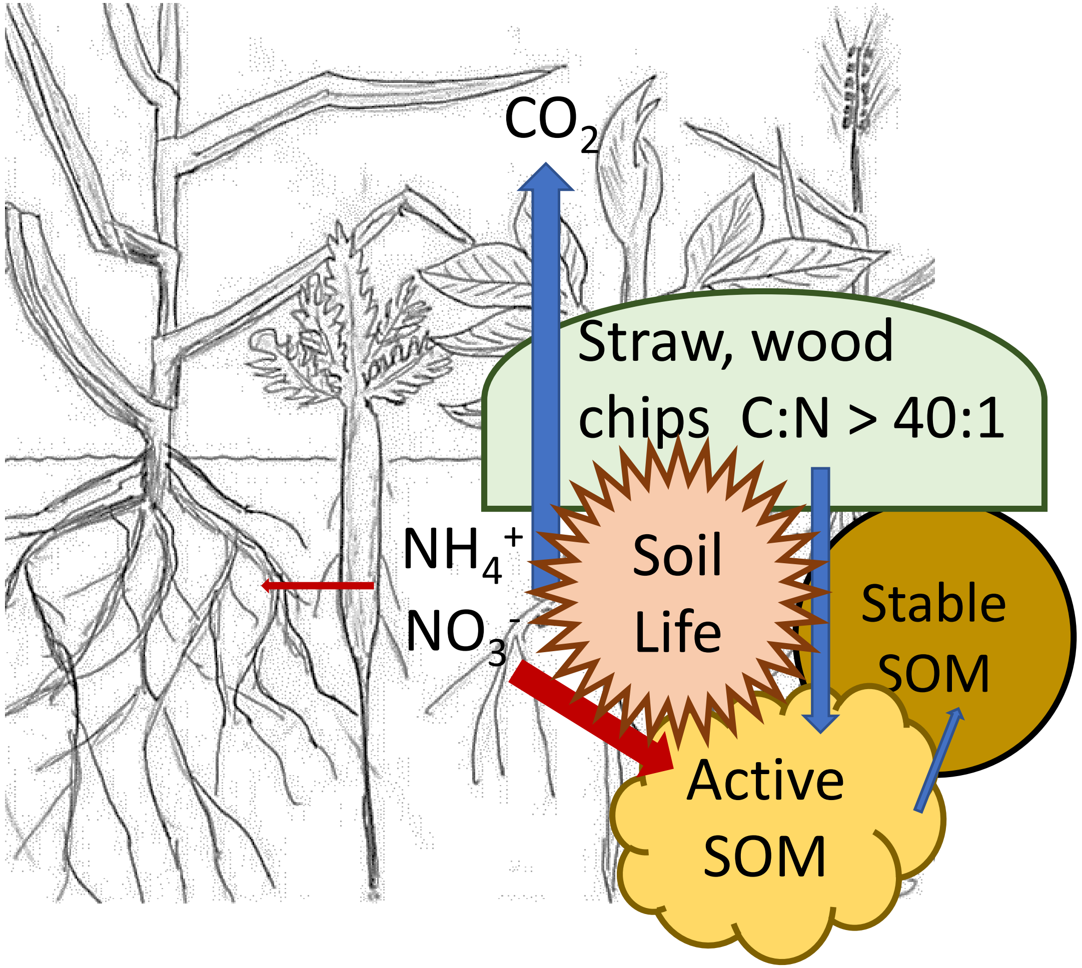
Soil Microbes Need a Balanced Diet to Do their Job
Carbon-to-nitrogen (C:N) ratio

High C:N (>35:1) inputs:

- Tie up N.
- Slow microbial processes.
- Form more CO_2 and less SOM.

Surface mulches protect soil life, tie up less N.

N-deficient broccoli after rye cover crop (left). Microbes are N-limited and grow slowly as they "burn off" excess C (right).



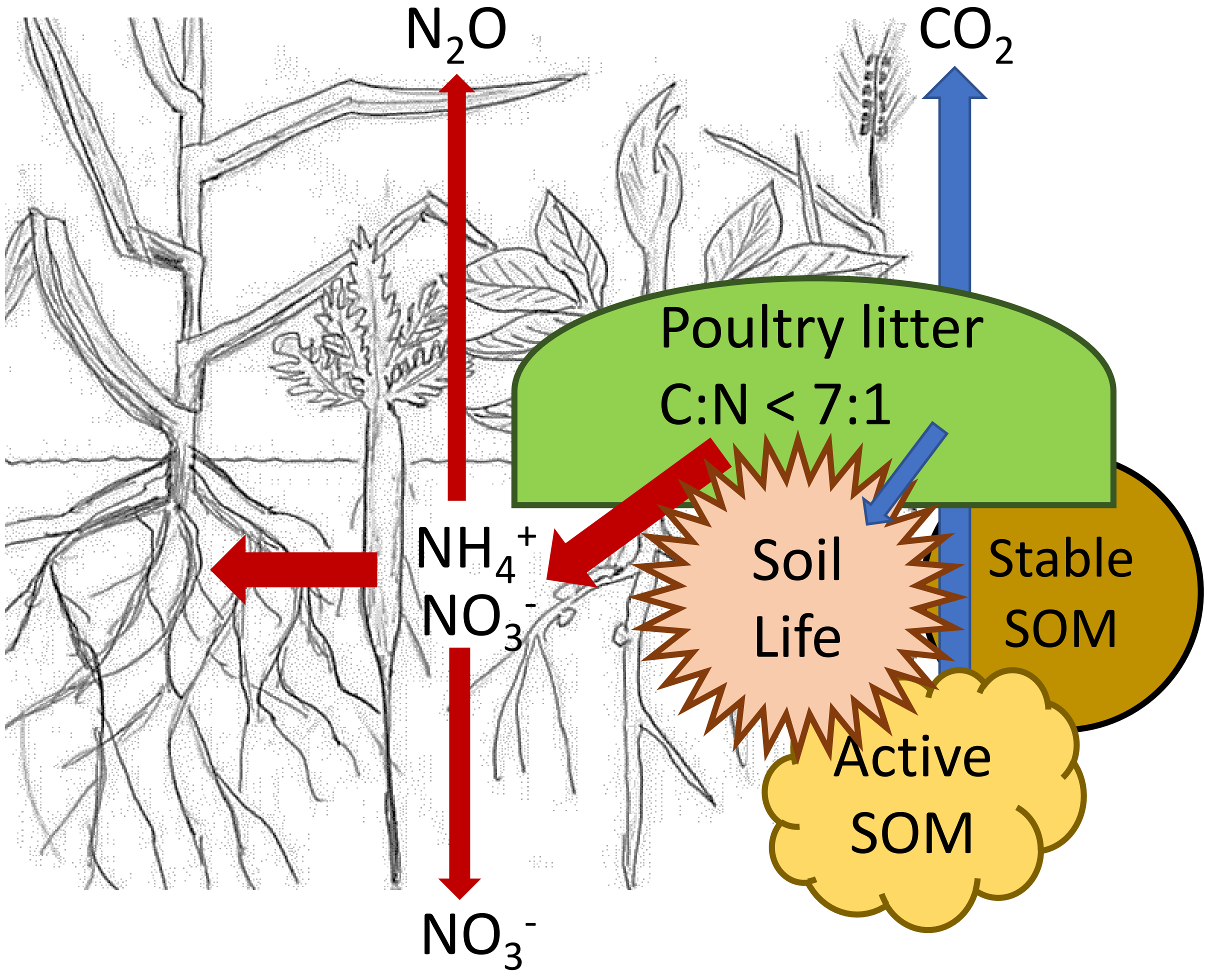
Soil Microbes Need a Balanced Diet to Do their Job

