# Soil Health and Organic Farming

## Nutrient Management for Crops, Soil, and the Environment

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# SOIL HEALTH AND ORGANIC FARMING

## NUTRIENT MANAGEMENT FOR CROPS, SOIL, AND THE ENVIRONMENT

## An Analysis of USDA Organic Research and Extension Initiative (OREI) and Organic Transitions (ORG) Funded Research from 2002-2016

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Cover photo: Organic Seed Alliance

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## Introduction

Throughout the history of organic farming, practitioners have recognized healthy, living soil as the foundation of crop, livestock and human nutrition (Howard 1847). Soil organic matter and soil organisms are the primary source of fertilizer on organic farms. In this context, the grower's job is to protect and nourish soil life and replenish organic matter and nutrients removed in harvest. The saying, feed the soil and the soil will feed the plant, has been the guiding principal of organic farmers since the movement began.

Concerns with conventional agriculture include its dependence on soluble nitrogen (N), phosphorus (P), and potassium (K) fertilizers. This "feed the crop" approach bypasses natural processes and can injure soil life, degrade soil quality, pollute surface and ground water with nutrients, and increase emissions of the powerful greenhouse gas (GHG) nitrous oxide ($N_2O$) (Carpenter-Boggs et al., 2016; Wander, 2015).

Organic producers replenish organic matter and nutrients with compost, manure, legume cover crops, and natural mineral fertilizers, and rely on soil life to mineralize (release) crop-available nutrients from these materials (Figure 1). This gradual, season-long process is thought to act as a "buffer" that reduces risks of under- and over-fertilization, making organic systems both more resilient (yield stability) and less likely to degrade water quality or emit GHG. However, several nutrient management issues have emerged for organic producers, including:

- The complex nature of biologically-regulated nutrient release makes it difficult to predict the amount and timing of nutrient availability to crops.
- Organic crop yields are often N-limited.

*Figure 1. Composted animal manure is an important nutrient source for organic farmers, Chris Coulan, USDA*

- Organic N sources used at higher rates to meet crop demand can leach N or release $N_2O$.
- The use of compost and manure as primary NPK sources can build up excessive soil P.
- Conventional soil test recommendations can be challenging to “translate into organic.”
- Practices that build long-term soil health and fertility can entail short-term yield tradeoffs.

Organic producers need additional science-based information and nutrient management tools to help them realize satisfactory production, soil health, and environmental outcomes. More than half of USDA funded organic research projects between 2002 and 2014 addressed various aspects of nutrient management and accomplished significant advances (Schonbeck, Jerkins, and Ory, 2016). Yet, nearly two-thirds of 1,403 organic farmers in a 2015 survey cited soil fertility and nutrient management as a high research priority (Jerkins and Ory, 2016). The goal of this report is to help organic and transitioning producers better understand practical implications of research outcomes, access practical tools, and adopt best nutrient management practices.

## Challenges in Organic Nutrient Management

The organic adage, “feed the soil, and the soil will feed the plant,” implies that applying organic materials to the soil in lieu of soluble fertilizers will guarantee adequate and balanced crop nutrition. To new and transitioning organic farmers, the soil life (soil food web, Figure 2) can seem like a magic black box that they trust will provide sufficient plant nutrients at just the right time to sustain yields without harming water quality or emitting GHG—but will it actually work? Organic crops are often nutrient limited and nutrient sources allowed by the USDA National Organic Program (NOP) can contribute to nutrient pollution (Baas et al., 2015; Caldwell et al., 2012; Edgell et al., 2015; Li et al., 2009; Ryan et al., 2015). Many factors affect the outcome of organic nutrient management practices, including:

- Regional and climatic factors, e.g., seasonal temperature and rainfall patterns.
- Soil texture, mineralogy, structure, aeration, moisture, and pH.
- Soil health; especially the activity, diversity, and balance of the soil food web.
- Crop rotation and recent cropping history.
- Amount and timing of nutrient demands of the crops grown.
- Amount, nutrient contents, and carbon: nitrogen (C:N) ratio of amendments applied.

