Build Soil, Sustain Yields, and Slash Costs

How to minimize fertilizer dependency in crop production

A workshop at the National Center for Appropriate Technology virtual conference

Growing Hope: Practical Tools for our Changing Climate
March 2, 2023 – 12:00 noon

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Presentation Notes

Slides 2-3– *How did we get here? – 20th Century nutrient management*

With the development of the Haber-Bosch process for converting inert atmospheric nitrogen (N_2) into ammonia (NH_3) and other industrial processes for converting insoluble phosphorus (P) and potassium (K) minerals into soluble forms, 20th Century farmers found a "quick fix" for declining soil fertility and crop yield, which were attributed to insufficient N, P, and K.

During the 1950s-1970s, standard soil test recommendations for NPK applications were based on estimates of crop nutrient uptake, yield goals, and yield response trials conducted on research station soils that had become depleted from years or decades of conventional management with excessive tillage and inadequate return of organic residues to sustain soil life. The community of soil life was mostly overlooked or seen as competing with the crop for nitrogen and other nutrients, tying-up soluble soil N as it decomposes organic residues. Recommended NPK rates were increased to account for anticipated losses through runoff, leaching, denitrification, microbial immobilization, and mineral-fixation of phosphorus. In the past era of cheap fertilizer, this added amount over and above anticipated crop utilization was viewed as a kind of "insurance" against crop nutrient deficiency and yield losses.

The reason to dwell briefly on the past is that this paradigm still informs 21st century fertilizer applications to a significant degree. On biologically active soils such as those that develop over time under organic management, the assumptions underlying this approach to identifying the right rates and forms of nutrients are out of date.

Slides 4-7 – *Effects of synthetic NPK: the Morrow Plots at U Illinois and other trials*

University of Illinois's Morrow Plots, the nation's longest-standing farming systems trials provided a unique opportunity for researchers to review the impacts of regular use of synthetic nitrogen (N), phosphorus (P), and potassium (K) fertilizer on soil organic carbon (SOC), total soil N (which is mostly various forms of organic N), and other aspects of soil health (Khan et al., 2007, 2013; Mulvaney et al., 2009).

The Morrow Plots were established in 1876. "At first, record keeping was not of the highest caliber, but by the turn of the 20th century it was clear that crop rotation was a useful component in preventing the depletion of soil quality" (Wikipedia). The six 0.1 acre plots currently located on the U. Illinois campus were established in 1901, and include three cropping systems:

- Continuous corn
- Corn – soybean since 1967 (corn-oats during 1901-66)
- Corn – oats – alfalfa since 1953 (corn-oats-clover during 1901-1952)

Khan et al (2007) and Mulvaney et al (2009) studied three fertility treatments within each of these rotations:

- Unamended
- NPK: Unamended until 1954, then 200 lb N/ac on corn; triple superphosphate and KCl applied as needed to maintain Bray-1 P at 50 lb/ac and exchangeable K at 300 lb/ac
- High NPK: Manure, rock phosphate, and limestone until 1966, then, 300 lb N/ac on corn; triple superphosphate and KCl as needed to maintain Bray-1 P at 100 lb/ac and exchangeable K at 500 lb/ac.

Despite the tremendous increases in crop yield and associated residue production (returning more organic carbon to the soil per year), the use of NPK fertilizer did not enhance SOC, total soil N reserves, or the capacity of the soil microbiome to mineralize (release) plant-available N from soil organic N. Furthermore, the higher rate of fertilization depleted SOC and soil N, especially in the subsurface parts of the soil horizon (6-to-18-inch depth).

Another surprise was the lack of correlation between K inputs and exchangeable soil K (this is the proportion of soil K that is measured and reported in a standard soil test). Surprisingly, the unamended Morrow plots from which K was removed in harvests had as high or higher exchangeable K than the fertilized plots. Other studies of soil K dynamics and crop response to KCl showed that exchangeable K is a poor indicator of actual crop K need, and that many crops, especially grasses and deep rooted crops, can access the "nonexchangeable" mineral-fixed K reserves, which are vast in most soil types (Khan et al., 2013).

The authors also noted that:

- Isotope tracer studies have shown that most of the N taken up by corn and other crops comes from soil N mineralization, and not from applied fertilizer.
- Nitrate-N appears less harmful to SOC and soil N cycling than the urea used in the Morrow trials and other ammonium-N sources, provided that the nitrate is applied at moderate rates at the time of maximum crop N demand.
- A lot of the harm to soil and crop quality from KCl fertilizer is related to the chloride anion. When K is needed (gives a positive crop response), K_2SO_4 is much safer.
- Overapplication of K from any source also directly affects soil physico-chemical properties, as the abundant K becomes fixed within clay minerals a process that causes the clay mineral structure to "collapse," thereby reducing both cation exchange capacity (CEC) and water-holding capacity.

Of the 24% of studies that showed yield responses to K, most "occurred on coarse-textured, organic, or highly weathered soils inherently low in K-supplying power (231 site-years); when the above-ground residues were removed (191 site-years); with crops having a shallow or low-density rooting system (62 site-years); and/or when subsoil rooting was restricted (12 site-years)" (Khan et al., 2013). Forage harvests can remove 200 lb K/ac or more annually, and long-term haying with no nutrient inputs can deplete plant-available soil K. Conversely, grain harvests remove relatively little K unless residues are also removed from the field. Residue removal greatly accelerates the loss of soil organic matter (SOM) and soil N driven by soluble fertilizers.

Although sandy soils can be low in K reserves, the sandy Ultisols of the southeastern US coastal plain have large K reserves, especially in the clay-enriched subsoil or B horizon.

Slide 8 – *20th Century organic farming: organic matter for fertility*

The organic farming movement of the early-mid 20th Century raised concerns that the new fertilizer technology could not sustain the health of the land, crops, livestock, or people because it bypasses the natural soil-based processes of recycling organic matter and plant nutrients from plant and animal residues to support new plant life and agricultural production.

Right from the start of the movement, organic farmers and scientists understood that the soil is a living ecosystem that needs to be tended as carefully as a livestock farmer cares for their animals. They adopted a suite of "feed the soil" strategies that simulate natural processes and reflect the four principles of soil health management adopted by NRCS in the early 2000s. On many organic farms, crop and livestock production were integrated to improve nutrient and resource cycling, create a more "whole" farm ecosystem, and reduce reliance on off-farm inputs. Synthetic fertilizers and pesticides were excluded to protect soil micro-organisms and earthworms, whose importance to soil fertility they understood.

Slides 9-10 – *21st Century nutrient management and soil test interpretation*

By the end of the 20th Century, some aspects of the organic farming paradigm began to gain traction among agricultural professionals. Most land grant university and other mainstream agricultural professionals now recognize the importance of beneficial soil organisms, soil organic matter (SOM) and soil health to long term sustainability of agricultural production and considered biologically derived as well as soluble nutrient sources in making nutrient management recommendations. The role of soil life shifted from mere competitor for nutrients to mediator of a two-way process of immobilization (which can protect water quality and conserve the nutrients for future use as well as reducing short term availability) and mineralization (releasing soluble nutrients to the current crop or other vegetation).

Note that heavy applications of fertilizer P and K drive the processes in the direction of mineral-fixation; thus, efforts to maintain high soil test P and K goals such as in the high NPK treatment in the Morrow Plots can lead to unnecessarily large and costly applications of these nutrients.

Standard nutrient recommendations now credit manure applications, cover crops, crop residues, and sometimes estimates of N mineralization from SOM. Application of the NRCS "4Rs" – right source, right rate, right timing, and right placement – can leads to more conservative application rates, targeted timing and placement, and a wider range of fast and slow-release nutrient sources, thus reducing losses and environmental harms.

Soil test reports rate the results for P, K, and other nutrients on a scale of very low (VL, critically limiting and highly likely that providing the nutrient will substantially improve yield), low (L, crop yield response to applied nutrient is likely), medium (M, a little below optimum, 50% chance that crop yield will respond), optimum or high (H, crop response unlikely, about 10%), or very high (VH, indicating ample, surplus, or excessive nutrient levels). Soil test P in the very high range threatens surface water quality and suppresses the activity of arbuscular mycorrhizal fungi that play important roles in soil and crop health. Any nutrient in the "very high" range could contribute to nutrient imbalances, reduced crop quality, or in some cases reduced yield, especially if nutrient levels are well above the threshold for a VH rating.