Carbon-to-nitrogen (C:N) ratio

Low C:N (<15:1) inputs:

- Speed microbial processes.
- Release soluble N rapidly.
- May leach nitrate or emit N_2O.
- May consume SOM.

Broccoli and weeds thrive after vetch cover crop (left). Microbes are C-limited and "raid" active SOM (right).



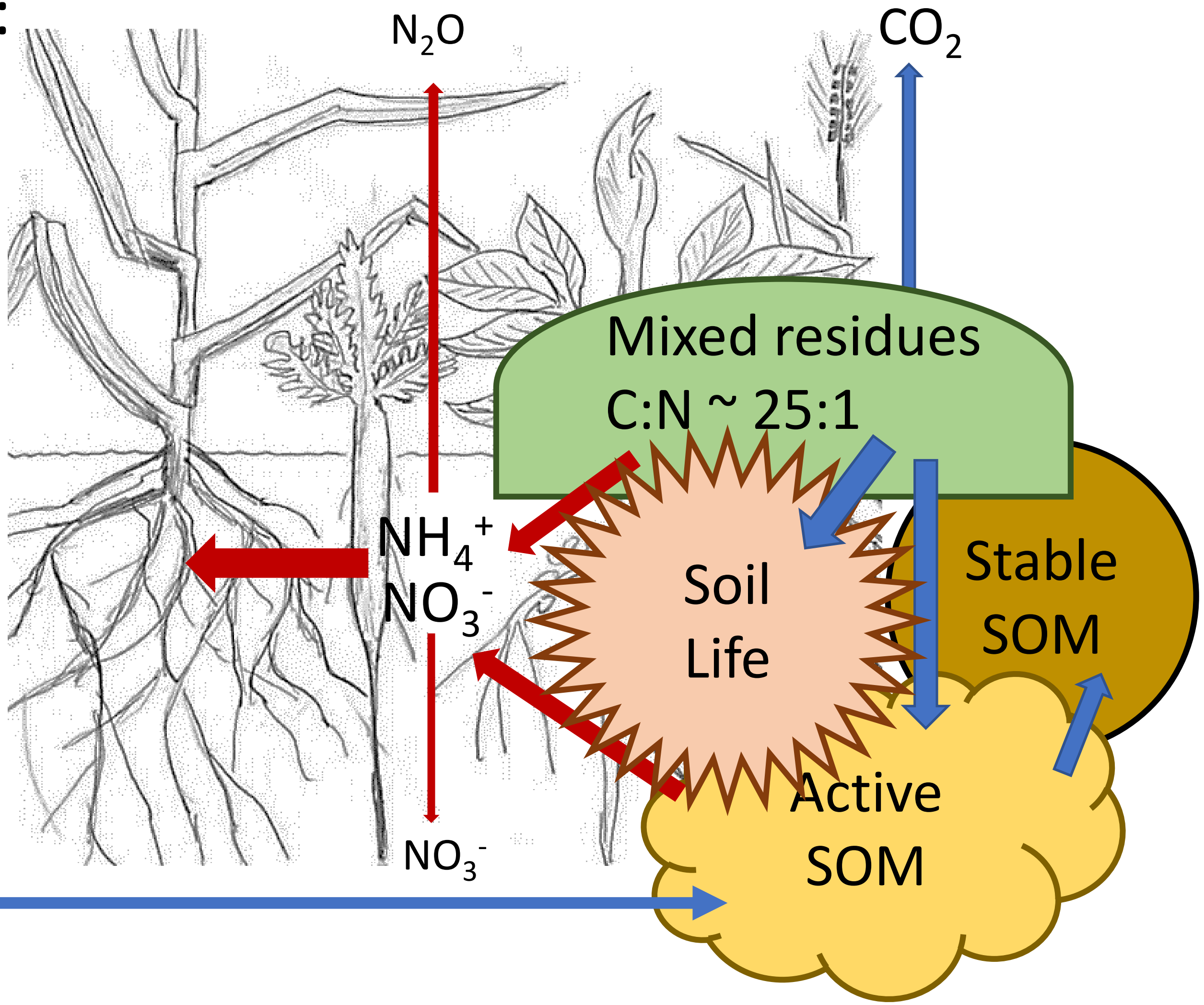
Soil Microbes Need a Balanced Diet to Do their Job

Carbon-to-nitrogen (C:N) ratio

Mixed inputs, moderate C:N (25-30:1):

- Provide slow-release N.
- Support microbial growth.
- Build SOM, and soil organic N reserves.
- Mitigate N losses.