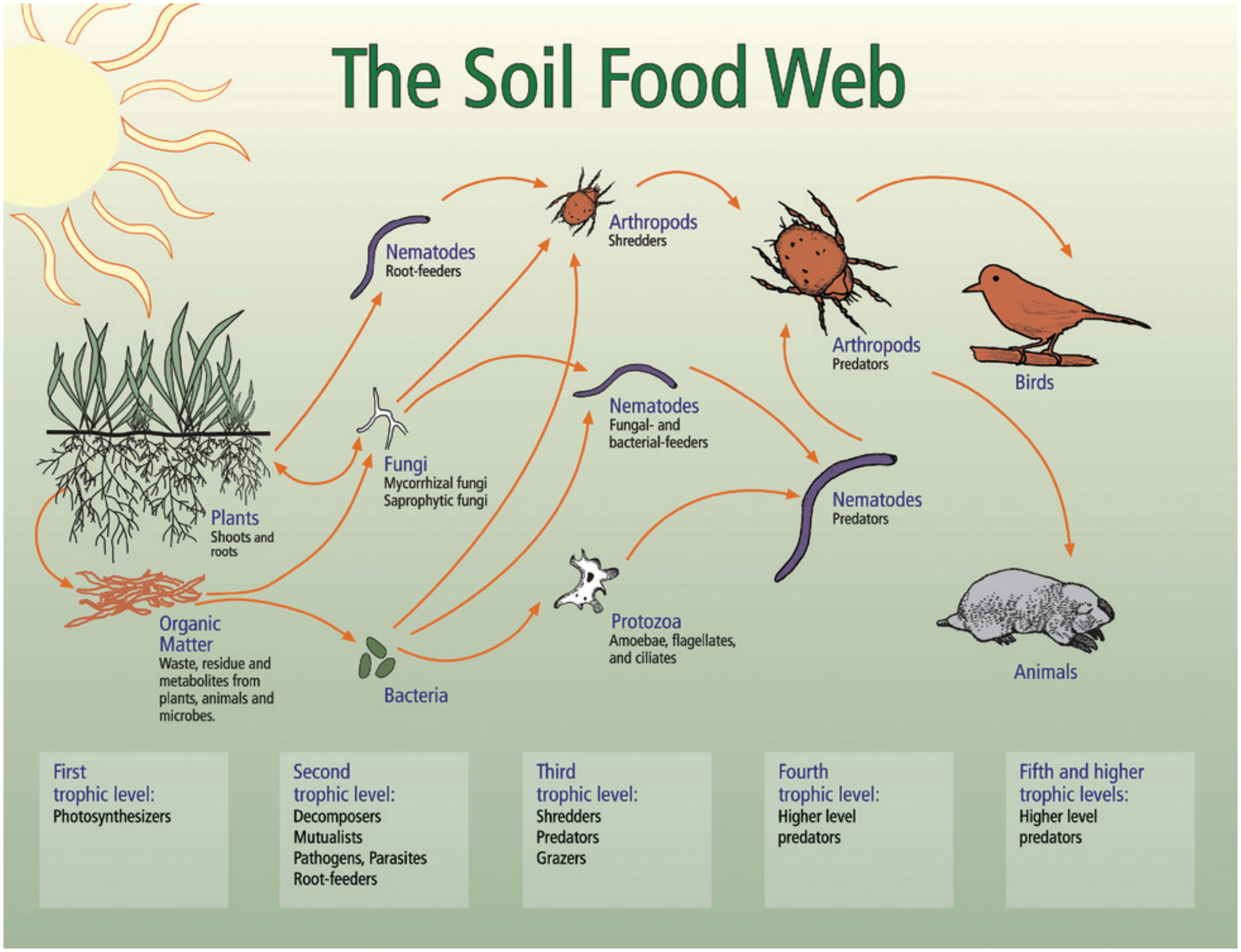

*Figure 2. The soil food web, USDA NRCS*

Research has begun to open the “black box” of soil life, identifying how key soil organisms and processes mediate nutrient retention and crop nutrition (Briar et al., 2011; Bhowmik et al., 2015a, 2015b; Ugarte and Zaborski, 2014). Some (but not all) organic fields demonstrate “tight nutrient cycling,” in which soil-microbe-plant interactions provide sufficient N to crops while maintaining low bulk soil soluble N levels (Jackson and Bowles, 2013). However, much remains to be learned about soil life and nutrient dynamics before practical applications can be developed for the gamut of crops, soils, climates, and agricultural regions.

In the meantime, many organic producers rely on standard soil tests as a starting point and attempt to meet conventional NPK recommendations with NOP-allowed materials. However, calibrating nutrient delivery via soil biology is more complex than feeding crops directly with soluble fertilizers, especially for N (Gaskell et al., 2009). In biologically active soils, nutrient levels reported on a soil test may not accurately reflect crop nutritional status, especially when strong plant-microbe interactions take place immediately adjacent to plant roots (rhizosphere).

Plant-available nitrogen (PAN) consists of the soluble forms nitrate-nitrogen ($NO_3$-N) and ammonium-nitrogen ($NH_4$-N). Organic crops become N-limited when N mineralization – conversion of organic N into PAN does not match crop N needs. This can occur when:

- Soil organic matter, biological activity, and overall soil health are below optimum, as often occurs in fields newly transitioning into organic production.
- Cold, wet, or hot dry weather interfere with biological processes that release PAN.
- Moisture constraints limit or foreclose the use of legume cover crops in semiarid regions.
- The crop requires a lot of N in a short period of time when cool soil conditions limit N mineralization, such as spring brassicas or spinach, or corn in cooler climates.
- The farmer seeks to improve soil health by reducing tillage, especially in cooler climates.
- High-carbon (C) organic materials or crop residues are used to build soil organic matter.
- Nutrient-rich inputs like poultry litter or an all-legume plowdown (incorporation into the soil) release PAN before the crop can utilize it, and the PAN is lost to leaching or denitrification.

Small-scale farmers often use compost and other organic nutrient sources liberally on high value crops like vegetables and strawberries, which can result in N and P excesses, nutrient leaching and runoff, and/or $N_2O$ emissions (Cavigelli et al., 2014; Edgell et al., 2015; Li et al., 2009, Muramoto et al., 2015). In addition to water quality risks, excessive soil P levels can tie up micronutrients and inhibit mycorrhizal (root-symbiotic) fungi that play important roles in plant health (Hu et al., 2015b; Magdoff and van Es, 2009; Wander, 2015; Wander et al., 2016). On the other hand, the high cost of organic nutrient sources can lead to sub-optimum application rates in large-scale production of lower-value grain crops (Caldwell and Ryan, 2013; Norton et al., 2014; Reeves and Creech, 2015), and an undesirable net drawdown in soil nutrient reserves, especially K (Mohler et al., 2009).

Timing can be critical for N released from a preceding crop in the rotation. For example, in upstate New York, the flush of PAN about six weeks after a red clover plowdown matched N demand by a following crop of field corn resulting in high yields and N efficiency (Ketterings et al., 2011). In contrast, broccoli residue incorporated just before late-fall strawberry planting in California released a large pulse of PAN six months before the strawberry N demand peaked, and some 100 lb. N/ac from the broccoli was leached by winter rains (Muramoto et al., 2015).

Another challenge is that the soluble and total nutrient contents in manure and compost from different sources can vary several-fold (Spargo, 2012a); thus using average values given in Extension bulletins or other references can lead to gross under- or over-application of nutrients.

Finally, most modern crop varieties have been bred and selected in and for conventional production systems, which provide nutrients in soluble forms. These varieties may be less adapted to organic systems that rely on biological processes for crop nutrition. Several farmer-researcher teams have received USDA funding to develop and evaluate cultivars in organic systems with biologically based nutrient management (Schonbeck, Jerkins, and Ory, 2016).

## Best Management Practices and Information Resources for Nutrient Management for Soil Health and Crop Yields in Organic Production

Organic nutrient management is inherently knowledge intensive and site specific. For example, while cover cropping plays a central role in annual crop rotations, the practice will look quite different for vegetable production in a sandy soil in Georgia, field crops in an Iowa silt loam, and dryland grains in an alkaline Montana soil. Yet, research has identified some broadly applicable trends and principles that can provide the basis for your fertility program. Start with these and select the best suite of practices for *your* farm based on:

- Soil type, texture and condition; topography; climate and rainfall regime.
- Land base, scale of operation, equipment, labor, and other resources.
- Farming system, enterprise mix, and nutrient needs of crops to be grown.
- On-farm and nearby sources of nutrients and organic matter.
- On-farm and nearby environmental considerations such as streams and other surface waters,

ground water, and ecologically sensitive habitats.
- Information resources developed for your region and cropping system (Table 1).

*Resources for basic principles of organic soil and nutrient management: 2, 3, and 4 in Table 1, pg. 17.*

## Getting Started: Soil Type, Soil Testing, and Meeting Crop Nutritional Needs

The first steps in organic nutrient management are to know your current soil and its nutrient status, and to monitor soil nutrient trends and crop responses.

Use the NRCS Web Soil Survey to identify your soil type(s) (series), texture, mineralogy, land capability class, and any drainage, erodibility, or other constraints.

Obtain soil tests for each field, including pH, P, K, secondary and micro-nutrients, SOM, and cation exchange capacity (CEC).

- Use conventional NPK and lime recommendations as a guide and adjust inputs depending on the organic materials applied, crop rotation, and soil conditions.
- Plan and manage nutrient inputs to attain and maintain “high” (H) levels (optimum), and to draw down “very high” (VH) levels (excess), especially for P and K.
- Monitor and manage other essential plant nutrients, including calcium (Ca), magnesium (Mg), sulfur (S), boron (B), copper (Cu), zinc (Zn), manganese (Mn), iron (Fe), and for legumes molybdenum (Mb).

> “*Soil organic matter contains an estimated 95 percent of soil N and 40 percent of soil P, and with the right levels and conditions, it may provide all of the N and P needs of a crop.*”
> (Rangarajan, 2009).

> “*I always recommend that farmers use test strips to evaluate a new organic fertility input.*”
> (Brian Caldwell, Cornell Cooperative Extension, 2016, personal communication)

- Monitor sodium (Na) and total soluble salts in salinity-prone soils and high tunnels.
- Retest fields every 1-3 years using the same lab to monitor trends and adjust inputs.
- Obtain crop foliar nutrient analyses to determine what the crop is actually "seeing." This can differ from soil test indications, especially in organic systems.
- Conduct side by side comparisons or test strips of a crop grown with and without the material to fine-tune nutrient applications or evaluate a new amendment.