Standard soil tests do not include nitrogen (N) because the levels of soluble N (nitrate and ammonium) vary so much from day to day depending on crop demand, N mineralization by soil life, and rainfalls (leaching and denitrification losses) that it is difficult to interpret to make recommendations. Thus, N recommendations are generally based on the crop being grown and yield goals, with total N input based on estimated total crop N uptake (harvested part plus residue) rather than harvest removal. Credits for expected N release from legume cover crops, crop residues, manure, and other organic amendments are subtracted from the total N recommendation to determine fertilizer N application. Some labs are now including a credit from N mineralization from SOM, with estimates based on soil texture and % total SOM.

Slide 11 - *Soil test recommendations for "high" soil P and K, and crop nutrient removals*

When P and K levels are in the optimum or high range, it may not make economic sense to apply the nutrient at all since the crop will not likely respond with increased yield or quality. The only reason to apply nutrients would be to maintain the optimum soil nutrient levels by replenishing nutrients removed in harvest. Yet, the Virginia Tech soils lab and private labs in Virginia and Tennessee recommend "maintenance" P applications level that exceed estimated harvest removals, and even recommend maintenance P and K for a "very high" soil test value.

Most crop harvests remove much larger amounts of N and K than P. Surplus P often accumulates in soil under either conventional or organic management and would be expected to do so if farmers follow the recommendations shown in this slide.

Diversified crop rotations and crop-livestock integration can contribute to nutrient use efficiency and reduce input costs through complementary nutrient demands and improved nutrient cycling. For example, vegetable harvests remove a lot of K and little P, while grain harvests remove only a fraction of the K taken up by the growing crop, and the majority of K is returned to the soil in residues. Hay or silage harvests remove large amounts of N and K, while grazing returns at least half of the nutrients consumed as the animals leave manure and urine in the pasture. Nonlegume harvests remove 50-200 lb N/ac while legume production crops can fix much of their own N and legume cover and forages replenish soil organic N.

Diversified crop rotations or mixed species cover crops, forages, or pasture also support greater microbial functional diversity, since legumes, grasses, crucifers, and other plant families support different and often complementary root microbiomes. Enhancing biodiversity is one of the four NRCS principles of soil health management, yet a large percentage of US cropland remains in low-diversity rotations like corn-soy or wheat-fallow, which can increase crop dependence on applied nutrients.

Sources for soil test recommendations cited on slide 11:

- Virginia Tech, 2018, Mid-Atlantic Commercial Vegetable Production Recommendations. https://www.soiltest.vt.edu/Files/handbooks.html.
- Private lab recommendations from soil test reports provided by Waypoint labs in Richmond, VA, Memphis, TN, and Wilson, NC. There was significant variation among labs in whether and how much P and K were recommended for a "high" or "very high" soil test report, with highest maintenance recommendations from the Memphis lab.

Sources for crop harvest NPK removal data on slide 11:

- Nutrient removal rates per bushel for grain harvests from George Silva, 2017, Michigan State University Extension, https://www.canr.msu.edu/news/nutrient_removal_rates_by_grain_crops.
- Nutrient removal rates for grass hay from University of California at Davis https://manuremanagement.ucdavis.edu/files/134365.pdf.
- Vegetable nutrient removals from University of Massachusetts, 2023, New England Vegetable Management Guide, Nutrient Removal from the Soil https://nevegetable.org/cultural-practices/removal-nutrients-soil.

Slide 12 – *Current LGU recommendations for P and K*

When I (presenter) went online to explore other Land Grant University (LGU) guidelines for P and K, evidence for real progress toward a more rational and sustainable approach emerged. Soil testing handbooks from several LGU now recommend one of the following for P and K when the soil tests "high" in these nutrients:

- Zero P and K
- Zero P or K, with regular soil testing to monitor trends, add P and K in future if needed.
- Only starter P and K to help seedling get established (U Maine, not shown in Slide 13).
- Maintenance application – replenishing P and K expected to be removed in harvest.
- Zero P or K for a "very high" soil test result – draw down to optimum through harvests.

Information on Slide 12 was obtained from:

- U Missouri - http://aes.missouri.edu/pfcs/soiltest.pdf.
- U Maine - https://umaine.edu/soiltestinglab/wp-content/uploads/sites/227/2016/07/handbook.pdf.

- U Georgia - http://aesl.ces.uga.edu/publications/soil/sthandbook.pdf.
- Michigan State U - https://www.canr.msu.edu/foodsystems/uploads/files/soil_test_interpretation.pdf.
- Iowa State U - https://www.agronext.iastate.edu/soilfertility/info/PM1688.pdf.
- Pennsylvania State U - https://agsci.psu.edu/aasl/soil-testing/fertility/handbooks/agronomic.
- Oregon State U - https://catalog.extension.oregonstate.edu/ec1478.

Slide 13 – *Grain crops may need little fertilizer on healthy soils*

Fertilizer trials were conducted over a five-year period with an organic corn-soy-wheat rotation with legume-cereal cover crops on an Orangeburg loamy sand in South Carolina (Kloot, 2017, 2018). The cover crops attained high biomass and substantial nutrient accumulations: 9000 lb dry matter, 110 lb N, 27 lb P, and 200 lbK per acre, which allowed the crops to attain full yields on half-rate N and no P or K. Furthermore, soil test P and K levels showed little or no decline during the five years. Many agricultural soils have tremendous subsoil K reserves that grass cover crop roots can access.

Kloot cited 13 on-farm trials representing a wide diversity of soil types and climates in North Carolina, North Dakota, Illinois, and Ohio that gave similar results. Rotations with healthy soils and high biomass cover crops maintain high grain yields on greatly reduced fertilizer inputs.

Slide 14 – *Tiny but mighty: soil life drives all soil functions*

Research over the past 35 year has documented the central role that the soil microbiome and larger organisms play in all aspects of soil function, and especially nutrient cycling and crop nutrition. Other functions – water storage, structure, disease suppression – support crop nutrition, as roots require adequate moisture and oxygen to absorb nutrients, and roots damaged by pest nematodes or microbial pathogens cannot absorb nutrients effectively.

Slide 15 - *Nutrients for carbon: an ancient partnership*

In natural plant communities and agroecological farming, plant nutrition depends on an ancient partnership between roots and beneficial microbes. Paleontological now know that the first land plants co-evolved with mycorrhizal symbionts some 450 million years ago, a relationship that proved essential to their survival on the prehistoric world's primitive soils. This partnership began the process of converting "dirt" (ground-up rocks and minerals) into living soil.

Plants "donate" 10 – 40% of their photosynthetic product to the soil life in the form of root exudates rich in sugars, amino acids, and other soluble organic compounds. In return, beneficial soil organisms in the rhizosphere (root zone, within 1/25 inch of the root surface) and microbial endophytes (living within roots) help plants absorb N, P, other nutrients, and moisture, and protect the plant from pathogens. Arbuscular mycorrhizal fungi (AMF) grow into the root tissue and out into the soil, expanding the effective root system severalfold, unlocking P and micronutrients for crop utilization, and helping to stabilize SOC. When bacteria and fungi feed on root exudates they multiply (rhizosphere microbial populations are typically ten times that of the bulk soil) and initially tie up soluble N and other nutrients. Microbial grazers – protozoa and bacterial- and fungal-feeding nematodes – are drawn close to crop roots where their food source is most abundant. As they feed on the microbial abundance, they release plant nutrients right in the root zone where crops can utilize them promptly and efficiently.

These biological processes can sustain plant nutrition even when soil tests show low levels of plant-available N, P, and other nutrients in the bulk soil. This phenomenon of *tightly coupled nutrient cycling* can protect water quality and mitigate greenhouse gas emissions.

Slide 16 – *How soil microbes feed crops while sequestering carbon.*

Soil microbes consume and process virtually all organic inputs to the land, including root exudates, above- and below-ground plant residues, manure, animal remains, and organic mulch. The microbes utilize part of the residues for their life processes, releasing CO_2 through respiration, and convert the rest into microbial metabolites and microbial remains ("necromass"), which comprise active SOM (available for re-processing by soil life) and stabilized SOM (protected from further breakdown). The most stable SOM forms when microbial byproducts and necromass become adsorbed to soil clays and silt particles, forming *mineral associated organic matter* (MAOM) (Bhattacharyya et al., 2022; Grandy and Kallenbach, 2015; Kallenbach et al., 2016; Prescott et al., 2021). Note that SOM is about 50% carbon (1 ton SOM = 0.5 ton SOC); thus, practices and processes that build SOM (all of which is ultimately derived from plant photosynthesis) also remove CO_2 from the atmosphere and sequester it in the soil.