Finished compost (C:N ~ 15-20:1) builds the active SOM pool and nutrient reserves.

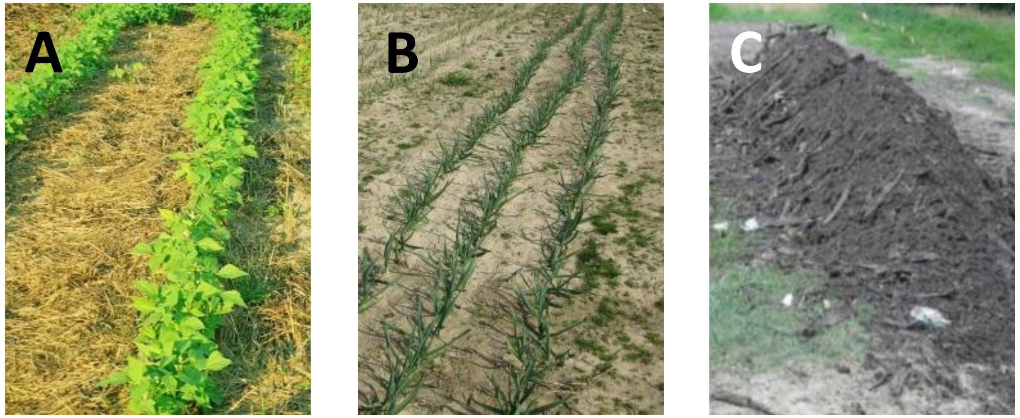


Building an Organic Nutrient Management Roadmap

Research findings and applying the 4 Rs of nutrient management to organic systems

Organic Advantages … and Challenges

- Best organic practices enhance soil capacity to nourish crops.
- Non-use of synthetics protects soil life.
- Crop diversity builds soil diversity.



Nitrogen

- "How much do I really need?"
- Delayed mineralization (A).
- Restoring depleted soils (B).

Phosphorus

- P buildup from compost (C).

The First R: Right Source

- *Organic (biological) or soluble (mineral / chemical)?*
- *Grown in place (cover crops, rotations) or applied (amendments)?*
- *On-farm or imported?*

Organic or soluble: *what does the research show?*

Comparison	Basis	Outcome
Organic *vs* soluble N	Multiple meta-analyses	Organic N enhanced SOM, reduced N leaching 43% and NH_3 52%, N_2O up 25%. Yields 5% lower.
Organic *vs* soluble NPK	Global meta-analysis	Organic fertilizer doubled biomass of microbes and bacteria- and fungal-grazing nematodes.
Organic system *vs* conventional.	Studies in NY, NC, SC, GA, VA	Organically managed soils showed 35-100% higher potential to mineralize N from SOM.
Organic *vs* soluble NPK	Two recent studies	Organic supported more diverse microbiome with improved N and P cycling, fewer pathogens

See Presentation Notes for references

Three Organic Nutrient Sourcing Strategies

Grown in place:

- Legume cover crops for N, mycorrhizal crops for P, etc.
- Deep-rooted crops to retrieve subsoil nutrients.

On-farm cycling:

- Return all on-farm residues to the soil.
- Minimize off-farm inputs.
- Integrate crop and livestock production.

Off-farm:

- Use society's organic "waste" to feed crops and soil.
- Rebuild fertility and sustain yield during transition.

Cover Crops: a Vital Organic Nutrient Management Tool

Cover crops:

- Build and protect soil health.
- Feed soil life.
- Fix N (legumes).
- Retain soluble N, protect water quality.
- Retrieve nutrients from subsoil.
- Add plant-available P (mycorrhizal species, buckwheat) and K (grasses) when needed.
- Never aggravate P or K excesses.

Above: pearl millet, vetch, buckwheat
Left: mix of mustard, winter peas, barley, and oats.

On-farm Nutrient Sourcing
Elmwood Stock Farm, Georgetown, KY

- 800-member CSA – meat, poultry, eggs, vegetables.
- 350 acres in permanent pasture (A).
- 200 acres alternate 3 years vegetables or grains with cover crops and 5 years pasture with multispecies rotational grazing (B, C).
- Only edible portion of vegetables, meat, and eggs sold; all grain fed on farm and all residues returned to the soil.
- Annual off-farm inputs:
    - < 1 lb/ac N and P_2O_5 and 10 lb K2O/ac on 200 cropland acres.
    - Salt and mineral-seaweed feed supplements for livestock.
- Outcomes:
    - Pasture phase restores cropland SOM and microbiome.
    - Farm sustains productivity and profitability

Off-Farm Organic Nutrient Sources

Compost or poultry litter?

Puyallup, WA (maritime) organic vegetable rotations receiving:

Compost

C:N ~ 20

or

Fertilizer,

C:N ~ 7

← Same total N →

After 11 years, soil receiving compost showed:

- 43% more total SOM than with poultry litter.
- 62% higher active SOM.
- 30% higher microbial activity.
- A soil microbiome with greater capacity to:
  - Mineralize N from SOM to meet crop need.
  - Immobilize excess N and limit N_2O emissions.
- Better soil structure and water infiltration.
- Yields comparable with poultry litter plots.

Bhowmik et al., 2016 and 2017.

Nutrient Source and NPK Balance: Vegetable Crops

Crop	Yield (tons/ac)[1]	Nutrient removal, lb/ac[1]		
		N	P_2O_5	K_2O
Cabbage	20	125	30	125
Onions	20	110	20	110
Potatoes	15	90	45	160
Spinach	10	100	25	100
Tomatoes	30	110	48	180
Compost (1-1-1), 5 t/ac adds:		100	100	100
Poultry litter (5-4-3), 1 t/ac adds:		100	80	60




[1] University of Massachusetts, 2023.

