Biological Nutrient Management:
Best Organic Practices for Soil Fertility and Resource Stewardship

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Presentation Notes

Slides 1-2 Title and acknowledgements

Slide 3 – *Goals of nutrient management*

Production goals include *optimum* yield, taking direct and environmental production costs into consideration; therefore, not necessarily maximizing yield. Conservation concerns focus mainly on the adverse impacts of soluble nitrogen (N) and phosphorus (P) on surface and ground water quality and greenhouse gas (GHG) emissions from fertilized soils. Much of the Commonwealth of Virginia lies within the Chesapeake Bay Watershed, for which nutrient impacts on water quality have become a major resource and environmental concern.

Organic farmers take a resource-conserving approach to nutrient management to build the soil's nutrient retention, cycling, and delivery capacity, thereby reducing the amount of nutrient input required for satisfactory yield.

Slide 4 – *Nutrient management criteria* (NRCS CPS 590 and NOP Standards)

Certified organic producers may also use the following non-biological nutrient sources and pH-correcting amendments (USDA, National Organic Program, undated):

- Natural (mined) mineral substances of low solubility, e.g. calcitic or dolomitic limestone.
- Natural sodium nitrate ("Chilean nitrate"), up to a maximum of 20% of the crop's total N requirement.
- Other natural (mined) mineral substances of high solubility (e.g., potassium sulfate, langbeinite or sulpomag), *except* those on the National List of prohibited non-synthetic substances (potassium and calcium chlorides, lead, arsenic, and fluo-aluminate minerals).
- Elemental sulfur.
- Magnesium sulfate for documented Mg deficiency.
- Soluble boron compounds for documented B deficiency.
- Sulfates, carbonates, oxides, or silicates of zinc, copper, iron, manganese, molybdenum, selenium, and cobalt when micronutrient deficiency is identified by soil or tissue test.

Slide 5 – *Soil fertility: Southern region organic farmers' perspectives*

In 2020, the Organic Farming Research Foundation (OFRF) conducted a survey of 1,059 certified organic including 85 in the Southern region (14 in Virginia), and 71 transitioning-organic producers to document their use of resource stewardship and production practices, their leading production and enterprise management challenges, and technical assistance needs (Snyder et al., 2022).

Our findings illustrate the extent to which the region's organic farmers implement the fertility management practices codified in the USDA National Organic Program (NOP) Standards. For example, 80% of Southern region respondents reported using cover crops regularly ("often" or "very often"), and 84% implement crop rotation. Two out of three Southern region organic farmers reported using organic fertilizers while less than half use manure and slightly over one out of three use compost. Nutrient management challenges can arise with overreliance on concentrated organic fertilizers such as pelleted heat-treated poultry litter products; these will be discussed later in the webinar.

Two out of three Southern region respondents identified soil fertility and nutrient management as a technical assistance need, which ranked a close third after organic weed, pest, and disease management and soil conservation and soil health.

Organic Nutrient Management 101 (Slides 6-18)

Slide 7 – *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 shortages of 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 further increased to account for anticipated losses through runoff, leaching, denitrification, microbial immobilization, and mineral-fixation of phosphorus.

The reason to dwell briefly on the past is that this paradigm still informs 21st century standard soil test recommendations 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.

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.

Early practitioners of the organic method implemented various "feed the soil" strategies that mimic natural processes and parallel the soil health practices advocated by NRCS over the past 20 years. They also sought to integrate crop and livestock production 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.

Slide 9 – *20th Century organic nutrient management: thinking beyond soluble NPK*
Slide 10 – *Micronutrients for crop health and nutritional value.*

From the beginning of the organic movement, practitioners recognized that soluble forms of NPK are not the only relevant forms of nutrients, that N, P, and some other nutrients exist in organic forms that plants can access provided that the soil is healthy, with an active and well-fed community of life that converts organic and even mineral-bound nutrients into plant-available forms. In addition, organic farmers and agricultural advisors paid attention to the whole spectrum of essential elements including the trace minerals or micronutrients essential to plants, animals, humans, and the nutritional quality of farm products (see Table 1 below). Note that several micronutrients play essential roles in N fixation and uptake of N and P.

Organic practices – crop rotation, cover crops, and using complex organic and natural-mineral fertility sources – promote balanced crop nutrition and help to provide trace elements.

Plant-available anions (negative charge) like nitrate, phosphate, sulfate, and borate exist mainly in the soil solution, and can easily leach out of the root zone during heavy rainfall or snowmelt. Plant available cations (positive charge) like K, calcium (Ca), magnesium (Mg), ammonium nitrogen (NH_4^+), and some micronutrients can also occur in the soil solution but are mostly adsorbed (held) on the soil's cation exchange capacity consisting of negatively charged clays and stable soil organic matter. Cations are less prone to leaching except in sandy soils low in organic matter and clay.