When adequately fed by living roots and their exudates (most important!), other organic residues, and a good supply of active SOM, the soil life plays a central role in carbon sequestration as well as the dynamic processing of crop residues and active SOM that underpins soil fertility and crop nutrition, especially in organic systems that do not use soluble inorganic fertilizers.

SOM can also become stabilized when it becomes integrated into the interior of soil aggregates, where is becomes less accessible to microbes and oxygen. Active SOM turns over in a few months to a couple of years. Aggregate-protected SOM may last for years to decades, and MAOM for centuries or millennia. Although SOM concentrations are greatest in the top 6 to 12 inches of the soil profile, substantial quantities of SOC become sequestered at greater depths as soluble organic matter is leached into the subsoil, deep roots release exudates, and their associated microbiome converts these resources into subsoil MAOM, which can persist for three or four times as long as topsoil MAOM (Button et al., 2022; Dynarski et al., 2020).

Slide 17 – *How to enhance the soil's capacity to sequester carbon and feed crops*

Beneficial microbes thrive in the rhizosphere when plants deliver sufficient root exudates. The first step to keep them healthy is to maintain living roots as much of the year as practical through tight crop rotations (no unplanted fallows during the growing season), prompt cover crop planting after harvest or relay interplanting into standing cash crops, perennial sod phases, or perennialized production systems such as alley cropping.

In a research review, Prescott et al (2021) identified three strategies to promote root exudation and thereby enhance carbon sequestration in the form of MAOM:

- Keep plant available N and P levels, and irrigation levels *slightly below the optimum for top growth*. These slight deficits do not inhibit photosynthesis, and thereby create a surplus of photosynthetic product that the crop sends into the root zone and the rhizosphere as root exudates. Yields are not significantly affected, quality is not affected or possibly improved, and net return may improve if lower fertilizer rates save money.
- Include legumes in the crop rotation or pasture mix. Unlike soluble N fertilizers, the N-rich root exudates from legumes provide excellent nutrition for soil microbes.
- Time rotational grazing events late in the rapid growth phase of the forages, as the rapid growth phase is also the time of greatest root exudation.

The pronounced SOM and soil N depletions at 6-18 inch depth in the Morrow Plots receiving the higher rate of NPK may have resulted in part from overstimulated top growth, which left less photosynthetic product available for root growth and root exudate production, and hence reduced formation of MAOM.

Reducing tillage intensity is important for soil health, nutrient retention, and crop nutrition. However, it does not appear essential to eliminate all tillage to maintain soil health and fertility. In a global meta-analysis, Morugán-Coronado et al. (2021) found that cropland soils managed with shallow non-inversion tillage (3-4 inches) supported nearly twice the bacterial and fungal biomass as soils under “conventional” tillage (turn-plowing 8-10 inches), whereas continuous no-till only enhanced fungal biomass about 28% and bacterial biomass not at all. They attributed the lower activity in no-till fields to surface sealing and restricted aeration, and did not speculate on the role of herbicides used in continuous no-till in limiting microbial activity.

While no-till without herbicides may be impractical for organic annual crop rotations, many organic farmers use shallow non-inversion tillage once or twice a year to incorporate cover crops, manage weeds, and prepare seedbeds. In addition, this moderate soil disturbance and aeration can promote biological N mineralization so that it is better timed for the following crop, especially in colder climates.

Slide 18 – *Biologically based nutrient management*

Organic farmers rely primarily on biological processes to meet crop nutrient needs, and supplement with NOP-allowed mineral and organic fertilizers. Concentrated organic nutrient sources may be essential for successful crop production during the first few years under organic management, after which the need diminishes as soil health improves.

As the soil life converts plant residues, manure, and other organic inputs into SOM, most of the N, P, and S in the residues become integral parts of the organic matter and are slowly released to plants through further action of soil organisms on the active fraction. K, Ca, Mg, and some micronutrients are released from residues into the soil as soluble cations. Negative charges on soil clays and stable, mineral-associated organic matter (MAOM) – the soil's cation exchange capacity (CEC) – adsorb and hold the cations in a plant-available yet not readily leachable form. In converting some of organic materials they consume into MAOM, soil organisms maintain and enhance the CEC, an important aspect of soil fertility.

In addition, soil minerals hold large nutrient reserves, particularly K), other cations, and micronutrients, which are gradually brought into plant available pools through the action of soil life and plant roots on the mineral component of the soil (biological weathering). Applying more K than needed reverses this process, as surplus K becomes mineral-fixed.

The capacity of the soil life to provide for crop nutrition through these processes is a key attribute of healthy agricultural soils. One notable aspect of soil health and plant nutrition is the depth of plant root accessible soil profile. While biological activity is slower at depths below 6 – 12 inches, plant roots and their associated microbiomes can grow as deep as five feet or more, retrieving leached nutrients (N, S, sometimes others), accessing K and other nutrients from soil mineral reserves, and forming long-lived subsoil MAOM.

Research has shown that the organic method is not "immune" to unwanted nutrient losses including runoff, leaching, and N_2O emissions; however, studies are identifying promising strategies for maximizing nutrient efficiency and minimizing losses and nutrient pollution.

Slides 19-21 – *Soil microbes need a "balanced diet" to do their job: the critical role of the carbon-to-nitrogen (C:N) ratio*.

Soil microbes thrive and become most efficient in converting residues into new microbial biomass and active and stable SOM when the residues have a weight ratio of carbon to nitrogen (C:N ratio) between 25:1 and 35:1. When the soil is fed residues with a higher C:N ratio, microbial growth is N-limited and likely constrained by scarcity of other nutrients as well. Since they must "burn off" the excess carbon, a higher proportion of the organic material is converted back into CO_2, and SOM builds only slowly (Grandy and Kallenbach, 2015).

Plants take up nitrogen mainly in the soluble nitrate and ammonium forms, thus "plant available nitrogen" or PAN = nitrate-N + ammonium N. In organic farming, crops must obtain PAN via mineralization of organic N in active soil organic matter, manure, cover crops, and other organic materials. Mineralization is a process mediated by the soil life, which thus acts as a "gatekeeper" for nitrogen cycling in organic systems. When N-poor residues are incorporated into the soil, microbes must reverse this process, utilizing soluble soil N to make up the deficit, immobilizing it in organic matter and microbial biomass and leaving less available for crop growth. Organic N fertilizer will be needed to avoid crop N deficiency and sustain yields.

When high C:N residues are left on the soil surface (e.g., straw or chipped brush mulch or roll-crimped cereal cover), N immobilization is less intense and is localized at the soil surface, and the mulch can benefit soil and crops by conserving moisture, protecting the surface from crusting, shielding soil organisms from direct sun and temperature extremes, and suppressing weed seeding emergence. Broccoli transplanted no-till into mowed cereal rye cover (slide 19 photo) suffered N deficiency because the growing rye took up available soil N.

When manure, succulent plant residues, or organic fertilizers with a C:N ratio below 15:1 are incorporated into the soil, a rapid release of PAN takes place, which can facilitate high yields in the next crop. However, soil microbes become carbon-limited and must consume some of the active SOM in order to grow and reproduce, so that a net loss of SOC can. Soil C and N dynamics may resemble that of the fertilized Morrow Plots.

Furthermore, if nitrate-N is released faster than crops can utilize it, heavy rain or irrigation can leach it below the reach of crop roots so that it is lost from the production system and may pollute groundwater. In addition, soluble soil N is subject to microbial denitrification whenever soil moisture is high and aeration is limited. Denitrified N enters the atmosphere as elemental N_2 gas (harmless other than the wasted fertilizer N) and N_2O, a powerful greenhouse gas.

In well managed organic systems, the "gatekeeper" – the soil life – can moderate though not eliminate these losses and environmental impacts. When a high biomass all-legume cover crop is tilled in, or when a long history of heavy organic inputs has built a *very* large pool of active SOM, N losses can be as great as in high-input conventional systems, and the high biological activity typical of organically managed soils can push N_2O emissions quite high if heavy rainfall occurs soon after a N-rich organic input. The challenge is to ensure that adequate N is available in the crop root zone, and at the same time minimize nitrate leaching and denitrification.