Note that standard soil tests do not report N *per se,* because soluble N levels are highly variable and difficult to interpret. A few labs offer an estimate of annual PAN mineralization from SOM. Conventional N recommendations are based on an estimate of total crop N needs. Several in-season N tests have been developed for field corn production, including the pre-sidedress soil nitrate test (PSNT, a measurement of soil nitrate-N concentrations between surface and 12 inch depth, taken when the corn crop is 6-12 inches tall) and the Illinois Soil Nitrogen Test (ISNT, an index of expected N release from SOM) to determine the need for sidedress N, and the late season corn stalk nitrate test (CSNT) to determine if N inputs were low, optimum, or excessive. However, the PSNT and ISNT may overestimate the need for N in organic grain rotations with legume plowdown ahead of corn (Ketterings et al., 2011), and these tests have not been calibrated for other crops.

Considerations for organic N management include:

- Estimate N credits from SOM mineralization, legumes, manure, and compost; then apply additional organic N if needed to meet expected crop N demand.
- Conduct side-by-side tests of crops grown with different amounts of supplemental N (including none) and adjust practices according to crop response.
- The ISNT, PSNT, or CSNT can be useful, but require interpretation for organic systems.
- Build and maintain the soil's capacity to provide PAN by replenishing SOM and organic N with legume and other cover crops, compost, and other organic inputs.
- Balance low- and high-C:N inputs to enhance nutrient cycling and minimize N losses.
- Use in-row drip fertigation (delivery of liquid fertilizers such as fish or fish-seaweed based products into the crop row via drip irrigation) to enhance precision of N amount, placement, and timing.

*Resources for soil, amendment, and crop foliar testing, nutrient budgets, and adapting recommendations for organic systems: 1, 2d, 2g, 3a, 3b, 3d, 4, 5, 9, 10, 13b, 13c, and 14 (fertigation) in Table 1, pg. 17.*

## Use Cover Crops to Provide N and Manage Nutrients

Cover crops add organic matter and N (legumes) to the soil and can enhance availability of P, K, and micronutrients when they test below optimum, yet will not add these nutrients where they are already ample (Figure 3). Because soil organic C and N must be replenished regularly, cover crops play a key role in soil and nutrient management in annual crop rotations, especially in soils high in P or K. Some cover crop considerations include:

- Choosing the best cover crops for your region, soils, and seasonal niche in the crop rotation.
- Planting legumes to add N to soils with low plant available N (PAN) levels.
- Planting non-legume covers in soils with high or surplus PAN.
- Planting a mixture in soils with moderate, variable, or unknown PAN. The legume will fill in where N is low, and non-legumes may dominate where N is higher.
- Using legumes to provide N when high soil P limits manure and compost use.
- Inoculating legume seeds with the correct Rhizobium strain to optimize N fixation.
- Adapting mixtures (species, seeding rates) for your site to obtain desired balance between N-fixing, nutrient recovery,

> *“Soil management is the foundation of organic farming, and nitrogen-fixing cover crops are a key component of any organic soil fertility management regimen.”*
> (Drinkwater, 2011b)

> *“[L]egume cover crops are often sufficient to provide the nitrogen needs of an organic corn crop in the mid-Atlantic region.”*
> (Cavigelli et al., 2014)

> *“A common misunderstanding about [cover] crops is that the N is used more efficiently because it’s from a plant source. N can be lost from a green manure system almost as easily as from chemical fertilizers, and in comparable amounts.”*
> (Sarrantonio, 2009)

and other functions (biomass, weed suppression, etc.).
  - Adjust non-legume seeding rates to avoid outcompeting the legume. Mixtures with legume comprising ~50% of top growth optimize biomass and N fixation.
  - Mow tall non-legume to enhance growth and N fixation by low-growing clovers.
  - Combine species with complementary growth habits (tall grass / vining legume) or growing season (summer grass or buckwheat / cool season clover or pea).
- Growing cover crops to maturity (full height, early bloom to early seed set) for maximum biomass, soil health benefits, N fixing, and nutrient recovery.
  - Terminate earlier in colder climates where decomposition and N mineralization are slower, later in warm climates with longer growing seasons.
- Using deep-rooted grasses or crucifers to scavenge surplus nutrients.
  - Oilseed, forage, or ‘tillage’ radishes are superb NPK scavengers, recovering excess nutrients from the top 4-5 feet of the soil profile.
  - Sorghum-sudangrass, rye, and other cereal grains and are good N scavengers.
- Managing cover crop N to match N needs of the following crop and avoiding leaching losses.
  - Cereal grains and other grasses with high C:N ratio can temporarily tie up N.
  - Legumes and crucifers have lower C:N ratio and release PAN rapidly. .
  - Cover crops terminated while still vegetative have lower

*Figure 3. Winter pea, crimson clover, and cereal rye cover crop mix, USDA NRCS*

> *“Expert farmers design their rotations to (1) earn income, and (2) increase soil quality or build soil capital.”* (Johnson and Toensmeier, 2009)

> *“[A]lternative rotations or different crops … may be considered to strategically capture, export, or contribute essential plant nutrients.”* (Rangarajan, 2009)

C:N ratio and faster PAN release than the same cover crops terminated at or after flowering.

  - Follow low-N covers like cereal rye with strong N fixers like soybean.
  - Follow N-rich covers with heavy N feeders like corn or cruciferous vegetables.
- Using cover crops in conjunction with compost or manure at appropriate rates may enhance long term soil health and fertility over either cover crop or inputs alone.

*Resources for cover cropping for organic nutrient management: 3a, 3b, 3c, 4, 5, 6, 7, 8, 9, 10, 11a, and 11b in Table 1, pg. 17. See the companion guide, Cover Crops: Selection and Management.*

## Rotate Crops Strategically

- Include a perennial legume-grass sod phase in the rotation to restore soil organic C and N reserves, reduce N leaching and denitrification, enhance soil potential to deliver PAN in a timely manner, and improve overall soil health.
- Include deep rooted perennial or annual crops to retrieve nutrients from the subsoil.
- Plant field corn or other heavy feeder after breaking a clover or alfalfa sod to make best use of legume N. Additional N (compost, manure, etc.) may not be needed.
- Interseed or frost-seed red clover or other low growing shade tolerant legumes into cereal grains, vegetables, or row crops where moisture is sufficient to sustain both crops.
- Perform a nutrient budget analysis for the complete rotation cycle, including all nutrient inputs and nutrient exported in harvests, to determine net nutrient flows, and adjust practices accordingly.

*Resources for crop rotation and nutrient management: 3a, 3c, 2, 11b, 13, and 13a in Table 1, pg. 17.*

## Use Manure, Poultry Litter, and Compost Judiciously

Multiple studies have confirmed that good quality compost builds long term soil health and fertility, and the benefits of cover crops, amendments (compost and manure), and conservation tillage appear *additive* and *complementary*. However, compost and manure must be used judiciously to avoid nutrient excesses. Some guidelines to consider include:

- Obtaining a complete nutrient analysis for any manure, poultry litter, or compost to be used.
- Adjusting application rates according to soil test P levels and amendment nutrient analysis.
    - On soils testing low to medium in P, use manure or poultry litter compost to meet (but not exceed) crop N needs and build soil P. Account for green manure and other N sources to better estimate actual crop N need.
    - On soils testing high or optimum in P, adjust application rates to replenish P removed in harvest but not more. If more N is needed, use legumes or low-P organic N sources like feather meal.
    - On soils testing very high or excessive in P, avoid poultry litter products, and use a plant-based finished compost at rates that allow a net drawdown in P.
- Using composted manure, which may build active and stable SOM, organic N, and overall soil health more effectively than raw manure.