Nutrient Source and NPK Balance: Field Crops

Crop	Yield[1]	Nutrient removal, lb/ac[1] N	P_2O_5	K_2O
Corn, grain	180 bu/ac	162	67	49
Soybean, grain	50 bu/ac	190[2]	40	70
Wheat, grain	80 bu/ac	96	50	30
Grass hay	5 t/ac	170	52	250
Corn, silage	20 t/ac (65% moist.)	189	61	142
Compost (1-1-1), 5 t/ac adds:		100	100	100
Poultry litter (5-4-3), 1 t/ac adds:		100	80	60



Doug Crabtree

[1] Land Grant University sources (see presentation notes). [2] Mostly provided by *Bradyrhizobium* symbiosis.

Mix and Match Sources to Get the Balance Right

Obtain nutrient analysis for soil and amendments.

- On soil testing low in P, use compost or manure to build P.
- On soil testing optimum (“high”) P, limit compost or manure to just replenish P removed in harvest.
- On soil with surplus (“very high”) P, avoid manure, use a plant-based compost sparingly.

Supplement N as needed with low-P sources:

- Legume cover crops.
- Feather meal (13-0-0), blood meal (12-0-0).
- Chilean nitrate (16-0-0) *limit: 20% of total crop N uptake.*

Rotate vegetables with grains and forages to balance nutrient demands.

The Second R: Right Rate

- *How much NPK do I really need?*
- *Economic Optimum Nitrogen Rate (EONR)*
  - *= f (yield response, fertilizer price, value of resource stewardship).*
- *Yield response = f (soil heath, management history)*
  - *Credit N mineralization from SOM as well as manure, cover crops*
- *Surplus soluble N reduces soil N mineralization capacity, threatens water quality, and increases N2O emissions.*

Total versus Available N

- Compost N availability 10 – 25% → need 20 – 50 t/ac for a 1% N compost (400 – 1,000 lb/ac total N) to provide 100 lb N to the crop?
  - Rapid buildup of P and other nutrient excesses.
  - Economically infeasible at multi-acre scale.
- Manure, legumes credited at 50% of total N → Often tilled in together to support organic grain production.
  - N_2O emissions may spike (Baas et al., 2015; Kemanian, 2021).
- Comparison of organic *vs* soluble N at equivalent N rates (Wei et al., 2021):
  - Based on *total* N, organic maintained yield, reduced N losses 30%.
  - Based on *soluble* N increased yield 6%, increased N losses 21%.

EONR for Field Crops can Drop to Zero in Healthy Soils!

- Soil test biological activity (STBA) (3-day respiration) is strongly correlated with all soil health pramaeters.
- STBA is a reliable indicator of how well the soil can supply N to crops.
- In soils with a wide range of STBA values in VA, NC, SC, and GA, the Economic Optimum Nitrogen Rate (EONR) was *zero* in:
  - 21 of 57 forage fescue trials.
  - 6 of 12 corn silage trials.
  - 12 of 36 corn grain trials.
- In a Clemson, SC soil under long term organic management, summer squash and tomato grown after rye + clover yielded well with no response to added N.

Franzluebbers, 2018a, 2018b; Franzluebbers et al., 2018; Robb & Zehnder, 2016

EONR Soars Above 200 lb/ac for Organic Broccoli!

- In CA and WA, organic broccoli responded dramatically to applied N with an EONR of 215 lb/ac, a rate which also:
  - Leached up to 180 lb N/ac.
  - Emitted 11 - 27 lb N_2O-N/ac, equivalent to oxidizing 1,400 – 3,400 lb SOC/ac.
- Broccoli harvest removed only 25 – 50% of applied N. The remainder leached as residues decomposed.
- Possible reasons for low N efficiency:
  - Mediterranean climate, dry growing season, winter rain.
  - Broadcast N application to crop with small root system.
  - Low N use efficiency in modern broccoli cultivars.

At Virginia Tech, organic broccoli looked heathy on cover crop N alone yet yields responded to additional N up to 150 lb/ac.