When soil microbes consume organic materials with a balanced C:N ratio, they become more efficient in generating new microbial biomass and active and stable SOM, and mineralize N at a slow, steady trickle that crops are more likely to utilize, leaving less to be lost to leaching, runoff, or denitrification. Using a variety of organic inputs with varying C:N ratios and a composite (average) ratio in the 25 – 35:1 range may be especially beneficial to multiple soil functions including nutrient cycling and retention (Bhowmik et al., 2016, 2017).

Finished compost consists of mixed organic residues that have already been processed by microbes, often in a thermophilic process (130-150°F) that rapidly converts the residues into a mixture of active and stabilized SOM. In a well-managed composting system, about half of the original carbon is converted to CO_2 while most of the N and other nutrients are retained and stabilized, resulting in a lower C:N ratio, typically 15 – 20:1. Unlike raw organic residues with this low a ratio, finished compost will mineralize only about 10 – 25% of its N to the current year's crop; however its content of active and stable SOM, other nutrients including P, cations, and micronutrients, and beneficial microbes will enhance soil fertility and replenish soil organic N that has been mineralized and taken up by crops.

Note that a "balanced diet" for microbes includes all essential nutrients, not just C, N, and P. For example, N-fixing and N cycling microbes require several micronutrients including Fe, Mo, Mn, and Cu. Plant residues, manure, compost, and organic fertilizers provide most of these nutrients in varying amounts, while soluble fertilizers essentially consist of "pure" NPK and can leave crops deficient in S, Mg, or micronutrients.

Slide 22-23 – *Building an organic nutrient management roadmap: advantages and challenges*

Nitrogen management can be especially challenging for organic farmers, especially when attempting to build long term soil health while maintaining adequate yields for the current crop. The complexities of biologically mediated soil nutrient dynamics can create challenges in determining how much N to apply in organic production and synchronizing the timing of N mineralization with crop N need.

Planting organic cash crops no-till through roll-crimped cover crops maximizes soil building yet can lead to severe yield tradeoffs, especially in colder or drier climates, with up to 63% yield losses in corn and oats related to N deficiency and weed competition (Carr et al., 2020; Delate, 2013). However, as noted above, shallow noninversion tillage integrated with cover crops and sound organic soil management can maintain healthy, biologically active soils while providing sufficient weed control and N mineralization to sustain yields.

Farmers undertaking organic transition in fields with a history of reliance on soluble fertilizers with inadequate organic inputs face additional challenges in providing for crop nutrition. Such soils often have depleted soil microbiomes and limited active SOM pools, and therefore cannot meet crop N needs from cover crops, compost, and SOM mineralization until soil health is restored. Strategies for the transition period include:

- Increase use of concentrated organic fertilizers such as poultry litter to sustain yields. This approach can delay restoration of SOM and soil health, deter development of microbial N mineralization potential, and perpetuate reliance on expensive inputs – a troublesome "catch 22" for organic producers.
- Begin with less nutrient-demanding production crops, rotate with cover crops, use compost to restore active SOM, and apply concentrated organic fertilizers in moderation. Small doses placed in crop rows (band application or drip fertigation) are most effective.
- Focus on soil restoration with continuous cover or sod crops + organic carbon amendments (compost, biochar, etc) for a few years before attempting organic crop production. This will rebuild soil health and soil microbiomes most quickly, but not all farms can afford to forego income for this long.
- Integrate livestock into the system to obtain grazing value from cover or sod crops. Sound rotational grazing can facilitate soil restoration.

Relying on manure and compost to meet crop N needs can build up surplus soil P. Once soil test P is in optimum range, these amendments must be limited to rates that just replenish P removed in harvests.

Slide 24 – *The first R: Right Source*

Slide 25 – *Organic or soluble: What does the research show?*

In a worldwide review of multiple meta-analyses comparing the impacts of different production systems and inputs on soil carbon and nitrogen dynamics, yields, and environmental impacts, Young et al (2021) found that, compared to soluble N, the use of organic sources of N substantially enhances total SOM, curbs N leaching and ammonia (NH_3) volatilization, but slightly reduces yields and may increase N_2O emissions. Managing biologically active soils for N_2O mitigation is a major challenge and a high research priority in the era of climate change.

Compared to soluble fertilizers, the use of organic nutrient sources roughly doubles soil microbial biomass with substantial increases in both fungal and bacterial communities (Morugán-Coronado et al., 2021), and doubles the biomass of bacterial- and fungal-feeding nematodes whose activities mineralize N for crop uptake (Puissant et al., 2021).

Studies at multiple sites have shown that organically managed soils have substantially greater ability to provide crop-available N through microbial mineralization from SOM (Berthong et al., 2013; Franzluebbers et al., 2018b, 2020; Spargo et al., 2011). This capacity is sustained by the replenishment of organic C and N through cover crops and amendments.

Other studies have documented qualitative differences in the microbial communities under organic vs soluble fertilizer regimes, with greater biodiversity, improved N and P cycling, and reduced disease pressure with organic nutrient sources (Li et al., 2022; Zhang et al., 2022).

Slide 26 – *Three organic nutrient sourcing strategies*

Best nutrient management combines all three strategies – grow fertility in place (cover crops), on-farm cycling, and off-farm resources. Any one alone has its limitations:

- Cover crops can meet the N needs of the following crop in warm, rainy climates, but may not in cold-temperate (Northeast, Great Lakes) or dry regions (Intermountain West), where N mineralization is slower (Carr et al., 2020). Plowing a perennial legume sod can meet the needs of a following corn crop, but N_2O emissions can occur (Han et al. 2017).
- On-farm cycling can sustain production for years; however, nutrients exported in farm products sold will eventually have to be replenished with off-farm inputs.
- Generous applications of compost and manure can rebuild depleted soils and support intensive organic production; however, P and other nutrient excesses can accrue, and high compost rates are not economically feasible at larger scale.

Our society wastes huge amounts of organic residue in ways that turn a vital resource into an environmental problem: livestock manure and urine (lagoons or stockpiles), yard trimmings, leaves, and food scraps (landfill). All of this can and should be composted and returned to the land to replenish soils and reduce fertilizer needs for crops. Care is needed to utilize tis resource to benefit large acreages rather than overloading smaller acreages with P and other nutrients.

Slide 27 – *Cover crops: a vital organic nutrient management tool.*

Cover crops play multiple roles in soil-friendly nutrient management. As a source of nourishing root exudates and residues to feed soil life and maintain soil organic matter, high biomass cover crops enhance the soil's long-term capacity to provide for crop nutrition. Winter grass and legume cover crops provide a "green bridge" to sustain mycorrhizal populations.

Cover crops help to regulate soil nutrient levels. When soil soluble N is scarce, legumes maximize N fixation, and some warm season grasses host N-fixing bacteria in their root zone. When soil soluble N is abundant, these cover crops switch to "scavenging mode," absorbing and holding the surplus N.

When plant-available P or K are below optimum, cover crops can enhance their availability. Buckwheat, most legumes, and grasses colonized by mycorrhizal fungi can retrieve P from insoluble organic and mineral sources (including rock phosphate amendments), while most grasses can unlock "mineral-fixed" K and return it to the topsoil in plant-available form. However, cover crops do not "fix" P and K from thin air the way they do C and N – thus, cover crops will not add unneeded P and K when soil levels are already ample.

Slide 28 - *On-farm nutrient sourcing - Elmwood Stock Farm, Georgetown, KY*

This successful, 800-member CSA farm sustains itself on very limited off-farm inputs. Legumes in the crop rotation and pastures likely replenish most of the N that leaves the farm in salable products, and other N fixing microbes in the soil and the root zones of grasses may also contribute. Regular soil tests will likely detect any future P and K drawdowns resulting from the very small annual off-farm inputs of these two nutrients.

University of Kentucky scientists have studied the integrated farming system at Elmwood Stock Farm and found that the five-year sod phase under rotational grazing restores SOM and microbial community to close to that of permanent pasture (Lin et al., 2020). However, when the sod is broken to resume crop production, a burst of SOM oxidation and N_2O emission occurs (Shrestha et al., 2019). Beginning in 2019, the farmers have experimented with grazing and shallow tillage to end the sod phase with less soil disruption, and with alternative crop rotations to optimize production, soil health, and GHG mitigation outcomes.