Nutrient reserves (not immediately available to plants, but potentially released through microbial and plant root biological processes) are held in soil organic matter (N, P, S, some micronutrients) and in soil minerals (P, K, Mg, Ca, micronutrients).

Soil organic matter and soil life play important roles in providing essential micronutrients for crops and livestock. Low-solubility cations like copper (Cu), zinc (Zn), iron (Fe), and manganese (Mn) become more plant available when they combine with soluble organic substances in the soil to form chelates, when soil microbes convert them to more soluble forms, and when mycorrhizal fungi facilitate plant uptake. Favorable soil pH (6.0 – 7.0 for most crops, and ~5.0 for blueberry and cranberry) plays an important role in crop access to micronutrients.

Boron (B) is present as soluble anions, and is often deficient in soils under warm, rainy climates. Virginia soils commonly need B supplements to sustain optimum production and quality, especially for alfalfa, broccoli and other brassica family vegetables, celery, and tomato, potato, and other solanaceous vegetables. Cu and Zn are sometimes low in Virginia soils, whereas Fe and Mn are generally ample, and occasionally in phytotoxic excess on acidic soils

(Na) and chlorine (Cl) are rarely deficient and can be present in excess in saline-alkaline soils of semiarid regions, or in overfertilized soils, especially in high tunnels.

Table 1. Essential macro and micronutrients, their forms in soil, and their roles in plant nutrition. Based on information in Weil and Brady (2017).

Element	Forms in the soil[1]	Essential nutritional roles
Nitrogen (N)	Anion, cation, organic	Structural component of proteins, enzymes, amino acids, chlorophyll, nucleic acids, vitamins, secondary compounds
Phosphorus (P)	Anion, organic, mineral	Structural component of nucleic acids, cell membranes (phospholipids), and ATP ("energy currency" of all organisms)
Potassium (K)	Cation, mineral	K^+ in solution vital for photosynthesis, energy production, enzyme activation, stress resilience
Sulfur (S)	Anion, organic, mineral	Structural component of proteins, enzymes, vitamins, secondary compounds
Calcium (Ca)	Cation, mineral	Cell wall component, membrane permeability, enzyme activation
Magnesium (Mg)	Cation, mineral	Central ion in chlorophyll molecule, activation of enzymes; energy, oil, and protein synthesis.
Sodium (Na)	Cation	Essential for animals and humans, can take some but not all of the roles of K^+ in plants
Silicon (Si)	Anion, mineral	Strengthens plant structure, stress resilience. *More research is needed and is ongoing.*
Iron (Fe)	Cation, chelate, mineral	Structural part of nitrogenase (N fixation), N and P nutrition, chorophyll synthesis
Manganese (Mn)	Cation, chelate, mineral	Enzymes for photosynthesis and N metabolism
Zinc (Zn)	Cation, chelate, mineral	Multiple enzymes, seed production and maturation
Boron (B)	Soluble boric acid (H_3BO_3), anion in alkaline soils	Enzymes, cell division and development, sugar translocation, nucleic acid and hormone synthesis
Copper (Cu)	Cation, chelate, mineral	Enzymes, photosynthesis, protein and carbohydrate metabolism, N fixation
Nickel (Ni)	Cation, chelate, mineral	Enzymes, seed filling and viability, N fixation
Molybdenum (Mo)	Anion, chelate, mineral	Structural part of nitrogenase (N fixation) and nitrate reductase enzyme
Chlorine (Cl)	Anion	Enzyme activation, photosynthesis
Cobalt (Co)	Cation, chelate, mineral	Essential for N-fixing bacteria, animals, people
Selenium (Se)	Anion, mineral	Essential for animals and people
Chromium (Cr)	Anion, cation, mineral	Possibly essential for animals and people

[1] Anion = negatively charged ion (e.g. NO_3^-) in soil solution or held on anion exchange sites in soil. Cation = positively charged ion (e.g., Ca^{++}) held on cation exchange capacity (CEC) or in soil solution. Chelate = metal ion held by an organic compound through multiple bonds. Mineral = present in insoluble mineral or mineral-fixed forms. Organic = integral part of soil organic matter (e.g., N and S in proteins or amino acids).