“*On a national basis, the [annual manure from cattle, hogs, and chickens] contains about 23 million tons of nitrogen [worth] $25 billion … If you’re not getting the full fertility benefit from manures on your farm, you may be wasting money.*

*“It’s impossible to give blanket manure application recommendations. They need to be tailored for every situation.”* (Magdoff and van Es, 2009, p 129)

“*Composts are excellent organic amendments for soil.”* (Magdoff and van Es, 2009, p 141)

- Using solid manure with bedding, which builds SOM more than liquid or slurry manure (which is rich in soluble N and low in C, and may even cause a net loss in SOM).
- Using poultry litter products in moderation. Reliance on these materials as the primary nutrient source can lead to:
  - Accumulation of excess P, Ca, Zn, or Cu in the soil, or alkaline soil pH.
  - Net SOM oxidation because of the low C:N ratio.
  - Increased risks of nutrient leaching, runoff, or $N_2O$ emissions.
- Balancing nutrient-rich manure with higher C:N materials or cover crops.
- Applying uncomposted (raw or aged) manure no less than 120 days prior to harvest of a food crop for NOP compliance and food safety.

*Resources for manure and compost management in organic systems: 2, 3a, 3d, 4, 10, 11b, 11c, 12, 13, and 20 in Table 1, pg. 17.*

## Nutrient Management for Cereal Grains

The amount and timing of N applications for winter cereal grains can be especially challenging in organic systems. A few tips based on organic research outcomes include:

- Applying N at planting to increase yield, and at mid-growth to boost grain protein.
- Utilizing and accounting for legume plowdown ahead of grain.
- Using heritage or ancestral wheat varieties, which may lodge at the high N rates recommended for modern wheat.

*Resources for nutrient management in organic cereal grains: 4, 11, 12, and 13 in Table 1, pg. 17.*

## Nutrient Management for Vegetables

Vegetable crops present special challenges in co-managing nutrients and soil health (Figure 4). Most are heavy feeders for N, P, and/or K, and most leave scant residues to feed soil life or restore SOM. In addition, many organic vegetable growers work with limited acreage, and must crop intensively just to stay in business. Some tips to maintain soil health and crop yields include:

- Testing soil, amendments, and crop foliage regularly to fine-tune nutrient budgets.
- Using side-by-side test strips to assess crop response to fertilizers.
- Integrating cover crops into the crop rotation to maintain SOM and soil health, fix N, scavenge nutrients, and reduce the need for applied nutrients.
- Reducing intensity or frequency of tillage whenever practical.
- Using in-row drip fertigation to deliver nutrients in synch with crop demand.
- Monitoring nutrient and salt levels in high tunnels, and replenishing SOM and organic N without adding excess P and other nutrients; include cover crops in the rotation if practical.

Figure 4. Intensive organic vegetable production, USDA NRCS

*Resources for nutrient management in organic vegetable crops: 3, 5, 8, 13, and 14 in Table 1, pg. 17.*

*See also the companion guide, Practical Conservation Tillage.*

## Nutrient Management for Berries and Tree Fruit

Fruit crops are not as heavy NPK feeders as vegetables, but they require moderate, timely N applications and balanced nutrition. Untimely (late season) N can compromise winter hardiness. Tree fruit are sensitive to micronutrient levels, especially boron (B) and zinc (Zn). Orchard floor and alley management practices can greatly impact soil health and crop nutrition. A few tips to consider include:

> “*Vegetable lands have generally been worked hard over many years and have a long way to go toward improved soil health.”*
>
> (Magdoff and van Es, 2007, page 273)

- Monitoring crop nutrition through regular foliar analysis.
- Avoiding or minimizing bare soil or tilled fallow; mulching or mowing for weed control.
- Considering the pros and cons of weed mat (landscape fabric) for crop rows:
  - Use weed mat to suppress weeds during crop establishment.
  - Lay mat in a “zipper” arrangement (two strips overlapping in crop row), to facilitate subsequent applications of compost and other amendments.
  - Monitor weed mat impacts on soil temperature, crop nutrition, and fruit quality.
  - Do a side by side comparison of weed mat versus other practices.
- Testing mulch materials and adjusting use rates accordingly. Organic mulches build SOM and soil health, but may tie up N, or add large amounts of N, P, K, and other nutrients.
- Maintaining alleys with grass-legume sod or other living mulch managed by mowing; blowing clippings into crop rows to provide N and build SOM.
- Acidifying compost if needed by adding 3 to 6 lbs. elemental sulfur per ton for blueberries, which require acidic soil (pH ~5.0) and respond better to plant-based compost than manure compost.
- Managing amount and timing of nutrient inputs carefully, especially for strawberries, in which pre-plant N may be readily leached before crop uptake can occur.

*Resources for nutrient management in organic fruit: 3d, 15, 156, 17, 18, 19, and 20 in Table 1, pg. 17.*

## Manage N and P to Protect Water Quality and Avoid Nitrous Oxide Emission

Organic nutrient management can be especially challenging in crops with high nutrient demands, and on land that has recently transitioned into organic production. In these circumstances, producers often compensate for the slower and less predictable release of nutrients from organic sources by increasing application rates. A few tips for minimizing environmental risks include:

- Starting with less nutrient-demanding crops on newly transitioned land.
- Avoiding over-applying N, especially on sandy, fast-draining soils subject to leaching, and on wet soils rich in organic matter, which are subject to denitrification.
- Planting cover or production crops with deep, extensive root systems to scavenge nutrients.
- Incorporating a succulent legume or crucifer green manure, which can release large amounts of

PAN in a short time. Plant a fast-growing heavy N feeder promptly after plowdown.

- Avoiding over-applying P, especially in ecologically sensitive watersheds. Take special care with poultry litter products where soil P is high or runoff to surface waters can occur.

*Resources for optimizing water quality and minimizing climate impacts in organic nutrient management: 3a, 3b, 19, and 20 in Table 1, pg. 17.*

## What About "Nutrient Balancing" and "Base Cation Saturation Ratio"?

The balance among C, N, P, and K in the soil impacts soil health, crop nutrition, and water quality, as discussed above. Note that crop production consumes five to ten pounds each N and K for each pound of P; thus manure or compost with equal amounts of N, phosphate ($P_2O_5$), and potash ($K_2O$) (e.g., 1-1-1) may build up soil P if used as the primary source of N or K.