Slide 29 - *Off-farm organic nutrient sources: which materials are best?*

A research team at Washington State University compared the crop and soil impacts of two nutrient sources in organic vegetable production in a maritime soil in Washington State: on-farm mixed compost made from dairy manure and bedding and yard waste (C:N ~20) at rates of 6 to 8 tons/ac annually, and composted poultry litter (C:N ~7) at 1.8 – 2.6 tons/ac annually. The total N amounts applied in the two treatments were similar. Crop yields, soil physical, chemical, and biological properties, and potential N_2O emissions were monitored over an 11-year period.

The higher C:N compost improved overall soil health, with substantially higher levels of active and total SOM, microbial activity, and enzyme activities involved in nutrient cycling; and a more balanced nematode community (Bhowmik et al., 2016, 2017; Cogger et al., 2013). Notably, the compost amended soil showed both a greater capacity to mineralize N for crop production and to immobilize excess soluble N. This suggests that reliance on concentrated, low C:N inputs like poultry litter may shift the soil microbiome in a way that weakens N cycling and provisioning, thereby perpetuating reliance on these inputs.

Crop yields in the two treatments were generally similar.

Slides 30 and 31 – *Nutrient Source and NPK Balance – vegetables and field crops*

A comparison of crop harvest nutrient removals and the NPK analysis of two of the most common organic nutrient sources – compost and poultry litter fertilizers – illustrate the need to avoid relying entirely on one source to meet crop nutrient needs in organic production. The table shows a typical analysis for finished compost made from a mixture of manure and plant residues (including but not limited to animal bedding materials). However, the actual nutrient content of compost varies widely depending on ingredients and composting process, and farmers should test their compost and develop nutrient budgets to determine optimal application rates. The analysis shown for poultry litter is that of a widely used, NOP permitted poultry fertilizer; other products may have a different analysis, which is shown on the bag or provided by the vendor.

Vegetable crops remove relatively little P compared to N and K. Similarly, field crops remove several times as much N as P. Grain harvests that leave residues in the field remove relatively little K, since much of this nutrient remains in the straw or stover. In contrast, forage or hay harvests remove especially large amounts of K as well as N. Thus, applying compost or poultry litter at rates to replenish crop N removals or to meet LGU "maintenance" recommendations for vegetable production in the mid-Atlantic region will result in a buildup of P in the soil, and possibly K as well for grain crop rotations that do not include forages or vegetables.

Crop rotations that alternate crops with contrasting nutrient demands can help maintain soil NPK balance. In addition, grazing forage or cover crops removes much less NPK than cutting forages for hay or silage, since nutrients are recycled back onto the land in manure and urine. Thus, crop-livestock integrated operations often have considerably reduced nutrient input needs, as shown by the example of Elmwood Stock Farm.

Sources for yields and nutrient removals:

- Nutrient removal rates per bushel for grain harvests from George Silva, 2017, Michigan State University Extension, https://www.canr.msu.edu/news/nutrient_removal_rates_by_grain_crops.
- Nutrient removal rates for grass hay from University of California at Davis https://manuremanagement.ucdavis.edu/files/134365.pdf.
- Nutrient removal rates for corn silage from https://www.cropnutrition.com/.
- Vegetable yields and nutrient removals from University of Massachusetts, 2023, New England Vegetable Management Guide, Nutrient Removal from the Soil https://nevegetable.org/cultural-practices/removal-nutrients-soil.

Slide 32 – *Mix and match sources to get the balance right*

Once soil test P attains optimum or high range, compost and manure inputs may need to be sharply reduced to avoid further P accumulation. Many options exist for providing N without P, including legume cover or forage crops, and legume production crops (soybean, fresh or dry beans and peas, lentils, etc) as well as NOP-allowed N fertilizers like feather meal, blood meal or alfalfa meal. In addition, there is growing evidence that N fixing microbes that are either "free living" in biologically active soils or associate with the roots of crops such as pearl millet, corn, and possibly some vegetables can contribute to the farm's N budget.

The large mineral K reserves in many soils, difficulty in relating soil test exchangeable K to crop K nutritional status, and the surprising lack of crop response to K applications in a majority of trials (Khan et al., 2013) suggest that it may not be necessary to replenish all of the K removed in crop harvests. It may be kinder to farm budgets as well as soil and crop quality to simply monitor trends in K levels in crop foliar analyses as well as soil tests, and provide K when an actual need is identified. NOP-allowed K sources include potassium sulfate, langbeinite or K-mag (provides Mg as well as K), hay or straw mulch, and wood ashes (use only on non-alkaline non-calcareous soils).

Slide 33 – *The second R: right rate*

One of the toughest questions in organic farming is: how much NPK do I really need? Nutrient dynamics in a biologically driven system like organic farming are so different from the assumptions of 20th century and even 21st century conventional nutrient management that soil test recommendations may not even be "translatable" into organic.

One helpful concept is the "economic optimum nitrogen rate" (EONR) which is amount of applied N that gives the best economic return based on yield, farmgate price, and price of fertilizer. Usually, the EONR is somewhat below the amount of fertilizer N that gives maximum yield, especially for organic fertilizers, which tend to cost more per pound of N. Resource stewardship considerations (reducing inputs to protect water quality and minimize direct and embodied GHG emissions) are harder to assign an economic value. Yet, when a farm's customers want or expect their food to have as benign an environmental "footprint" as practical, a direct economic benefit can arise from reduced fertilizer use and better stewardship.

Crop yield responses to nutrient inputs can vary widely with crop, recent management history, soil type and texture, soil organic matter and biological activity, climate and current weather conditions, and overall farming system. More research is needed to help organic producers manage nutrients, especially N. In the meantime, farmers may need to do simple side-by-side trials with and without a nutrient input, or with different rates of applied nutrients, and then determine if there was a yield response, and if so, whether it paid for the input.

One of the tradeoffs that farmers may face is that, while using concentrated N (e.g., poultry litter) to meet crop N demand may improve yield in the short term, continued reliance on concentrated

N may delay or even prevent the development of increased soil capacity for biological N mineralization to meet the needs of future organic crops.

Slide 34 – *Total versus available N*

Rates for organic nutrient resources are often based on their "available" N percentage, the fraction of N in the amendment that becomes available to crops during the season of application. However, this can lead to costly and potentially polluting over-application and GHG emissions. For example, some organic producers incorporate manure or poultry litter with a legume green manure to ensure sufficient N for a heavy feeder like corn, and this can result in excessive N_2O emissions (Baas et al., 2015; Kemanian, 2021).

Because soil biological activity mineralizes N and other nutrients from residues and active SOM to support crop growth, it may only be necessary to replenish the SOM reserves to balance N removals in harvest, and therefore to use organic N sources at rates based on their total N content. A recent global meta-analysis of 129 studies (Wei et al., 2021) indicates that this may be true. In comparisons of organic versus conventional soluble N sources, organic applications based on *total* N maintained yields and reduced N leaching and runoff losses by an average of 30%. Organic applications based on *soluble* N content nudged yields an average of 6% above conventional yields, but also resulted in N losses 21% higher than the conventional treatment.

Slide 35 – *EONR for field crops can drop to zero in healthy soils*

Researchers at North Carolina State University have developed a "soil test biological activity" (STBA) index based on measuring soil respiration at 25°C (77°F) during a 3-day period after rewetting air-dry soil to 50% water-filled pore space. They found that STBA reliably indicates the soil's capacity to make N available to crops through N mineralization from SOM, and that STBA is positively correlated with crop yield without additional N and negatively correlated with crop response to applied N. In multisite trials across VA, NC, SC, and GA in a diversity of soil types and textures, EONR decreased to zero in sites with the highest STBA values, including more than one out of three trials with corn grain, corn silage, and fescue forage (Franzluebbers, 2018a, 2018b; Franzluebbers et al., 2018a).

Similarly, long-term best organic soil management and high biomass winter rye-crimson clover cover crops (total N 130 b/ac) supported good organic tomato and summer squash yields with no response to added N (Robb & Zehnder, 2016).

Slide 36 – *EONR soars above 200 lb/ac for organic broccoli*

Field trials at University of California Santa Cruz evaluating organic broccoli yield response to 0, 75, 150, and 225 lb N/ac in the form of blood, meat, and feather meals indicated an economic optimum nitrogen rate of 215 lb/ac (Li et al., 2009). These N rates led to major N losses in leaching and N_2O emissions sufficient to negate up to a ton or more per acre of SOC sequestration. Providing two-thirds of the N in the form of compost and legume-cereal cover crops cut N_2O emissions by half but did not curb nitrate leaching.