Soil tests for micronutrients often do not accurately reflect actual crop nutritional status with regards to these essential trace elements. Depending on the crop and variety, soil-root microbiome, overall soil health, soil mineralogy, and pH, crops may obtain sufficient amounts of micronutrients that shows "low" on the soil test, or conversely suffer deficiency despite a "sufficient" soil test value. Therefore, organic farmers (and many non-organic specialty crop farmers as well) often use a foliar nutrient analysis to assess crop nutritional status and identify micronutrient supplement needs more accurately.

Moderate micronutrient deficiencies can often be corrected with the use of seaweed or fish-based foliar fertilizers or soil amendments, or compost made from a diversity of materials. More severe or persistent deficiencies can be addressed with NOP-approved micronutrient minerals. Good organic management, maintaining desirable soil pH, compost made from a diverse mix of materials, and additional supplementation when indicated by foliar and soil tests can ensure optimal levels of micronutrients.

While all nutrients are important to soil, plant, animal, and human health, the remainder of this webinar will focus on nitrogen and phosphorus, which have the greatest potential impact on water resources, soil health, and greenhouse gas emissions.

Slide 11 – *21st Century nutrient management: feed the plant and the soil.*

By the end of the 20th Century, most land grant university and other mainstream agricultural professionals recognized 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, crop-available 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" 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.

Diversified crop rotations help nutrient management through complementary nutrient demands (root depth, spread, and architecture) and greater microbial functional diversity (legumes, grasses, crucifers, other forbs supporting different 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.

Slide 12 – *Tiny yet mighty: soil organisms perform all key functions of healthy soil*
Slide 13 – *In organic farming systems, soil organisms drive nutrient cycling and crop nutrition*

Research over the past 20 years has shown the central role that the soil microbiome plays in all aspects of soil function, and especially nutrient cycling and crop nutrition (red highlighted items in slide 13). Other soil health functions – water storage, structure, and 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 14 – *Organic nutrient management*

Organic farmers rely primarily on biological processes to meet crop nutrient needs, and supplement with NOP-allowed mineral and faster-releasing organic fertilizers. These more concentrated nutrient sources may be essential 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 active and stable organic matter, 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 the residues and active SOM into MAOM, soil organisms maintain and enhance the CEC, an important aspect of soil fertility.

In addition, soil minerals hold large nutrient reserves, particularly potassium (K), other cations, and micronutrients, which are gradually brought into the exchangeable (plant available) pools through the action of soil life and plant roots on the mineral component of the soil (biological weathering).

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.

Most organic farms import some organic amendments from off-farm sources, including manure, compost, municipal leaves, yard trimmings, and food scraps, to replenish nutrients and organic matter consumed in production or removed in harvest.

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

These biological processes can sustain plant nutrition even when soil tests show suboptimal (low to medium) levels of soluble plant-available nitrogen (PAN), phosphorus (P) and other nutrients in the bulk soil. This phenomenon of *tightly coupled nutrient cycling* can protect water quality and mitigate greenhouse gas emissions. Recent paleontological findings indicate that the first land plants co-evolved with mycorrhizal symbionts that proved essential to their survival on the prehistoric world's primitive soils.

Slides 16-18 – *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).

Most important for the organic farmer to consider is that plants take up nitrogen mainly in the soluble nitrate and ammonium forms, thus "plant available nitrogen" or PAN = nitrate-N + ammonium N. Crops must have access to PAN, either directly from soluble fertilizers, or 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 and the rhizosphere microbiome, which thus act as nitrogen "gate-keepers" in organic systems. When N-poor residues are tilled in, microbes must utilize 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.

However, 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 within the soil profile is far less intense, and the mulch can benefit soil and crops by conserving moisture, protecting the soil surface from crusting and soil organisms from direct sun and temperature extremes, and suppressing weed seeding emergence.

In the illustration, organic broccoli transplanted no-till into mowed cereal rye cover (photo) has suffered N deficiency because the growing rye took up much of the plant available soil N prior to cover crop termination.

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, although with potential environmental costs. Because the soil life is carbon-limited, it must consume some of the carbon in active SOM to grow and reproduce, so that a net loss of soil carbon can occur. 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 food web and root microbiome – 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 organic matter, N losses can be as great as in high-input conventional systems.

The challenge is to ensure that adequate PAN 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 such as the composting windrows managed by organic farmer William Hale of Louisa, VA (central Piedmont), about half of the original carbon is converted to CO_2 and the other half into stabilized organic C, while most of the N and other nutrients are retained and stabilized, resulting in a lower C:N ratio, perhaps 15:1 or 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, the other 75-90% become part of the soil's organic N pool, which plays a critical role in sustaining long term fertility through gradual mineralization. In addition finished compost builds soil fertility in other ways, including active and stable SOM, other nutrients including P, cations, and micronutrients, and beneficial microbes.