The relative amounts of the cation nutrients calcium (Ca), magnesium (Mg), potassium (K), and sodium (Na) can exert subtle effects on soil biology and crop nutrition. Extremely high levels of one cation can accentuate plant deficiency in another. The Base Cation Saturation Ratio (BCSR) method recommends base saturation of 65-80% Ca, 10-20% Mg, 2-5% K, and 0.5-3% Na for optimum crop health and pest resistance. However, research has not supported large investments in mineral amendments simply to make a particular soil conform to these criteria if plant nutrition is adequate at current levels (Schonbeck, 2000). Some nutrient balancing guidelines include:

- Balancing N, P, and K inputs to match crop demands; build soil P or K only if needed.
- Balancing C and N to optimize organic matter, soil life, and nutrient cycling.
- Liming to correct acidic pH; use *calcitic* (high-Ca) limestone if Mg tests "very high" (>20%) and *dolomitic* (high-Mg) limestone if Mg tests "low" (<10%).
- Very high K can aggravate Ca or Mg deficiency, and *vice versa*. Address the deficiency and avoid or minimize additions of the surplus nutrient.
- Performing a foliar analysis to identify crop nutrient deficiencies or excesses.
- Using lime, sul-po-mag, and potassium sulfate with care and in small increments to avoid upsetting nutrient balance on sandy, low-CEC soils.

- For physiological Ca disorders such as blossom end rot or tip burn, foliar Ca applications with a NOP-approved material may be more effective than soil-applied lime or gypsum.

*Resources for nutrient balancing and BCSR: 3a, 3d, and 22 in Table 1, pg. 17.*

## Table 1. Information Resources and Tools for Organic Nutrient Management

1. **NRCS Web Soil Survey** http://websoilsurvey.sc.egov.usda.gov/App/HomePage.htm**.**
2. **Soil and Fertility Management in Organic Farming Systems page on eXtension** http://articles.extension.org/pages/59460/soil-and-fertility-management-in-organic-farming-systems.
    - a. *Organic Soil Fertility* (M. Wander, N. Andrews, and J. McQueen, 2016)
    - b. *Soil Fertility in Organic Farming Systems: Much More than Plant Nutrition* (Wander, 2015)
    - c. *Nutrient Management Plans and Fit with Organic Systems Plan* (C. Gala and M. Wander, 2015)
    - d. *Nutrient Budget Basics for Organic Farming Systems*. (M. Wander, 2015)
    - e. *Soil Microbial Nitrogen Cycling for Organic Farms*. (L. Jackson, 2010)
    - f. *Managing Manure Fertilizers in Organic Systems*. (M. Wander, 2015)
    - g. *Conventional Chemical Soil Testing in Organic Farming Systems* (E. Phillips, 2014, U. Illinois)
    - h. *Soil Nematodes in Organic Farming Systems*. (C. Ugarte and E. Zaborski, 2014)
3. **SARE Books** http://www.sare.org/Learning-Center/Books.
    - a. **Building Soils for Better Crops: Sustainable Soil Management** (F. Magdoff and H. van Es, 2009, 294 pp.)
    - b. **Managing Cover Crops Profitably, 3rd Edition** (Clark, A., ed., 2007, 244 pp.)
    - c. **Crop Rotation on Organic Farms, a Planning Manual** (C.L. Mohler and S. E. Johnson, eds., 2009, 156 pp.) Published jointly by SARE and Cornell University.
    - d. **Using Organic Nutrient Sources** (E. Sanchez, 2009, 16 pp, NE SARE). http://www.nesare.org/Dig-Deeper/Useful-resources/Northeast-guides-and-books/Whole-Farm-Nutrient-Planning-for-Organic-Farms.

4. **Risk Management Guide for Organic Producers** (K. Moncada and C. Sheaffer, 2010, University of Minnesota, 300 pp). Chapters on soil health, soil fertility, crop rotation, and organic corn, soybean, cereal grain, and forages. http://organicriskmanagement.umn.edu/

5. **Soil Fertility in Organic Systems: A Guide for Gardeners and Small Acreage Farmers** (D. Collins, C. Myers, C. Cogger, and R. Koenig, 2013). Pacific Northwest Extension bulletin PNW 646, 19 pp. http://cru.cahe.wsu.edu/CEPublications/PNW646/PNW646.pdf, linked from http://csanr.wsu.edu/program-areas/organic-agriculture/.

6. **Using Cover Crop Mixtures to Achieve Multiple Goals on the Farm** (Mary Barbercheck et al., Penn State, 2014). Webinar, integrating weed management with other cover crop goals. http://articles.extension.org/pages/71186/using-cover-crop-mixtures-to-achieve-multiple-goals-on-the-farm-webinar.

7. **Cover Crop page on eXtension,** http://articles.extension.org/pages/59454/cover-cropping-in-organic-farming-systems**.** Articles with practical nutrient-management info:

   a. *Estimating Plant-Available Nitrogen Contribution from Cover Crops* (Webinar)

   b. *Assessing Nitrogen Contribution and Rhizobia Diversity Associated with Winter Legume Cover Crops in Organic Systems* (Webinar)

   c. *Legume Inoculation for Organic Farming Systems*

   d. *Making the Most of Mixtures: Considerations for Winter Cover Crops in Temperate Climates*

   e. *Optimizing the Benefits of Hairy Vetch in Organic Production* (Webinar)

   f. *Radishes – a New Cover Crop for Organic Farming Systems*

   g. Articles on cereal rye, buckwheat, hairy vetch, and other individual cover crops

8. **Special Supplement on Legumes as Cover Crops** The Natural Farmer, Summer, 2011. http://www.nofa.org/tnf/Summer2011B.pdf. Articles include:
    a. *It's Elemental: How Legumes Bridge the Nitrogen Gap*
    b. *In the Mix: Effective inoculation pairs active rhizobia with symbiotic legumes*
    c. *Perennial Favorite: Legumes Boost Fertility and Smother Weeds in Asparagus*
    d. *Building Soil with Cover Crops at the Poughkeepsie Farm Project*
    e. *A Holistic View: Leguminous Cover Crop Management in Organic Systems*
    f. *Roxbury Farm: Cover Cropping and Soil Building on a Working Farm*
    g. *An Interview with Eric Nordell: Cover crops to Suppress Weeds, Boost Biomass, and Fix Nitrogen*
9. **Estimating Plant-Available Nitrogen Release from Cover Crops** (D.M. Sullivan and N. D. Andrews, 2012). Pacific Northwest Extension bulletin 636. Step by step guide. https://catalog.extension.oregonstate.edu/sites/catalog/files/project/pdf/pnw636.pdf.
10. **Organic Fertilizer and Cover Crop Calculators for Pacific Northwest regions west and east of the Cascades** http://smallfarms.oregonstate.edu/node/54.
11. **Carolina Organic Commodities and Livestock Conference 2012: Selected Live Broadcasts** http://articles.extension.org/pages/61970/carolina-organic-commodities-and-livestock-conference-2012:-selected-live-broadcasts.
    a. *Increasing Soil Fertility and Health Through Cover Crops* (Julie Grossman)
    b. *Soil Fertility Management in Organic Grain Cropping Systems* (John Spargo)
    c. *Soil Fertility Management for Organic Wheat Production* (John Spargo)

12. **Cereal Grain Nutrient Management in the Northeast**

    a. *Management for High-Quality Organic Wheat and Ancient Grain Production in the Northeast* (Benscher, D., G. Roth and E. Dyck. 2013). http://articles.extension.org/pages/66869/management-for-high-quality-organic-wheat-and-ancient-grain-production-in-the-northeast.

    b. *Topdressing Organic Hard Winter Wheat to Enhance Grain Protein* (E. Mallory, 2013). http://articles.extension.org/pages/68227/topdressing-organic-hard-winter-wheat-to-enhance-grain-protein.

    c. Factsheets - *Assessing Winter Grain Stands in Early Spring* (E. Mallory, undated). https://extension.umaine.edu/localwheat/resources/factsheets/assessing-winter-grain-stands-in-early-spring/.

    d. *Northern New England Local Bread Wheat Project* (E. Mallory and H. Darby) videos and fact sheets on organic winter and spring grain production, including nutrient management guidelines. https://extension.umaine.edu/localwheat/.