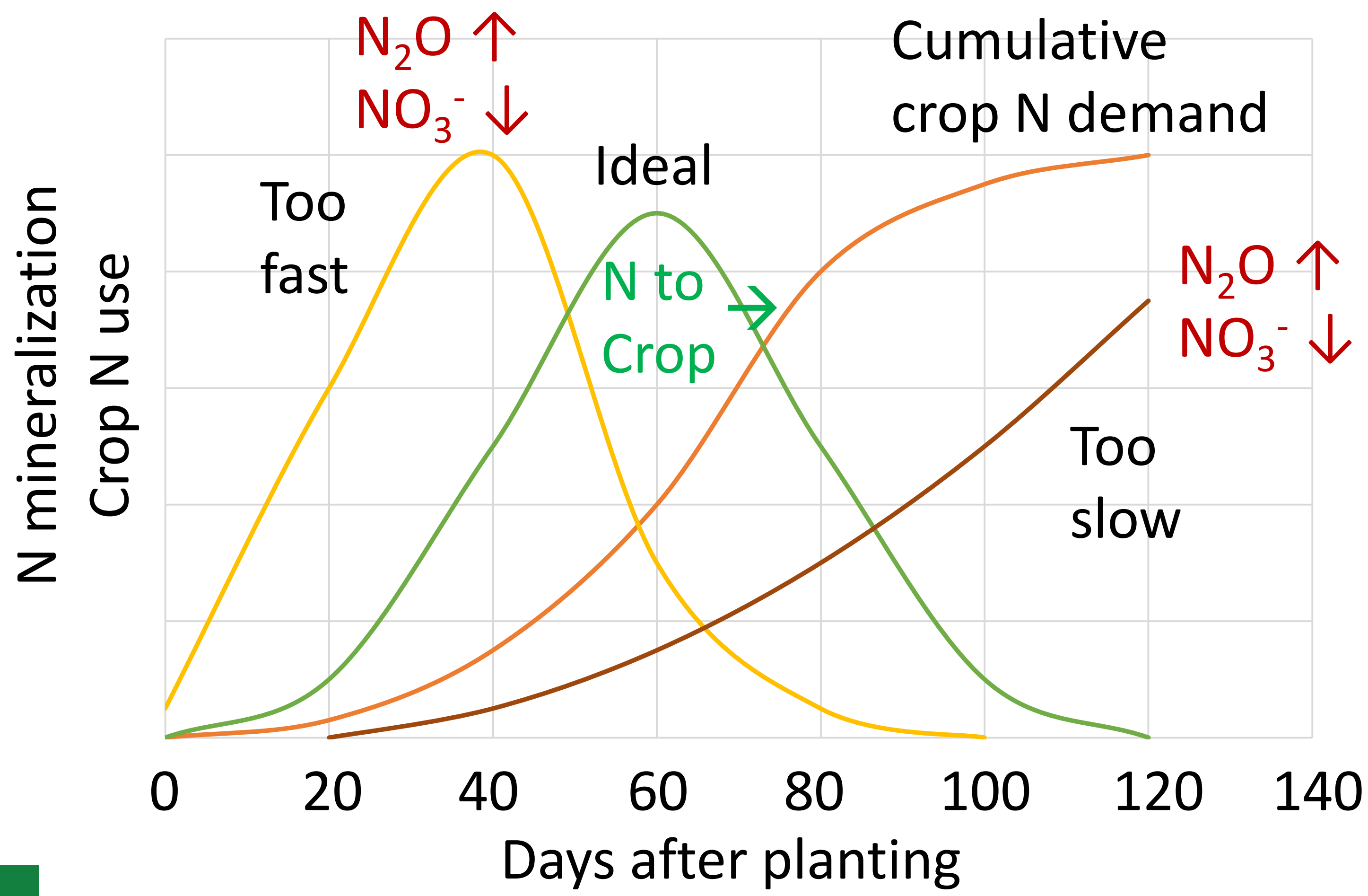
The Third R: Right Timing

- *Precision timing for organic N fertilizer is difficult.*
- *When timing is off, both crop N deficiency and N losses to groundwater, surface water, or atmosphere can occur in the same season.*
- *Timing is less critical for most other nutrients, which can remain in the soil until crops need them.*

Synchronizing N Release with Crop N Demand

When organic N is mineralized too early or too late in the season:

- Crop is N deficient.
- Nitrate leaches.
- Soil emits N_2O during wet conditions.
- Farmers do not recover the costs of organic fertilizer.



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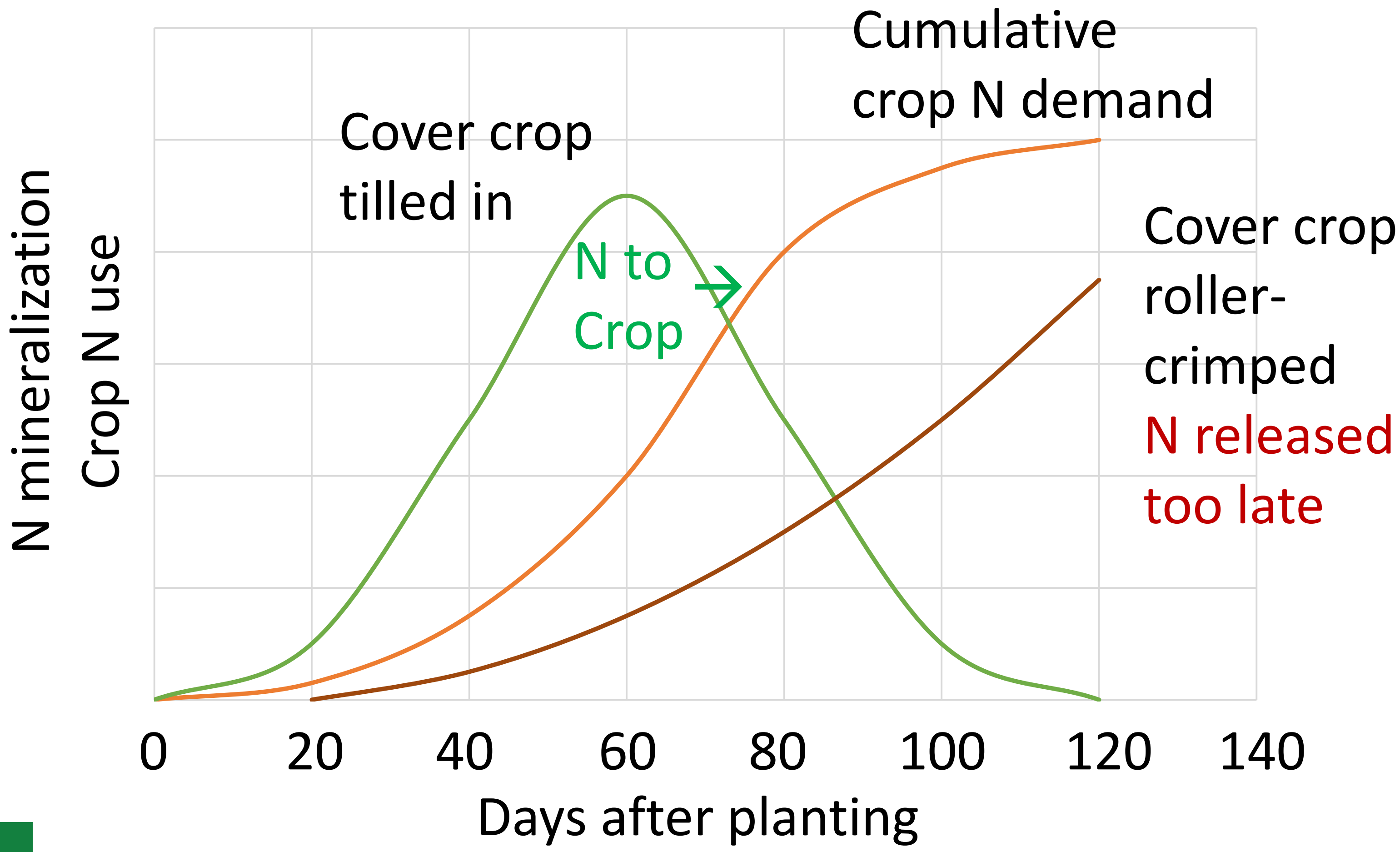
Upper Midwest Mollisol silt loam