Trials on five organic farms in coastal and interior Oregon (seven site-years) confirmed that organic broccoli yields show a significant linear response to added N (as feather meal) of 11 to 88 lb marketable yield per lb N and did not plateau until > 200 lb N/ac (Collins and Bary, 2017). At a market price of $2.50/lb, broccoli yield increases returned several times the cost of the feather meal (about $6/lb N) at all sites. Thus, the high market value of organic broccoli, combined with the strong yield responses resulted in a high EONR.

Why was organic broccoli so inefficient in N uptake, leaving so much in the field to leach? Broadcast application of fertilizers on a crop with a fairly narrow lateral root spread may have been a factor. In addition, the Mediterranean climate pattern of winter rain and dry summer (broccoli grown during the dry season with irrigation) may have slowed mineralization from the organic fertilizers, then promoted leaching in winter without cover crops. However, other trials by Virginia Tech in Blacksburg, VA (rainy summer) showed yield responses to at least 150 lb N/ac in addition to the N from a roll-crimped vetch + rye cover crop.

In addition, modern broccoli cultivars may lack genetic traits for nutrient use efficiency such as effective association with beneficial microbes involved in nutrient cycling and uptake.

Slides 37-40 – *The third R: right timing: synchronizing N release with crop N demand*

Precision timing through split applications is fairly straightforward for soluble N sources and more challenging for organic sources that must undergo biological processing before plant uptake. N that is released too soon or too late to match crop N demands is often lost to leaching, resulting in both reduced crop yields and threats to groundwater quality. Timing may be less critical for less-soluble nutrients (P, some micronutrients) and cation nutrients (K, Ca, Mg), which can be held on the soil's CEC until crops need them.

N demand in most annual crops goes through three distinct phases; a "lag" period during the first 3-4 weeks after planting when crop N needs are relatively small, a vegetative phase of rapid plant development and high N demand, and a maturation phase, during which N uptake slows as plant N reserves translocated from leaves to developing fruit, grain, or tuber.

N use efficiency is maximized when the release of soluble N from fertilizers, amendments, and soil organic matter is synchronized with the period of high N demand, so that crops are not N limited, yet excess soluble N does not remain in the soil for extended periods of time. If N is released too quickly, early season rains may leach it out before the crop can utilize it. If N becomes available only after the crop has entered the maturation phase, the crop is again N-limited, and risks of late season or post-harvest N leaching or N_2O emissions are increased.

An organic fertility program that provides ideal crop N nutrition in warm, moist, well-aerated, biologically active soil may release N too slowly in cold, wet, or dry conditions, or when soil biological activity is low. For example, organic no-till corn planted into roll-crimped cover crops often gives low yields in the upper Midwest. Even though the region's Mollisol soils have high fertility, the cool climate, short growing season, and heavy soil textures can delay biological N mineralization so that the corn may not obtain sufficient N from a roll-crimped legume cover crop, whereas tilling the cover crop releases N more quickly and supports good corn yields.

Conversely, in the southeastern US coastal plain, warm rainy climates, long growing seasons, and sandy Ultisol soils promote rapid N mineralization – possibly too rapid if the cover crop is tilled in. In these conditions, a roller-crimped rye + vetch cover may provide more timely N delivery to the crop.

Slide 41 - *Asynchrony of N supply and N demand in an organic strawberry field in the Northern region, CA*

This slide is taken from a 2015 webinar with permission from Dr. Joji Muramoto of University of California at Santa Cruz.

Strawberry is a major crop in California, accounting for 85% of US production. About 9% of CA strawberry acreage is organic. Strawberries are grown in coastal regions of central CA, where mild, dry summers allow prolonged harvests and high yields.

The long lag phase in the strawberry crop's N utilization can render preplant applications of organic N sources ineffective. The strawberry crop in this diagram, planted in November after broccoli harvest, was unable to utilize some 260 lb nitrate-N mineralized from broccoli residues and pre-plant organic fertilizer. Winter rains leached most of this N out of the root zone long before the strawberry crop began taking up N more rapidly in late spring (Gaskell et al., 2009; Muramoto et al., 2015). Preplant N from other sources such as summer cover crops and compost is similarly mineralized and lost during the winter.

Slide 42 – *Winter cover crop recovers leftover N*

While strawberry planted after broccoli cannot utilize the leftover N, vigorous, deeper-rooted winter cover crops can do so quite effectively.

Dr. Eric Brennan of USDA Agricultural Research Service in the Salinas Valley of California conducted an eight-year trial (Salinas Organic Cropping Systems Experiment) on a Chualar loamy sand, which has a root-restrictive layer about 30 inches below the surface. A double cropping system of spring lettuce followed by fall broccoli sustained high lettuce yields (1000 boxes/ac, about 30 lb/box) only when a winter cover crop was grown prior to the lettuce. When the field was left fallow over winter, lettuce yields declined sharply to a few hundred boxes per acre, and sometimes to a total crop failure. Cover crops of rye alone, mustard, or rye with vetch, fava, and pea were similarly effective, indicating that their main benefit was not N fixation per se, but recovery of N left over from the broccoli crop. Broccoli was fertilized with about 145 lb N/ac (from organic sources), only about 25% of which was removed in harvest. During winter fallow, winter rains leached the N from the entire root-accessible zone, whereas vigorous winter cover crops recovered N and their residues delivered it to the lettuce (Brennan, 2018).

In addition, the combination of cover crops plus compost enhanced soil microbial activity to a much greater degree than the compost alone, even though the compost provided most of the organic carbon inputs (Brennan & Acosta-Martinez, 2017).

Slides 43-44 – *The fourth R: right placement – delivering N directly to the roots*

Band application or in-row drip fertigation can deliver N and other nutrients right in the root zone. In biologically active soils, root zone microbes can help deliver soluble N to crop roots.

What if the soil life could act as a "gatekeeper," delivering N in the root zone to meet crop demand while keeping bulk soil soluble N levels low enough to prevent nitrate leaching and N_2O emissions? This happens in the legume-Rhizobium symbiosis, in which atmospheric elemental nitrogen is "fixed" into plant-available N to the benefit of both symbionts, as shown by the soybean in this illustration. Non-leguminous plants can also host N-fixing bacteria, though not in visible nodules, and this partnership can contribute significantly to the plant's N nutrition, especially in warm-season grasses like pearl millet.

Can other soil organisms help plants access the large store of soil organic N by mineralizing just the right amount at the right time in their root zone? There is strong evidence that this can happen. Rhizosphere (root zone) microbial population densities are typically 10 times those of bulk soil. Plant roots give off chemical signals that attract the "right" microbes into their vicinity, then feed them with nourishing root exudates. In turn, the microbes help the plants acquire the moisture, N, and other nutrients they need, and increase plant resilience to stress and diseases.

Slide 45 – *N cycling patterns in organic tomato in California*

The slide summarizes findings from a study of 13 organic tomato fields in central California.

The four fields that showed "tightly coupled nitrogen cycling" with low soil soluble N levels yet adequate crop nutrition and high yields were amended primarily with compost derived from a diverse mixture of organic materials (C:N ~20:1). This was supplemented with a light in-row application (band or drip fertigation) of more concentrated N (blood meal or Chilean sodium nitrate). The soils had also been under organic management with cover crops for a number of years. The investigators documented evidence that the soil microbiome and plant root enzymes interacted to enhance N availability within the rhizosphere without overloading the bulk soil with soluble N (Bowles et al., 2015; Jackson, 2013; Jackson & Bowles, 2013).

In contrast, two N-deficient fields with less healthy soils and untimely (previous fall) organic N applications were unable to mineralize sufficient N for crop nutrition. Seven other fields were "N-saturated," fields receiving most of their N in relatively concentrated (low C:N) forms such as poultry litter, seabird guano, and/or an all-legume green manure showed high microbial activity but with lower levels of N cycling enzymes and higher levels of enzymes involved in SOM oxidation. Once again, concentrated N from any source (organic or synthetic) reduced SOM accrual and development of the soil's N mineralization capacity. However, the use of *small* amounts of concentrated N within crop rows to ensure crop N sufficiency during periods of high demand (as in the tightly coupled fields) does not seem to interfere with the development of SOM, N mineralization capacity, and other soil functions.

The authors stated that, since the plant root enzymes involved in tightly coupled N cycling occur widely across crop species, this phenomenon could occur in many crops and locations.