13. **Cornell Organic Cropping Systems Trials** Grain and vegetable rotations, nutrient management, and soil health. http://www.hort.cornell.edu/extension/organic/ocs/.

    a. **What's Cropping Up Newsletter.** Articles and updates–excellent resource. http://scs.cals.cornell.edu/extension-outreach/whats-cropping-up

    b. **Illinois Soil Nitrogen Test** (ISNT) Cornell University Extension Fact Sheet 36. http://nmsp.cals.cornell.edu/publications/factsheets/factsheet36.pdf. *Sample submission form at* http://nmsp.cals.cornell.edu

    c. **Pre-sidedress Nitrate Test** (PSNT), Cornell University Extension Fact Sheet 3. http://nmsp.cals.cornell.edu/publications/factsheets/factsheet3.pdf

    d. **End of Season Corn Stalk Nitrate Test** (CSNT) http://nmsp.cals.cornell.edu/projects/nitrogenforcorn/StalkNtest.pdf

14. **Fertigation in Organic Vegetable Production Systems** (C. Miles, J. Roozen, E. Maynard, and T. Coolong, 2015) http://articles.extension.org/pages/29712/fertigation-in-organic-vegetable-production-systems.

15. **Organic Blueberry Production Research Project** (B. Strik, D. Bryla, and D. Sullivan. 2015) http://articles.extension.org/pages/31680/organic-blueberry-production-research-project. **Organic Blueberry Production Research Project: Roots** (L. R. Valenzuela, D. R. Bryla, D. M. Sullivan, and B. C. Strik. 2014). http://articles.extension.org/pages/32763/organic-blueberry-production-research-project:-roots

16. **Organic Blackberry Production: Tips Learned from an Ongoing Research Study** (B. Strik, D. Bryla, and L. Valenzuela. 2014). http://articles.extension.org/pages/70279/organic-blackberry-production:-tips-learned-from-an-ongoing-research-study.

17. **Organic Stone Fruit Production** (J. Reeve, B. Black, D. Alston, C. Ransom, R. Ward, S. Martini, 2016, Utah State University Extension). https://extension.usu.edu/productionhort/htm/organic/organic-stone-fruit-production.

18. **2nd International Organic Fruit Research Symposium** Recordings at: http://articles.extension.org/pages/64359/2nd-international-organic-fruit-research-symposium.
    a. *Effects of Weed and Nutrient Management Practices in Organic Pear Orchards* (C. Ingalls, U California at Davis)
    b. *Organic and Integrated Orchard Floor Management* (J. Reeve, Utah State U)
    c. *The Effects of Four Ground Cover Management Systems and Three Nutrient Sources on the Development and Performance of an Organic Apple Orchard in the Southern US* (C. Rom, USDA-ARS, Arkansas)

19. **Design and Management of Organic Strawberry/Vegetable Rotations** (C. Shennan and J. Muramoto, 2016). http://articles.extension.org/pages/73281/design-and-management-of-organic-strawberryvegetable-rotations.

20. **Nitrogen Management in Organic Strawberries: Challenges and Approaches** (J. Muramoto, M. Gaskell, and C. Shennan, 2015). http://articles.extension.org/pages/73279/nitrogen-management-in-organic-strawberries:-challenges-and-approaches.

21. **Greenhouse Gases and Agriculture: Where does Organic Farming Fit** (Webinar) (L. Carpenter-Boggs, D. Granatstein, and D. Huggins, 2016). http://articles.extension.org/pages/30835/greenhouse-gases-and-agriculture:-where-does-organic-farming-fit-webinar.

22. **Outcome of Soil Nutrient Balancing in Sustainable Vegetable Production** (M. Schonbeck, 2000). Summary of OFRF-funded research into BCSR on five farms in Virgnia. http://www.ofrf.org/research/grants/outcome-soil-nutrient-balancing-sustainable-vegetable-production. Click on link for complete report (27 pp).

# Current Science on Organic Nutrient Management and Soil Health

## An Analysis of USDA Organic Research and Extension Initiative (OREI) and Organic Transitions (ORG) Funded Research from 2002 – 2016

Research into organic soil and nutrient management over the past 15 years has generated much new information, including several overarching trends with practical implications:

- A perennial grass-legume sod phase in the crop rotation enhances SOM and organic N reserves, often improves yields, and can reduce N leaching.
- Cover crops, compost, and reduced tillage each make substantial, additive, and complementary contributions to soil health and crop nutrition.
- Where no-till is not practical, cover crops and compost with judicious tillage can still enhance soil health and fertility.
- Compost and manure application rates should be calibrated to avoid P excesses.
- A diversity of organic inputs that include both high and low C:N materials optimizes soil health and crop nutrition, and may promote tight nutrient cycling.
- High-analysis amendments (e.g., poultry litter) or succulent green manure plowdown can release PAN too fast, resulting in N leaching $N_2O$ emissions, or accelerated loss of SOM.
- Timing of N applications relative to crop demand can be critical in organic systems.

Other key findings apply to specific regions or cropping systems. In the following discussion of USDA funded organic research, reference is given to location and cropping system to help the reader understand the context and potential applicability to her/his farm.

## Estimating Crop N Needs and the Role of Soil Life in N Release

Standard N recommendations for most crops start with the known N needs of the crop rather than soil test data *per se*. N credits for manure, compost, and cover crops, based on estimates of PAN (usually 50% of total N for manure and green manures, and 10-25% for finished compost), are subtracted from the crop N need to determine how much fertilizer N to apply. N rates can be fine-tuned by measuring soluble soil N early in the growing season (Magdoff and van Es, 2009), or estimating soil-derived PAN based on %SOM (Collins et al., 2013).

Additional N management tools have been developed for conventional production of field corn, including the pre-sidedress nitrate test (PSNT) to determine whether and how much sidedress N to apply, and the late-season Corn Stalk Nitrate Test (CSNT) to discern whether the season's N inputs were limiting, optimal, or excessive. Adapt-N (http://www.adapt-n.com/) is a new simulation tool to help producers fine-tune N management during the season. Based on soil texture and organic matter, field history, crop rotation, pre-plant inputs, and daily weather data, the model allows producers to cut N inputs substantially, saving money and water quality (Moebius-Clune et al., 2014). However, the model requires intensive monitoring and data input and does not address organic production systems.

The Illinois Soil Nitrogen Test (ISNT) is a new laboratory protocol that measures soil amino-sugar N, an index of potential soil PAN from mineralization and thereby an indicator of whether a corn crop would respond to added N (Godwin et al., 2009; Khan et al., 2001). The ISNT has been suggested as a N management tool for organic grains (Ketterings et al., 2011). However, plant-soil-microbe interactions in the rhizosphere can deliver N and other nutrients to the crop that cannot be detected by lab procedures in the absence of plant roots (Drinkwater, 2012, Jackson, 2010). For example, *Azospirillum* and other free-living diazotrophic (N-fixing) bacteria can fix up to 20 lb. N/ac annually in the rhizosphere of non-legumes like corn or cereal grains if bulk soil PAN is low (Drinkwater, 2011, Drinkwater and Buckley, 2010).