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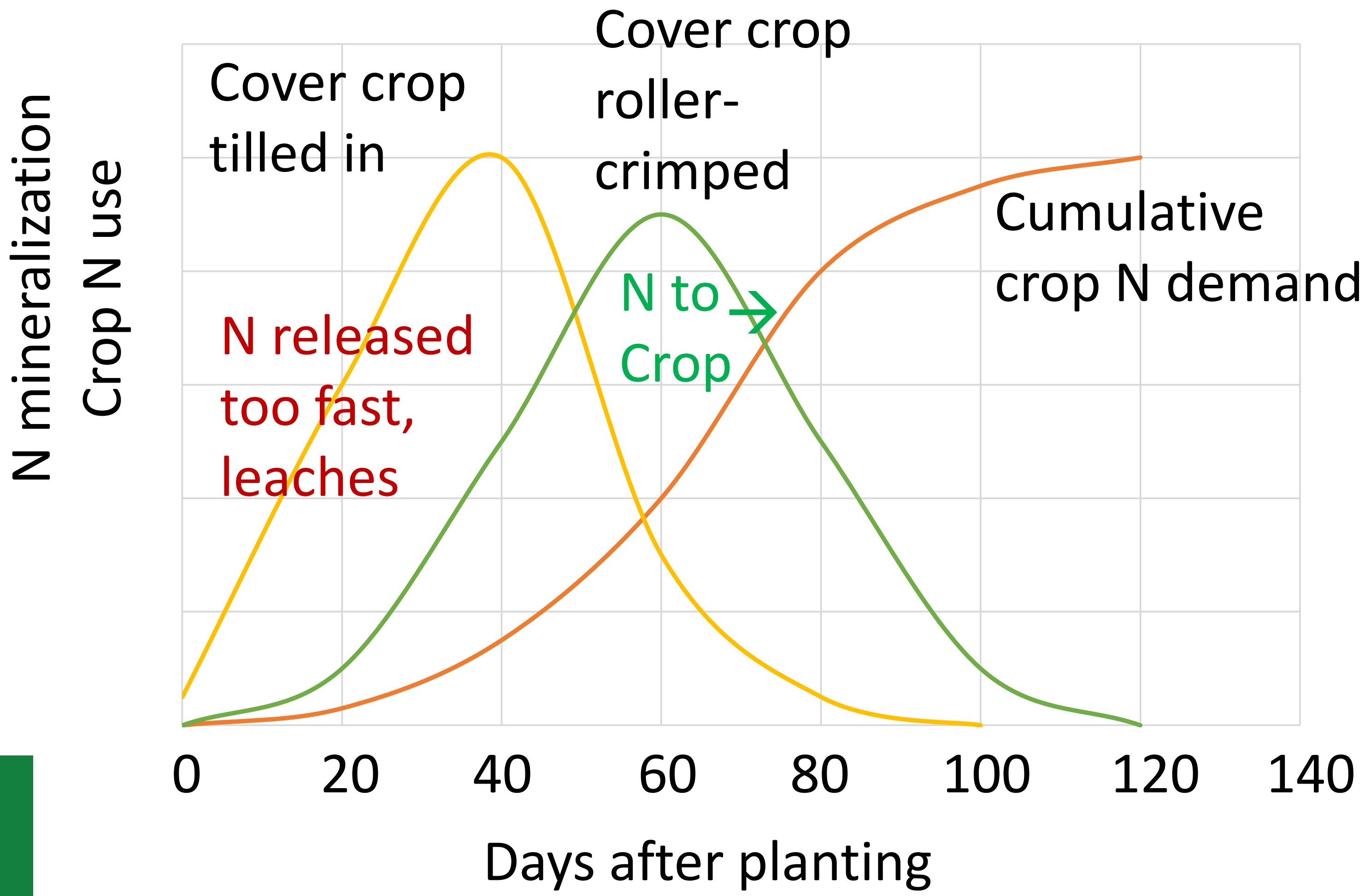
Southeast Coastal Plain, Ultisol, loamy sand