Note that a "balanced diet" for microbes includes all the nutrients discussed earlier – 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 19 – *The whole is greater than the sum of the parts*

One of the hallmarks of the organic method is *systems thinking*. Rather than relying on a single input or practice, successful organic farmers combine diverse crop rotations, cover crops, compost and/or other organic inputs, and judicious tillage to build the soil's capacity to nourish crops, thereby reducing the need for costly organic fertilizers. Research has shown that "stacking practices" builds more SOM and better soil functions than single practices (Delate et al., 2015; Hurisso et al., 2016).

Organic systems emphasize agricultural diversity, including long rotations that include multiple plant families, intercropping and relay planting, and integrating livestock into cropping systems to support a more diverse and complete soil food web and make best use of soil nutrients. Recent studies have found that intercropping legumes with vegetable crops can modify the soil microbiome to enhance N cycling and reduce fertilizer needs (Cuartero et al., 2022; Stratton et al., 2022).

Organic no-till, even rotational no-till, can be challenging because of yield tradeoffs related to N limitation and weed pressure. However, a recent meta-analysis has shown that reduced tillage – shallow, non-inversion tillage such as the high-speed disk working at 3 – 4 inches, can maintain twice the microbial biomass as either moldboard plowing or continuous no-till with chemical weed control and inadequate cover cropping (Morugán-Coronado et al., 2022).

Organic Nutrient Management Challenges (Slides 20-47)

Research findings and applying the 4Rs to organic systems

Slide 21 – *Organic advantages and challenges*

Organic rotational no-till systems that integrate high-biomass cover crops terminated by roller-crimping, diverse crop rotation, and organic soil amendments can maximize soil health parameters such as total and active SOM, soil organic N, and microbial biomass and diversity. However, yield tradeoffs can be severe, especially in colder or drier climates, with up to 63% yield losses in corn and oats related to inadequate PAN and heavy 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.

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.
- Begin with less nutrient-demanding production crops, rotate with cover crops, use compost to restore active SOM and concentrated organic fertilizers in moderation.
- 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. 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. These challenges will be explored in the following slides.

Slides 22-33 – *The first R: right source*

Slide 23 – *Organic versus soluble – what does the research show?*

The goal of this literature review slide is to address the question “why organic?” through a nutrient management lens.

While soluble NPK fertilizers have boosted crop yields and thereby potential organic matter return to the soil via root exudates and residues, a University of Illinois review of the Morrow Plots and 25 other farming systems trials around the world have given mixed results, indicating that soluble fertilizers do not always build SOM and soil organic nitrogen reserves, with some studies showing a downward trend. (Khan et al, 2007; Mulvaney et al, 2009).

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. Combined (organic + soluble) N fertilizer programs showed the same advantages over soluble N alone in SOM and lower N2O emissions, though the all-organic N had the lowest NH_3 and leaching potential. Managing biologically active soils under organic nutrient management for N_2O mitigation is a significant challenge and a research priority.

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). Organic nutrient sources also double the biomass of bacterial- and fungal-feeding nematodes (Puissant et al., 2021). These nematodes play a vital role in N mineralization and crop N nutrition in organic systems.

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, which suggests that organic nutrient management can be based on total N rather than PAN.

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 24 – *Three organic nutrient sourcing strategies*

Best nutrient management combines all three strategies – grow fertility in place (cover crops), on-farm cycling, and supplements from off-farm sources. Each one alone has its pitfalls:

- Cover crops can meet the N needs of the following crop in warm, rainy climates including most of Virginia, but may not do so in cold-temperate (Northeast, Great Lakes) or dry (Intermountain West) regions where N mineralization is slower (Carr et al., 2020). Plowing a perennial legume sod can meet the needs of a following corn crop, but substantial 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.

In Virginia, industrial scale poultry operations generate large amounts of poultry litter (PL) which both organic and non-organic farmers commonly use as a nutrient source. Studies show that, compared to soluble NPK only, PL can benefit soil health and fertility, although N2O emissions are increased (Lin et al., 2022). Also, finished compost (C:N ~15-20) builds more

SOM and microbial activity and function in organically managed soils than PL (C:N ~ 7) (Bhowmik et al., 2016, 2017).

Slide 25 – *Cover crops: a vital organic nutrient management tool.*

Cover crops play vital, multiple roles in soil-friendly nutrient management. As a key source of organic carbon 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 and most legumes can retrieve P from insoluble organic and mineral sources (including rock phosphate amendments), while most grasses can unlock "mineral-fixed" K to replenish the supply of exchangeable (plant-available) K. 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.