High inputs of N from NOP-allowed sources can result in excessive soil PAN that leach to groundwater (Li et al, 2009), accelerate SOM breakdown, interfere with beneficial plant-soil-microbe interactions, and reduce soil and crop health (Wander et al., 2016). In New York corn trials, dairy manure improved SOM retention over chemical N, but both systems leached similar amounts of $NO_3$-N overwinter (Sadeghpour et al., 2016). In lieu of "organic by substitution," Wander (2015) recommends an integrated strategy that relies on crop rotation, cover crops, judicious tillage, maintenance of living plant roots in the soil profile, and a balance of nutrient-rich and carbon-rich organic inputs that builds the soil's capacity to feed the crop without N leaching or losses of organic matter.

In a study of 13 organic tomato fields in central California, Jackson and Bowles (2013) identified two distinct pathways from N deficiency to N sufficiency in organic systems: *N saturation*, in which N-rich organic inputs maintain high soluble soil N and crop yields, but increase risk of N leaching; and *tight N cycling*, in which diverse organic inputs build soil organic matter and biological activity, PAN is released in the crop rhizosphere and efficiently utilized so that bulk soil PAN and leaching remain low. Farms that showed tight N cycling in tomato production had "the highest total and labile soil C and N and received organic matter inputs with a range of N availability" (Bowles et al., 2015). These fields also showed increased activity of several soil and plant root enzymes related to N cycling and uptake. Jackson (2013) states: "Since genetic pathways regulating N uptake are highly conserved across plant species, studies on these N metabolism genes in a model plant such as tomato are highly relevant to other crops."

*Figure 5. Soil Nematode, USDA ARS)*

Soil nematodes that feed on bacteria and fungi release PAN in the process, and thereby play a major role in crop nutrition and possibly N leaching. The burst of bacterial growth after green manures are tilled in, leads to a flush of bacterial feeding nematodes and PAN (Ugarte and Zaborski, 2014). Similarly, bacterial- and fungal-feeding nematodes multiply after manure incorporation (Nahar et al., 2003).

## Cover Crops, Legume-Fixed N, Nutrient Recovery, and Timing of Nutrient Release

The vital role of cover crops in co-managing soil health and nutrients in annual cropping systems has been widely established (Delate et al., 2015; Hooks et al., 2015; Sheaffer et al., 2007; Tavantzis et al, 2012). While legume cover crops can fix up to 200 lb. N per acre, at most half of this becomes available to the following crop. However, the cost of cover crop PAN has been estimated at $0.30-2.00/lb, compared to

$5-6/lb for poultry litter N (Andrews and Sullivan, 2015; Spargo 2012a). Furthermore, the “unavailable” fraction of cover crop N adds to the soil organic N pool. In “mature organic soils,” sufficient N may be mineralized from SOM and the cover crop to meet N needs for heavy feeders like corn and tomato (Teasdale, 2012).

In order to fix N effectively, the legume-rhizobia symbiosis requires good soil tilth and drainage, favorable pH (~6.0-7.5), adequate soil P, K, and micronutrients including molybdenum (Mb) and cobalt (Co), and not too much soluble N (Drinkwater, 2011b). N fixation rates peak at flowering, and planting dates should allow legumes to develop substantial biomass and flower before termination. Legume N fixation is further enhanced by three-way symbiosis of plant, rhizobia, and mycorrhizal fungi (Drinkwater, 2011a).

The N fixing efficacy of different strains of rhizobia can vary widely for dry bean and soybean (Orf et al., 2015), and hairy vetch (Hu et al., 2015a). Because field soil rhizobia populations are often low or dominated by low-efficacy strains, inoculation of legume seeds with commercial inoculants from reputable and NOP-approved sources is widely recommended. However, the quality of commercial inoculants varies (Drinkwater, 2011b), and applied inocula may be outcompeted by native strains (Hu et al., 2015a). Efforts are underway to optimize rhizobia strains, inoculation methods, and related factors in N fixation.

The percent of legume N content derived from fixation of atmospheric $N_2$ may vary inversely with soil N (Jackson, 2010, Drinkwater, 2011b), which in turn depends on field history, soil biology, recent N inputs, and whether the legume is grown alone or with non-legumes. Yet, N fixation by red clover or field pea varied little with soil PAN in upstate New York (Schipanksi and Drinkwater, 2011, 2012). In a multi-site study, percent of soybean N from fixation varied inversely with *total* soil N, which increased with years in organic production (Grossman, 2010).

In North Carolina, the fine roots of crimson clover, hairy vetch, and Austrian winter pea have been shown to make a substantial contribution to soil organic C and crop-available N, as the fine roots comprise 70% of the legumes’ below-ground biomass and release up to half of their N content within a week after termination (Hu et al., 2015a; Figure 6). The same study showed that terminating the cover crop by flail mowing can enhance microbial biomass and N mineralization by 16-17% compared to disking or herbicide.

A cover crop mixture of legume and nonlegume can help balance soil C and N, as the legume fixes more N where soil soluble N is low, and the nonlegume scavenges N that might otherwise leach where soil soluble N is high (Drinkwater, 2011b). In Mid-Atlantic organic vegetable rotations, grass + legume cover crops provided "greater ecosystem services" than either alone (Hooks et al., 2015). However, performance of cover crop mixtures varies with growing season, soil PAN, and both competitive and complementary relationships among components. For example, a rye-canola-winter pea-red clover mix was dominated by rye in northern Pennsylvania and canola in southern Pennsylvania, pea developed substantial biomass only where soil soluble N was low, and clover was suppressed by the faster-growing annuals (Barbercheck et al., 2014).

*Figure 6. Hairy vetch, USDA NRCS*

Researchers are working with farmers to fine-tune cover crop mixtures and seeding rates to optimize nutrient dynamics, soil conservation, and other cover crop functions (Kaye, 2016). In the Pacific Northwest, vetch-oat or vetch-phacelia mixtures accrued more total N than vetch monoculture, largely because the erect non-legumes provided support for vetch vines (Andrews and Sullivan, 2010). In upstate New York, percent of N derived from fixation in red clover or field pea was significantly enhanced in mixtures with grasses compared to legume monoculture. Red clover frost-seeded into cereal grains (a common farmer practice in the region) put on sufficient growth after grain harvest to enhance total N fixation, whereas legume biomass and N were reduced by competition in clover-orchardgrass or oat-pea mixes (Schipanski and Drinkwater, 2010, 2012; Drinkwater, 2011b). In Pennsylvania, "nutrient retention, weed suppression, and soil erosion could be achieved simultaneously with mixtures that achieved rapid fall cover and included a winter hardy grass," but these mixes fixed less N and supplied less PAN to a subsequent corn crop (Kaye et al., 2016). The team recommended using low seeding rates for the winter grass component and managing for low soil $NO_3^-$-N levels at time of cover crop planting to promote N fixation (Kaye, et al., 2016).