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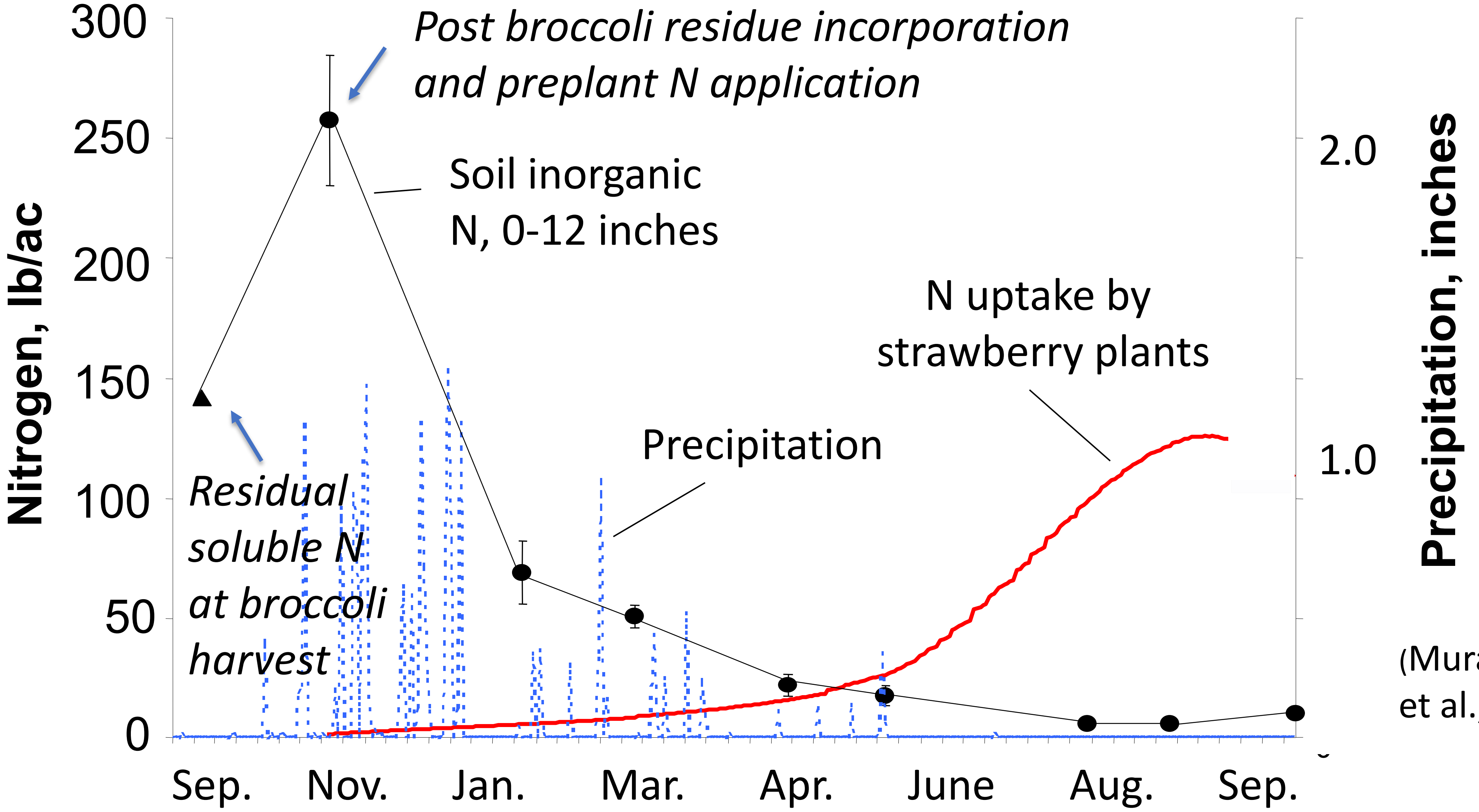
Asynchrony of N supply and N demand in an organic strawberry field in the Northern region, CA



(Muramoto et al., 2004)

Winter Cover Crop Recovers Leftover N

Spring lettuce

Fall broccoli

Winter fallow or cover crop

Cover crop N recovery → higher lettuce yield

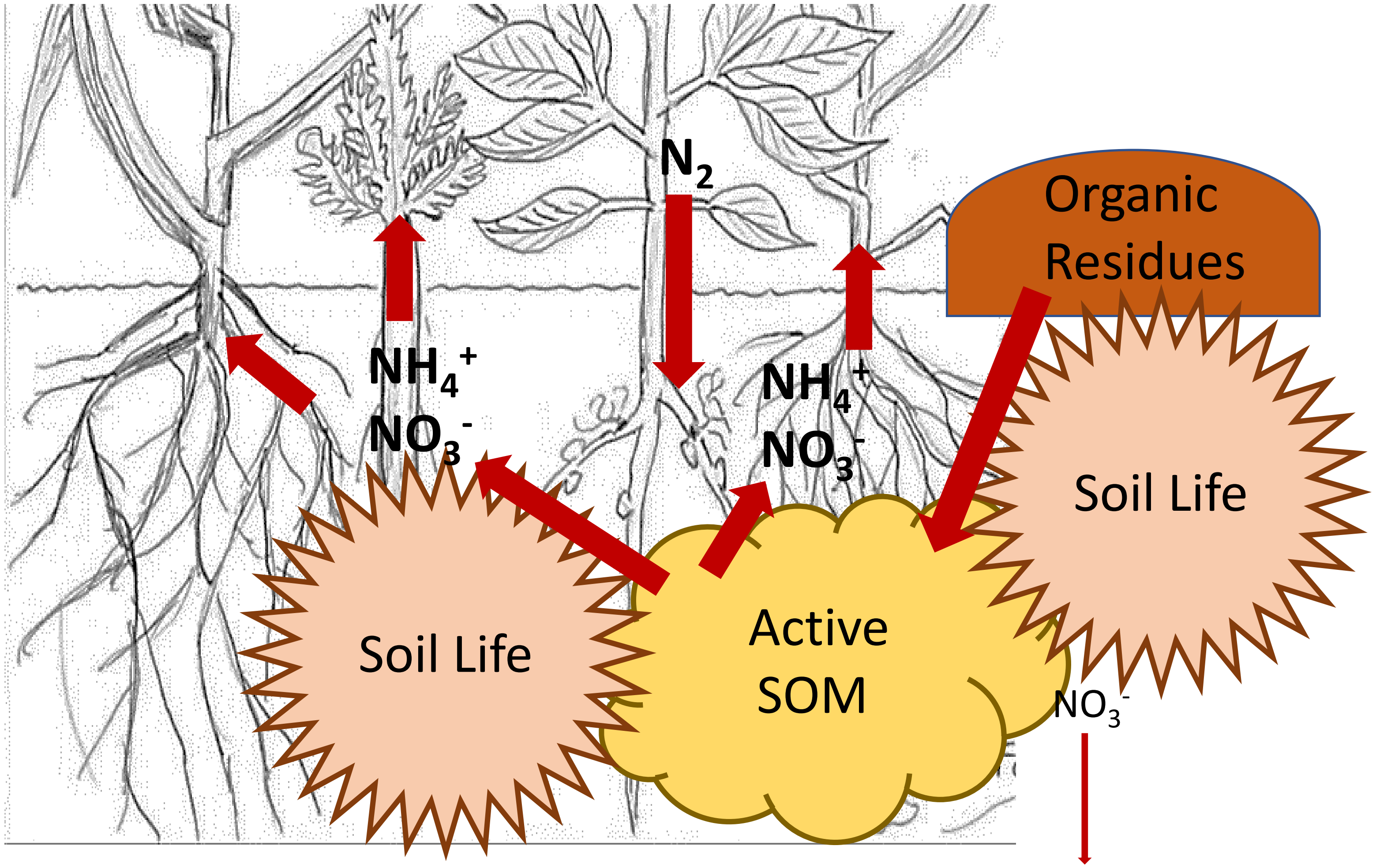
Eric Brennan, USDA ARS, https://www.youtube.com/watch?v=JurC4pJ7Lb4

The fourth R: Right Placement

Deliver nutrients where crops can utilize them most efficiently:

- *Band application*
- *In-row drip fertigation*
- *Promote rhizosphere nutrient cycling*

Delivering N Directly to the Roots



What if we can manage the soil microbiome to mineralize N right in the rhizosphere for more efficient plant uptake and assimilation, thus minimizing losses?