Slides 46-47 – *The fifth R: right crop genetics; development of N-efficient field corn*

For example, landraces of corn have been identified that meet part of their N requirement through symbiotic N fixation, and efficiently obtain the rest of their N from the soil through enhanced partnership with other beneficial microbes. Endophytic N-fixing *Burkholderia, Herbaspirillum*, and *Gluconacetobacter* appear especially efficient, meeting 40% of the crop's N requirement. Root microbiomes of modern hybrids include *Fusarium* strains that inhibit the N-fixers; conversely, the N-fixing endophytes in land races suppress *Fusarium*.

Dr. Walter Goldstein and colleagues at Mandaamin Institute in Elkhorn, WI collected germplasm from Mexican and South American land races that had been grown for centuries without modern agricultural fertilizers and other inputs and had thus acquired these N efficiency traits. They crossed the N-efficient land races with standard Corn Belt hybrids and inbreds to develop hybrids with enhanced root systems (larger, better association with soil microbiota that fix N or otherwise assist the crop in nutrient acquisition), yields equivalent to standard hybrids, higher grain protein quality (methionine content, important for organic poultry feed), and much better resilience to drought, low soil N, and other stresses (Goldstein, 2015, 2016, 2018).

Slide 48 – *Varietal nutrient efficiency in other crops*

Open pollinated land races of grain sorghum form much stronger AMF associations than modern hybrids. When grown in low-fertility soil with AMF but without fertilizer, land races gave 3-fold higher yields than the hybrids, and also higher protein and mineral content (Cobb et al., 2016).

Crop and microbial genetics play a substantial role in efficacy of legume N fixation. Both legumes and their *Rhizobium* symbionts show a wealth of genetic diversity that can provide the basis for breeding and selection for enhanced N fixation (Drinkwater and Grossman, 2018; Hardarson and Atkins 2003). Plant root-mycorrhizal associations are also modulated through both plant and fungal genetics, resulting in species-specific variation in AMF efficacy. Substantial varietal differences in AMF colonization have been documented in carrot, pepper, corn, other grains, and legumes, leading to recommendations that plant breeders select for AMF efficacy (Douds, 2009; Hamel, 2004; Silva, 2016; Weil and Brady, 2017).

Slides 49-51 – *Summary of organic nutrient management tips.*

The summary is based on the research and farmer experience summarized above. Note that, while relying on poultry litter fertilizers (PL) as a *primary* source of nutrients can hinder efforts to build soil health, PL can play a valuable supplementary role to maintain crop yields, especially on soils low in P, and especially when used in conjunction with higher C:N organic inputs to provide soil life with a "balanced diet."

Because soil test K appears unreliable as an index of actual crop need, check crop K status with foliar tests, especially if soil test K is a little below optimum ("medium"). Apply NOP-allowed K (potassium sulfate, or langbeinite if Mg is also low) when:

- Foliar tests show suboptimal K or crops show K deficiency symptoms.
- Repeated forage harvests, or intensive vegetable production draws heavily on soil K.
- Soil test K drops sharply into the "low" range, especially after heavy K removals.
- The farm's soil type is known to have limited K reserves.

Literature Cited

Baas, D. G., G. P. Robertson, S. R. Miller, N. and Millar, N. 2015. Effects of Cover Crops on Nitrous Oxide Emissions, Nitrogen Availability, and Carbon Accumulation in Organic versus Conventionally Managed Systems. Final report for ORG award 2011-51106-31046.*

Berthong, S. T, D. H. Buckley, and L. E. Drinkwater. 2013. Agricultural management and labile carbon additions affect soil microbial community structure and interact with carbon and nitrogen cycling. Microbial Ecology 66: 158-170.

Bhattacharyya, S. S., G. H. Ross, K. Furtok, H. M. N. Iqbal, and R. Parra-Saldivar. Soil carbon sequestration – An interplay between soil microbial community and soil organic matter dynamics. Science of the Total Environment 815 (April 2022). https://doi.org/10.1016/j.scitotenv.2022.152928.

Bhowmik, A. A-M. Fortuna, L. J. Cihacek, A. Bary, P. M. Carr, and C. G. Cogger. 2017. *Potential carbon sequestration and nitrogen cycling in long-term organic management systems.* Renewable Agriculture and Food Systems, 32 (6): 498-510.

Bhowmik, A., A. Fortuna, L. J.Cihacek, A. I.Bary, and C. G.Cogger. 2016. *Use of biological indicators of soil health to estimate reactive nitrogen dynamics in long-term organic vegetable and pasture systems*. Soil Biology and Biochemistry 103: 308-319.

Bowles, T. M., A. D. Hollander, K. Steenwerth, and L. E. Jackson. 2015. *Tightly-Coupled Plant-Soil Nitrogen Cycling: Comparison of Organic Farms across an Agricultural Landscape*. PLOS ONE peer-reviewed research article. http://journals.plos.org/plosone/article?id=10.1371/journal.pone.0131881

Brennan, E. 2018. Lessons from long-term, cover crop research in the Salad Bowl of the World – 10 minute youtube video, https://www.youtube.com/watch?v=JurC4pJ7Lb4

Brennan, E. B., and V. Acosta-Martinez. 2017. Cover cropping frequency is the main driver of soil microbial changes during six years of organic vegetable production. Soil Biology and Biochemistry 109: 188-204.

Button, E. S., J. Pett-Ridge, D. V. Murphy, Y. Kuzyakov, D. R. Chadwick, and D. L. Jones. 2022. Deep-C storage: Biological, chemical and physical strategies to enhance carbon stocks in agricultural subsoils. Soil Biology and Biochemistry Volume 170, July 2022, 108697.

Carr, P. M, M. A. Cavigelli, H. Darby, K. Delate, J. O. Eberly, H. K. Fryer, G. G. Gramig, J. R. Heckman, E. B. Mallory, J. R. Reeve, E. M. Silva, D. H. Suchoff, and A. . Woodley. 2020. Green and animal manure use in organic field crop systems. Review article. Agronomy Journal 112 (2): 648-674.

Cogger, C. G. M. Ostrom, K. Painter, A. Kennedy, A. Fortuna, R. Alldredge, A.; Bary, T. Miller, D. Collins, J. Goldberger, A. Antonelli, and B. Cha. 2013. Designing Production Strategies for Stewardship and Profits On Fresh Market Organic Farms. Final report for OREI award 2008-51300-04460.*

Collins, D. P. and A. Bary. 2017. *Optimizing nitrogen management on organic and biologically intensive farms.* Proceedings of the Special Symposium on Organic Agriculture Soil Health Research at the Tri-Societies Annual Meeting, Tampa, FL, October 22-25, 2017. http://articles.extension.org/pages/74555/live-broadcast:-organic-soil-health-research-special-session-at-the-tri-societies-conference.

Delate, K. 2013. Developing Carbon-positive Organic Systems through Reduced Tillage and Cover Crop Intensive Crop Rotation Schemes. Final report for ORG award 2008-51106-19021.*

Douds, D. D. 2009. *Utilization of inoculum produced on-farm for production of AM fungus colonized pepper and tomato seedlings under conventional management*. Biological Agriculture and Horticulture 26: 353-364.

Drinkwater, L., E. and J. M. Grossman. 2018. *Harnessing variation in vetch and rhizobia populations to optimize nitrogen fixation*. ORG award 2018-51106-28778

Dynarski, K. A., D. A., Bossio, and K. Scow. 2020. Dynamic stability of soil carbon: reassessing the "permanence" of soil carbon sequestration. Frontiers in Environmental Science. Vol 8 (November 2020). https://doi.org/10.3389/fenvs.2020.514701.

Franzluebbers, A. J. 2018a. *Soil-Test Biological Activity with the Flush of CO2: III. Corn Yield Responses to Applied Nitrogen*. Soil Science Society of America Journal, Volume 82, Issue 3, https://doi.org/10.2136/sssaj2018.01.0029.

Franzluebbers, A. J. 2018b. *Short-term C mineralization (aka the flush of CO2) as an indicator* *of soil biological health*. CAB Reviews 2018 13, No. 017. doi: 10.1079/PAVSNNR201813017.

Franzluebbers, A. J., S. Pehim-Limbu, and M. H. Poore. 2018a. *Soil-Test Biological Activity with the Flush of CO2: IV. Fall-Stockpiled Tall Fescue Yield Response to Applied Nitrogen*. Agronomy Journal, Volume 110, Issue 5, https://doi.org/10.2134/agronj2018.03.0146.