Climates across most of Virginia are mild enough to grow cover crops year-round. During winter, fall-planted cold-hardy covers like cereal grains, vetch, winter pea, and crimson clover go dormant during cold snaps and resume growth when temperatures rise above freezing, providing ample cover by early to mid-spring.

Slides 26-28– *Farm Story: Strategic Cover Cropping in Louisa, VA*

Farmer, author, and educator, Pam Dawling has developed a sophisticated and flexible approach to maximizing year round soil coverage, living root, plant biomass, nutrient cycling, and diversity through cover cropping in a four-acre vegetable operation, Twin Oaks Farm in Louisa, VA, which provides year round produce for a community kitchen serving 100 people.

Pam developed her ten-year crop rotation and detailed guidance for what cover crop to plant and when to plant them, based on personal experience and knowledge gained through decades of farming at this site. She has given many webinars and presentations, writes regularly for the periodical *Growing for Market* and has written two books, *Sustainable Market Farming: Intensive Vegetable Farming on a Few Acres* and *The Year-Round Hoophouse: Polytunnels for All Seasons and All Climates*. For more information, visit www.sustainablemarketfarming.com.

Pam has tried various undersowing strategies with good track records in the Northeast and has found that not all of them work in Virginia. For example, she does not overseed rye and vetch into kale because the latter is harvested well into winter in central Virginia and would be overwhelmed by the cover. Red clover seeded into winter squash at onset of vining is choked out as the vines grow so rapidly in the heat of a Louisa, VA summer, whereas red and white clover do well seeded into fall brassica crops. Crimson clover is a poor choice for undersowing sweet corn because it is just too hot during corn season for this cool season crop. Instead, she sows a mixture of oats and soybean into corn.

Timing is critical.If the overseeded cover (soybean and oats into sweet corn, or clovers into fall brassicas) is sown too early, it competes against the food crop, and if it is sown too late, shade and moisture competition from the food crop interferes with cover crop establishment. In addition, cultivating to remove weeds or work-in cover crop seed may damage the roots of large plants, such as corn more than knee-high. Precise timing has been part of her success, both with relay planting and post-harvest cover crop planting.

With climate change causing more erratic weather patterns, Pam takes an adaptive approach to maintain living cover. For example, spring cover crops include a mixture of cool-season cereal grains with soybean and/or buckwheat so that at least one of the cover crops will thrive should the spring bring unusually cold or hot weather. In the event that a cover crop or production crop fails, she has contingency plans to keep the soil fed until it is time for the next vegetable planting. Sorghum-sudangrass with its high biomass and extensive root system is her cover crop of choice when a summer vegetable crop fails or finishes early, or if the clovers in the green fallow year become thin or weedy during the heat of summer.

Slide 29 - *On-farm Nutrient Sourcing Elmwood Stock Farm, Georgetown, KY*

Elmwood Stock Farm, located in a region with a climate similar to the Appalachian ridge-and-valley region of Virginia, maximizes within-farm nutrient cycling through their crop-livestock integrated system and by selling only the edible portion of vegetables, meat, poultry, and eggs. Fertilizer and feed supplement purchases amount to only a few pounds per acre of NPK, which reduces costs, minimizes buildup of nutrient excesses, and protects water quality.

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). The farmers are now using intensive grazing and shallow tillage to end the sod phase with less soil disruption and have found that this approach maintains subsequent crop yields. They are also experimenting with alternative crop rotations (annual forage/cover crops with one vegetable or feed grain every other year) to optimize production, soil health, and GHG mitigation outcomes.

Slide 30 – *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 (PL, 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.

Compared to PL, 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 PL may shift the soil microbiome in a way that weakens N cycling and provisioning, thereby perpetuating reliance on these inputs.

Slide 31 – *Nutrient source and NPK balance: vegetable crops*

Typical yields, and estimates for N (lower figures), P, and K removal based on nutrient concentrations given in Knotts Handbook for Vegetable Growers, 5th ed (D. N. Maynard and G. J. Hochmuth, 2007) cited in Wander (2009).

The higher values for N removals are based on vegetable nutritional contents (N = protein / 6.25) cited in Nutrition Almanac, 3rd edition (Donne, 1990).

Extension recommendations for N (regardless of soil test) and for P and K at "high" (optimum) soil test P and K levels are from Virginia Tech (2018).

Nutrient replenishment to maintain optimum soil nutrient levels should aim to balance inputs with exports through harvest. NPK recommendations for fertility maintenance seem appropriate for K, high for N (especially head brassicas), and severalfold too high for P.