N Cycling Patterns in Organic Tomato in California

- **N deficient** – low soil soluble N, low yield.
  - Low SOM and low microbial activity.
  - Poorly timed N release from fall-applied manure.
- **N saturated** – high soluble N, high yield, N leaching risk.
  - High rates of concentrated organic N.
  - Moderate SOM, high microbial activity.
- **Tightly coupled N cycling** – low soluble N, high yield.
  - Most of N provided as finished compost (C:N 15-18).
  - Small amounts of concentrated N in row.
  - High SOM and microbial activity.
  - N mineralization and rapid uptake in root zone.

Bowles et al., 2015

A little liquid N (fish emulsion or Chilean nitrate) via in-row drip provides a boost.

The fifth R: Right Crop Genetics

Crop cultivars bred and developed in and for organic production systems:

- *Nutrient efficiency*
- *Deep, extensive root systems*
- *Enhanced partnership with beneficial soil organisms*

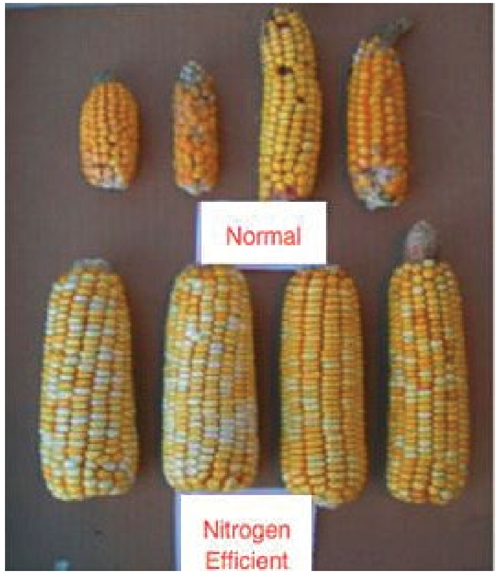
"Cultivars bred under conventional management – aided by synthetic fertilizer, herbicides and pesticides – will likely not be as productive under organic management."

Hultengren, et al., 2016. Organic Seed Alliance, http://www.seedalliance.org/.

Nitrogen-efficient Field Corn Cultivars

- N-efficient land races (Mexico, Central America) crossed with modern hybrids.
- Require half as much N as standard hybrids; thrive on organic N sources.
- N-fixing bacteria in the crop root zone meet up to 40% of crop N need.
- Similar yield to standard hybrids with higher protein % and quality.
- Maintain yield on poor soils.
- Large root system enhances drought tolerance and nutrient uptake.

Mandaamin Institute



On low-fertility tropical soil, a Corn Belt hybrid suffers N deficiency and forms stunted ears, while Mandaamin's N-efficient corn maintains vigor and produces large, full ears.

Mandaamin Institute, Elkhorn, WI. http://www.mandaamin.org/

Varietal nutrient efficiency in other crops

- Land races of grain sorghum host mycorrhizal fungi more effectively than modern cultivars and sustain yields on low-fertility soils.
- Both legume and their *Rhizobium* microbial symbionts show genetic variability that can be utilized to breed for enhanced N fixation.
- Cultivars of carrot, pepper, corn, other grains, and legume show genetic variation in efficacy of mycorrhizal symbioses, indicating an opportunity to breed for mycorrhizal-enhanced nutrient efficiency.
- *Can broccoli be bred and selected for N use efficiency so that we can enjoy this nutritious vegetable without such a huge* N_2O *footprint?*

Organic Nutrient Management: General Tips

- Build and maintain healthy living soil:
  - Maximize living cover, living roots, and biodiversity.
  - Stack practices: rotation + cover crop + compost + reduced till.
  - Avoid N and P surpluses.
  - Balance low and high C:N organic inputs.
  - Integrate crops and livestock.
- Do a soil test … and don’t take it *too* seriously. Supplement with:
  - Direct observation of soil and crop condition.
  - *Foliar analysis* – what is the *crop’s* nutritional status?
  - Soil health test – STBA, permanganate oxidizable soil C, Cornell Comprehensive Assessment of Soil Health (CASH) or other.

Organic Nutrient Management: Nitrogen

- Meet the majority of crop N requirement from slow-release compost or legume-grass cover crop mixes.
- Base application rates on total N content, not “available N.”
- Apply concentrated organic N in small doses during peak crop demand via in-row drip fertigation or band applied solid fertilizer.
- Use adaptive N management:
    - Do side-by-side trials with different rates of N (including zero).
    - As soil health improves, reduce or phase-out concentrated N inputs.
- Plant N-scavenging cover crops after harvest, or relay-interplant:
    - Especially after heavily fertilized crops and before rainy seasons.

Organic Nutrient Management: P and Other Nutrients

- Use nutrient budgets, maintain optima, and draw down surpluses.
  - If soil test P is low, use compost generously. Poultry litter is OK.
  - If soil test P is high, limit compost and manure to P maintenance levels ~30-50 lb P_2O_5/ac. Use legumes or feather meal for N.
  - If soil test P is very high, avoid manure and use compost sparingly.
- Base K applications on actual need, not soil test alone
  - Crop K deficiency or heavy K drawdown (hay, intensive vegetables).
  - Grasses and deep-rooted crops can bring subsoil K to the surface.
  - K sources include K_2SO_4, K-mag, and organic mulches such as hay.
- Attend to all nutrients, not just NPK.

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