Franzluebbers, A. J., M. R. Pershing, C. Crozier, D. Osmond, and M. Schroeder-Moreno. 2018b. *Soil-Test Biological Activity with the Flush of CO2: I. C and N Characteristics of Soils in Corn Production.* Soil Science Society of America Journal, Volume 82, Issue 3, https://doi.org/10.2136/sssaj2017.12.0433.

Franzluebbers, A. J., S. C. Reberg-Horton, and N. G. Creamer. 2020. *Soil carbon and nitrogen fractions after 19 years of farming systems research in the Coastal Plain of North Carolina*. Soil Science Society of America Journal, Volume 84, pp 856-876.

Gaskell, M., M. Bolda, J. Muramoto, and O. Daugovish, 2009. *Strawberry Nitrogen Fertilization from Organic Nutrient Sources.* Acta *Horticulturae* (ISHS) 842:385-388.

Goldstein, W. 2015. Breeding corn for organic farmers with improved N efficiency/N fixation, and protein quality. Proceedings of the Organic Agriculture Research Symposium. https://eorganic.info/node/12972.

Goldstein, W. 2016. Partnerships between Maize and Bacteria for Nitrogen Efficiency and Nitrogen Fixation. Bulletin 1. Mandaamin Institute, Elkhorn, Wisconsin, 49 pp. http://www.mandaamin.org/about-nitrogenfixing-corn.

Goldstein, W. 2018. High Methionine, N Efficient Field Corn from the Mandarin Institute/ Nokomis Gold Seed Co.Proceedings of the 9th Organic Seed Growers Conference, Feb 14-17, 2018, Corvallis OR, pp 25-26. https://seedalliance.org/all-publications/.

Grandy, S., and C. Kallenbach. 2015. Microbes drive soil organic matter accumulation in organic cropping systems. Recording from the Organic Agriculture Research Symposium, LaCrosse, WI February 25-26, 2015, http://eorganic.info/node/12972.

Hamel, C. 2004. Impact of arbuscular mycorrhizal fungi on N and P cycling in the root zone. Can J Soil Sci. 84(4):383-395.

Han, Z., M. T. Walter, and L. E. Drinkwater. 2017. Impact of cover cropping and landscape positions on nitrous oxide emissions in northeastern U.S. agroecosystems. Agriculture, Ecosystems and Environment vol. 245: pp 124-134.

Hardarson, G., and C. Atkins. 2003. Optimising biological N2 fixation by legumes in farming systems. Plant and Soil 252 (1):41-54.

Hultengren, R., M. Glos, and M. Mazourek. 2016. *Breeding Research and Education Needs Assessment for Organic Vegetable Growers in the Northeast*. Cornell University, 35 pp. http://hdl.handle.net/1813/44636.

Jackson, L. 2013. *Researcher and Farmer Innovation to Increase Nutrient Cycling on Organic Farms.* Proposal and final report for OREI project 2009-01415. https://nifa.usda.gov/data/data-gateway.

Jackson, L. and T. Bowles. 2013. *Researcher and Farmer Innovation to Increase Nitrogen Cycling on Organic Farms* (Webinar). http://articles.extension.org/pages/67391/researcher-and-farmer-innovation-to-increase-nitrogen-cycling-on-organic-farms-webinar.

Kallenbach, Cynthia M., Frey, Serita D., & Grandy, A. Stuart. 2016. Direct evidence for microbial-derived soil organic matter formation and its ecophysiological controls. Nature Communications 7, Article number: 3630 https://www.osti.gov/pages/servlets/purl/1363941.

Kemanian, A. R. 2021. *Smart tillage to reduce N_2O emission from organic agriculture.* ORG award 2019-51106-30189.*

Khan, S. A., R. L. Mulvaney, T. R. Ellsworth, and C. W. Boast. 2007. *The myth of nitrogen fertilization for soil carbon sequestration.* J. Environ. Qual. 36:1821–1832.

Khan, S. A., R. L. Mulvaney, and T. R. Ellsworth. 2013. *The potassium paradox: implications for soil fertility, crop production, and human health*. Renewable Agriculture and Food Systems: doi:10.1017/S1742170513000318. 25 pp.

Li, C., Salas, W. and Muramoto, J. 2009. *Process Based Models for Optimizing N Management in California Cropping Systems: Application of DNDC Model for nutrient management for organic broccoli production*. Conference proceedings 2009 California Soil and Plant Conference, 92-98. Feb. 2009. http://ucanr.edu/sites/calasa/files/319.pdf.

Li, J., Y. Yang, J. Wen, F. Mo, and Y. Liu. 2022. Continuous manure application strengthens the associations between soil microbial function and crop production: Evidence from a 7-year multisite field experiment on the Guanzhong Plain. Agriculture, Ecosystems, and Environment vol. 338 article 108082.

Lin, D., R. L. McCulley, J. L. Nelson, K. J. Jacobsen, and D. Zhang. 2020. Time in pasture rotation alters soil microbial community composition and function and increases carbon sequestration potential in a temperate agroecosystem. Science of the Total Environment 698, https://doi.org/10.1016/j.scitotenv.2019.134233.

Morugán-Coronado, A., P. Pérez-Rodríguez, E. Insolia, D. Soto-Gómez, D. Fernández-Calvino, and R. Zornoza. 2022. *The impact of crop diversification, tillage and fertilization type on soil total microbial, fungal and bacterial abundance: A worldwide meta-analysis of agricultural sites*. Agriculture, Ecosystems, and Environment 329, Article 107867, May 2022.

Mulvaney, R. L., S. A. Khan, and T. R. Ellsworth. 2009. *Synthetic nitrogen fertilizers deplete soil nitrogen: a global dilemma for sustainable cereal production*. J. Environ. Qual. 38:2295–2314.

Muramoto, J., C. Shennan, and J., M. Gaskell. 2015. *Nitrogen management in organic strawberries: challenges and approaches*. (Webinar) https://eorganic.org/node/14818.

Prescott, C. E., Yi. Rui, M. F. Cotrufo, and S. J. Grayston. 2021. Managing plant surplus carbon to generate soil organic matter in regenerative agriculture. J. Soil & Water Conservation 76(6): 99A-104A.

Puissant, J., C. Villenave, C. Chauvin, C. Plassard, E. Blanchart, and J.Trap. 2021. *Quantification of the global impact of agricultural practices on soil nematodes: A meta-analysis.* Soil Biology and Biochemistry Volume 161, October 2021, 108383.

Robb, D. and G. Zehnder. 2016. Weeds, nitrogen, and yield: measuring the effectiveness of an organic no-till system. Final report for Southern SARE project GS13-126. https://projects.sare.org/project-reports/gs13-126/.

Shrestha, D., O. Wendroth, and K. L. Jacobsen. 2019. Nitrogen loss and greenhouse gas flux across an intensification gradient in diversified vegetable rotations. Nutrient Cycling in Agroecosystems, https://doi.org/10.1007/s10705-019-10001-8.

Silva, E. 2016. Creating climate-resilient organic systems by enhancing arbuscular mycorrhizal fungal associations. OFRF project summary. https://grants.ofrf.org/research/grants/creating-climate-resilient-organic-systems-enhancing-arbuscular-mycorrhizal-fungi.

Spargo, J. T., M. A. Cavigelli, S. B. Mirsky, J. E. Maul, and J. J. Meisinger. 2011. *Mineralizable soil nitrogen and labile soil organic matter in diverse long-term cropping systems*. Nutr. Cycl. Agroecosyst (2011) 90:253–266.

Wei, Z, E. Hoffland, M. Zhuang, P. Hellegers, and Z. Cui. 2021. *Organic inputs to reduce nitrogen export via leaching and runoff: A global meta-analysis*. Agriculture, Ecosystems, and Environment 291. https://doi.org/10.1016/j.envpol.2021.118176.

Weil, R. R., and N. C. Brady 2017. The Nature and Properties of Soils, 15th Edition.

Wikipedia entry for Morrow Plots. https://en.wikipedia.org/wiki/Morrow_Plots.

Young, M. D., G. H. Ros, and W. de Vries. 2022. *Impacts of agronomic measures on crop, soil, and environmental indicators: A review and synthesis of meta-analysis*. Agriculture, Ecosystems, and Environment 319. https://doi.org/10.1016/j.agee.2021.107551.

Zhang, H., X, Zheng, X. Wang, and W. Xiang. 2022. Effect of fertilization regimes on continuous cropping growth constraints in watermelon is associated with abundance of key ecological clusters in the rhizosphere. Agriculture, Ecosystems, and Environment vol. 339 article 108135.