Note the low nutrient removal rates for vegetable harvests, especially P. Moderate rates of compost and poultry litter – two amendments commonly used for NPK in organic vegetable production – can approximate Extension recommendations but will build up soil P over time.

Slide 32 – *Nutrient source and NPK balance: field crops*

Nutrient removal estimates for the yields shown are based on Virginia Tech Extension data for nutrient contents per bushel of grain or ton of forage.

Grain crops remove relatively more N and P, and less K, compared to vegetables. Most of the K taken up by the crop is returned in residues. Forage harvests remove substantial amounts of all three nutrients.

Compost and pelleted poultry litter applied at rates sufficient to replenish N will build up P and (for grains) K.

Slide 33 – *Mix and match sources to get the balance right*

Rotating vegetables, grains, and forages with complementary nutrient demands can help balance soil levels and facilitate nutrient budgeting. Growing vegetables with compost or poultry litter year after year will build excess P, while rotating to hay can help draw down the P surplus. Haying year after year can deplete soil P and K reserves, whereas grazing recycles half or more of the nutrients via manure and urine deposition.

Slides 34-38 – *The second R: right rate*

Slide 35 – *Total versus Available N*

Historically recommended rates for organic nutrient resources have been based on their "available" N percentage, the fraction of N in the amendment that moves into the crop during the season of application. However, this can lead to costly and potentially polluting over-application and GHG emissions (Baas et al., 2015). Because soil biological activity mineralizes N and other nutrients from 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 fertilizer application rates based on *soluble* N content nudged yields up by an average of 6% above conventional yields, but also resulted in N losses 21% higher than the conventional treatment.

In warm-temperate, rainy regions such as Virginia, N mineralization from SOM and slow-release N sources can often meet crop needs, and organic N application rates based on total N content will usually sustain crop yields in soils with moderate to high biological activity.

Slide 36 – *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). This and other similar soil series occur in the coastal plain of Virginia.

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, and Kloot (2017, 2018) noted that many soils have tremendous subsoil K reserves that grass cover crop roots can access. Similarly, farmers in a diversity of locations and soil types (NC, ND, IL, OH) have greatly reduced fertilizer inputs and maintained high grain yields by building soil health with high biomass cover crops.

Slide 37 – *Economic optimum nitrogen rate (EONR) for crops in healthy soils can drop to zero*

Researchers at North Carolina State University have documented a close correlation between "soil test biological activity" (STBA, a three-day soil microbial respiration test) and the soils' capacity to make N available to crops through SOM mineralization, and conducted N fertilizer-yield response trials at multiple locations. Farmer fields with high STBA, managed organically or in accord with the NRCS soil health principles, showed so little response to added N that their EONR was zero for corn grain, silage, or fescue forage production (Franzluebbers, 2018; Franzluebbers et al., 2018a). Similarly, high biomass rye-clover cover crops (total N 130 b/ac) supported good organic tomato and summer squash yields with no response to added N, even when the vegetables were no-till planted into roll-crimped covers (Robb & Zehnder, 2016).

In a review of multiple field trials, Khan et al (2013) found that standard K recommendations are far higher than necessary, and sometimes lead to decreased soil health or crop quality. Based on this finding, organic producers with soils testing below optimum in K may not need nearly as much potassium sulfate (K_2SO_4) as suggested by standard soil test recommendations. Using less will save growers money and protect soils from salinity burdens.

Slides 38 and 39 – *Farm story: optimizing fertility in a sandy coastal plain soil*.

Rick and Janice Felker of Mattawoman Creek Farms in Cape Charles, VA (Eastern shore) grow 11 acres of organic vegetables for a CSA, including 1/3 acre under high tunnels. Cover crops and vegetable crop residues (all of which are returned to the soil) provide the primary sources of carbon and nitrogen to sustain soil fertility. Organic fertilizers – pelleted poultry litter 5-4-3 or spent mushroom soil, are applied at moderate rates based on crop need

Outdoor crops are grown in rotation with a winter rye + hairy vetch cover crop, which is planted over the entire field (beds and alleys) to maximize biomass. In spring, the cover crop is mowed, pulled onto bed tops with a front-mounted disk bedder and mixed in shallowly with a rear mounted tiller. For late-planted vegetable crops, the cover crop is mowed and allowed to regrow for a few weeks, during which the vetch fixed additional N. After allowing the cover crop to break down for a few weeks, the farmers add the organic soil amendments and till 3-4 inches deep to prepare the seedbed.

Rotations are "tight" with no unplanted fallow. High tunnels are multi-cropped with same-day "bed flips" (final harvest, amend, and plant next crop on the same day).

Subsurface (3-4 inches) drip irrigation encourages deeper rooting, and infrequent, deep watering helps prevent salt buildup in high tunnels. Noninversion tillage is routinely done with a rototiller run at low PTO speed and higher tractor forward speed (2.5 mph) to minimize damage to soil aggregates and protect soil biology and soil health.

In the farmer's words, "the soil gets better every year" in both field and high tunnel, crop growth and yield are excellent, and crops no longer need in-row fish-seaweed drip fertigation for N. Soil test P remains in the optimum (non-excessive) range and high tunnels show no significant salt buildup even after ten years' continuous production without flushing for salt removal.

This farm exemplifies successful organic nutrient management based primarily on living plants and their residues and legume N fixation, with light use of applied organic fertilizers as a supplement.

Slides 40 and 41 – *Precision organic nutrient management to protect the Chesapeake Bay*

Keenbell Farm, the intensive livestock-crop integrated operation featured in the first webinar of this series, also takes extra measures to protect nearby streams, and thereby the Chesapeake Bay. These include intensive soil sampling for precision application of organic nutrient sources to prevent buildup of N and P excesses. Poultry and pork, which require some feed grain as well as pasture to thrive and produce well, are rotated into areas that need the extra nutrient input provided by their manure.

Other watershed stewardship measures include riparian buffers that are twice the minimum width required by regulation and keeping the steeper hillsides in permanent pasture to avoid runoff and erosion. The integrated soil health management system – tight crop rotations, mixed species cover/forage crops under management intensive rotational grazing, and no-till planting – has resulted in a doubling of total SOM and a greatly increased water- and nutrient-holding capacity, so that nutrient and sediment transport to the farm's water bodies is virtually zero.

Slide 42 – *Broccoli: a challenging crop for nutrient management*

A few crops, including head brassicas such as broccoli and cauliflower, seem to utilize N inefficiently. Field trials at University of California Santa Cruz and on five organic farms in Washington State showed a strong linear yield response in organic broccoli to N applied in concentrated organic sources such as blood, meat, and feather meals, with an economic optimum N rate of 200 lb/ac or more with or without compost or legume-cereal cover crop, indicated an economic optimum nitrogen rate of 215 lb/ac (Li et al., 2009; Collins and Bary, 2017). However, broccoli harvest removed only about 45 lb N/ac, and most of the rest was leached or denitrified during the winter rainy season. Leaching losses have been estimated at 100 – 180 lb/ac, and an additional 11-27 lb N/ac were lost as N2O, a greenhouse gas emission equivalent to the loss of 1,400 – 3,400 lb soil organic carbon per acre (Brennan, 2018; Li et al., 2009; Muramoto et al., 2015).

Why does organic broccoli show such a high EONR while other heavy feeders like corn might reach zero EONR on healthy soils? Part of the answer lies in the high market value of organic broccoli (more than $2/lb wholesale compared to perhaps $10/bu = $0.17/lb for organic feed grain corn).

Why is 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 in California and Oregon (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 at Virginia Tech in Blacksburg, VA (rainy summer) have shown yield responses to 150 lb N/ac in addition to the N from a roll-crimped vetch + rye cover crop.

Slides 43-48 – *The third R: right timing*

Precision timing through split applications is straightforward for soluble N sources and more challenging for organic sources that must undergo biological processing before plant uptake.

Slide 44-46 – *Synchronizing N release with crop N demand*

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 N is translocated from leaves to developing fruit, grain, or tuber.

N use efficiency is maximized when the release of plant-available nitrogen (PAN) 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. N released too slowly becomes available only after the crop has entered the maturation phase, resulting in crop N limitation and an increased risk of late season leaching or denitrification losses.

An organic fertility program that provides ideal crop N nutrition in warm, moist, aerobic, biologically active soil may release N too slowly in cold, wet, or hot dry conditions, or if soil life and soil health are below par.

For example, organic no-till corn planting into roll-crimped cover crops often results in severe N deficiency and yield reductions in cooler regions with medium to fine textured soils, such as the northern half of the Corn Belt. Similar conditions may occur in the Appalachian region of Virginia, where temperatures average 10-15°F lower than the Piedmont and Tidewater regions, and many of the Ridge-and-Valley soils have a loam or silt-loam texture. Field trials with vegetable crops transplanted no-till into roll-crimped cover crops have shown similar N-related yield limitations.

Conversely, in the coastal plain of Virginia, warm rainy climate, long growing season, 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 47 - *Asynchrony of N supply and N demand in an organic strawberry field in the Northern region, CA*

This slide, taken from a 2015 webinar with permission from Dr. Joji Muramoto of University of California at Santa Cruz, shows an extreme example of poor timing of N mobilization relative to crop N demand. While this example is from a region very different from Virginia, it illustrates the challenge of synchronizing N mobilization with N demand.

California hosts 85% of US strawberry production. In the coastal regions of central CA, mild, dry summers allow prolonged harvests and high yields of disease-free fruit. However, N management for organic is especially challenging because of the long lag phase in the crop's N utilization, which often renders 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).

During the time of greatest N demand by the strawberry crop (June-August), dry summer conditions hinder N mineralization from SOM and from slow-release organic sources like compost; thus, in-row drip fertigation may be the only practical means to meet the crop's N demand.

In Virginia, warm, rainy summers and moderately cold winters help synchronize N mineralization with crop demand. However, the increasingly erratic rainfall patterns associated with climate change including both "flash drought" and deluge are making N timing more challenging.

Slide 48 – *Winter cover crops recover leftover N*

While strawberry planted after broccoli in central California cannot utilize the leftover N, vigorous, deeper-rooted winter cover crops 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 is well drained but has a root-restrictive layer at 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. Whenever 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 NOP allowed 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 comprised the majority of organic carbon inputs (Brennan & Acosta-Martinez, 2017).

These findings are relevant for Virginia, as our winters often deliver sufficient moisture to leach or denitrify any soluble N leftover from the preceding growing season. Especially with climate change resulting in warmer winters with more rain, less snow, and less ground freezing, N leaching risks during winter fallow may become quite similar to those seen in central California.

Slides 49-52 – *the fourth R: right placement*

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 may help with the "right placement" of soluble N.

Slide 50 – *Delivering N directly to the roots*

What if the soil life could deliver soluble N directly to plant roots as they need it, without flooding the bulk soil with soluble N that would be subject to leaching and denitrification? This happens in the legume-Rhizobium symbiosis, in which atmospheric 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. For example, landraces of corn have been identified that derive up to 40% of their N requirement from N fixing rhizosphere microbes, and plant breeders have successfully transferred this trait to modern grain corn hybrids, enabling them to thrive and yield in low-N soils and on greatly reduced fertilizer rates (Goldstein, 2015, 2016, 2018). Some other warm-season grasses including pearl millet can also host N-fixing microbes to meet part of their N requirement.

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, increase plant resilience to stress and diseases.

Slide 51 – *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 a fairly high C:N compost (20:1) derived from diverse organic materials mixed together. 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 were unable to mineralize sufficient N for crop nutrition, while seven N-saturated fields that received most of their N in relatively concentrated (low C:N) forms showed high microbial activity but with lower levels of N cycling enzymes and higher levels of enzymes involved in SOM oxidation.

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.

These nutrient management strategies will likely work well in Virginia. Building soil health enhances N cycling and can reduce EONR for heavy feeder crops in the southeastern US to zero (Franzluebbers, 2018; Franzluebbers et al., 2018a). In-row drip fertigation (as shown in the photo) or band application can give crops a needed N boost at critical times without flooding the bulk soil with soluble N, thereby maintaining the soil microbiome's capacity to mineralize N from SOM and minimizing N leaching losses.

Slide 52 – *How to promote root zone N mineralization*

Beneficial microbes thrive in the rhizosphere when plants deliver sufficient root exudates. In a research review, Prescott et al (2021) identified three strategies to promote root exudation and thereby enhance microbial activity and soil biological functions:

- Keep plant available N and P levels, and irrigation levels slightly below the optimum for top growth. These slight deficits do not inhibit photosynthesis; therefore they create a surplus of photosynthetic product that the crop sends into the root zone and the rhizosphere as root exudates. Yields are not adversely affected and may benefit from enhanced root growth and rhizosphere microbiome.
- Include legumes in the crop rotation - they provide excellent nutrition for soil microbes.
- Time rotational grazing events late in the rapid growth phase of the forages.

The authors did not evaluate impacts on N cycling; however, providing sufficient microbial "food" in the form of root exudates seems likely to enhance this microbial function as well.

Avoiding N and P excesses and limiting use of concentrated (low C:N) organic N sources appears important for sustaining the desired soil microbiome. However, the California tomato study suggests that, if crops need a boost (e.g., in early development before they develop a deep and extensive root system), using small doses of concentrated N in the row may be compatible with efficient biological N cycling.

Finally, there is growing evidence that crop cultivars have genetic differences in their capacity to partner with beneficial microbes, and that crops can be bred and selected for nutrient efficiency. The USDA Organic Research and Extension Initiative is funding several farmer-participatory plant breeding endeavors that are exploring this potential.

Slide 53 – *Summary of organic nutrient management tips*

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