In summer cover crop plantings in upstate New York, chickling vetch, cowpea, forage soybean, crimson clover, and berseem clover fixed a higher percentage of their N when planted with Japanese millet or sorghum-sudangrass than when planted alone (Drinkwater and Buckley, 2010), and *total* N fixation increased for cowpea + millet (Drinkwater, 20111b). Legume-buckwheat mixtures had reduced N fixation because the buckwheat suppressed the legume. Mowing buckwheat when it reached its full height allowed clover to increase 5-fold in biomass and 8-fold in N fixation, and mowing sorghum-sudangrass doubled clover biomass (Drinkwater and Buckley, 2010). Thus, timely mowing shifted the interaction between tall, warm-season non-legumes and low-growing cool season clovers from competitive to complementary.

Planting and termination dates have substantial impacts on cover crop biomass and N. Recommended latest planting dates for hairy vetch to obtain 4,000 lb./ac biomass by the spring frost-free date are August 24 in Binghamton, New York, September 28 in Beltsville, Maryland, and October 18 in Raleigh, North Carolina (Teasdale, 2012). For optimum N contribution, cover crop termination should be delayed until the legume flowers (Drinkwater, 2011b). In Beltsville, vetch terminated in mid-May had 4,000 lb. biomass and 130 lb. N, compared to 2500 lb. and 90 lb., respectively when the crop was terminated in mid- April (Spargo, 2012a). In the North-Central region, organic corn yields have become N limited when the biomass and N content of a preceding winter annual legume was limited by poor stand establishment, winterkill, or other adverse conditions (Delate, 2013; Reinbott, 2015).

A legume or cruciferous green manure can release PAN too rapidly, so that N is lost before the following crop can utilize it (Grossman, 2012,Shennan and Muramoto, 2016). Because hairy vetch has a high N content (up to 160 lb./ac) and low C:N ratio (10:1 to 14:1), mixing vetch with rye have been recommended to reduce risks of N leaching or denitrification (Teasdale, 2012).

Radish cover crops (oilseed, forage, or ‘tillage’ radishes) can scavenge more than 100 lb./ac N, and substantial amounts of P and K from the top five feet of the soil profile, especially where a history of manure application, recently broken sod, or under-utilization of nutrients by the preceding crop left the soil rich in soluble nutrients (Gruver et al., 2016). Similarly, mustard cover crops reduced soil nitrate-N levels in central California (Jackson et al., 2008). Unlike cereal grains, crucifers break down and release recovered nutrients rapidly, and prompt planting of a heavy feeder is recommended to utilize the N and minimize leaching (Gruver et al., 2016).

## Nutrient Management for Organic Grains: Crop Rotation and Legume-Fixed N

In a low-rainfall part of Minnesota, a four-year soy-oat/alfalfa-alfalfa-corn rotation gave higher organic corn yields and accrued more soil organic C and N than a two year soy-corn rotation (Sheaffer et al., 2007). Adding a winter cover crop of hairy vetch to either rotation proved challenging in this northern location; however, when successful, this cover crop enhanced crop-available P, soil aggregation and "potentially mineralizable C." An organic corn-soy-oat-alfalfa rotation also reduced N leaching losses compared to conventional corn-soy in Iowa, despite higher total N applications in the organic system (Delate et al., 2014). In Maryland, organic grain systems with longer crop rotations had higher SOM and PMN than conventional (till or no till) corn-soy-wheat rotations (Spargo, 2012a).

A Cornell team evaluated a three-year organic grain rotation of soybean followed by winter spelt with red clover frost-seeded in March of the second year, and plowed down the following spring just before corn planting. Over four seasons, the clover added 74-168 lb. total N/ac-year, and mineralization of clover N peaked about six weeks after plowdown in good synchrony with corn N demand (Ketterings et al, 2011). Although the ISNT indicated a need for applied N, the clover apparently met this need. Corn yields were drought limited the first year (87 bu/ac) and high (~150 bu/ac) the other three years, and did not respond to poultry litter compost (4-5-2). In contrast, winter spelt planted after soybean responded to the compost, and its use on spelt but not on corn gave the best net economic returns (Caldwell et al., 2012; Caldwell and Ryan, 2013). Similar findings were reported from a soy-spelt-corn rotation in Pennsylvania. Compared to triticale + hairy vetch planted after spelt harvest, frost-seeding red clover and timothy into standing spelt in 2015 reduced soluble soil N levels yet increased corn grain or silage yields in the 2016 season (Barbercheck, 2016).

Organic N (feather meal or poultry litter) sidedressed at midgrowth (corn) or in spring (winter cereals) may be utilized more efficiently than pre-plant applications, as indicated by corn yield response (Spargo, 2012a) and wheat protein levels (Spargo, 2012b). In northern New England, N applications at planting or early spring on organic winter wheat enhanced yield but grain protein levels remained below optimum, while N applications at later stages (flag leaf or boot) enhanced grain protein (and baking quality without increasing yield (Mallory, 2012). In some site-years, manure enhanced both yield and protein, possibly because it released N over an extended period. Spring-planted cereal grains are considered light feeders, and Northeast organic producers are advised to avoid over-applying nutrients (Harwood and Darby, undated).

In northeast Nebraska, yields of winter wheat after corn or alfalfa showed a 10-20% response to a pre-plant manure application of 20 tons/ac, whereas additional N in spring did not affect grain protein (Shapiro, 2013). High native fertility sustained good yields (50-66 bu/ac) and protein (13%) across all treatments. In Washington State, organic wheat protein levels responded to N applications at late boot at rates up to 60 lb./ac (Jones et al., 2011).

Ancestral wheats show less response to N and may not need N application after a legume green manure (Benschler et al., 2013). Organic yields of emmer, einkorn, and spelt responded to added N when pre-existing fertility was "low," but not when initial fertility was enhanced by a previous legume crop (Sorrels et al., 2015).

Organic soybeans generally perform well at low soluble N levels that would limit other crops such as corn. For example, corn and wheat responded to compost in Missouri while soybean did not (Reinbott, 2015). Soybeans have been successfully grown no-till in a roll-crimped cereal rye cover crop in Illinois (University of Maryland, 2014), Missouri (Clark, 2016), and North Carolina (Reberg-Horton, 2012), and in soils amended with high-carbon materials like straw or sawdust to inhibit weed growth (Stinner and Phelan, 2008). While the no-till system did not work as well in northeast Nebraska (Shapiro, 2013) or a multi-site study across the northern US (Delate, 2013), yield reductions were less in soybean (~35%) than in corn (~65%). In upstate New York, corn and spelt yields were initially depressed by up to 30% during the three-year transition to organic, while soybean yields remained commensurate with the conventional control (Caldwell et al., 2012).

Dry common bean (*Phaseolus vulgaris*) fixes some N but derives the majority of its N from the soil. A preceding cover crop of clover did not much affect yield but significantly increased protein content of dry beans in some site-years in Michigan (Heilig and Hill, 2014).

## Benefits of Perennial Sod Phase in the Rotation to Soil Quality and Nutrient Cycling

In a comparison of crop rotation strategies during the three-year transition to organic production in Ohio, three years in mixed-species hay sod resulted in higher soil microbial biomass and populations of bacterial feeding nematodes (which promote N mineralization) compared to vegetable/winter annual cover or summer cultivated fallow/winter annual cover rotations (Briar et al., 2011).

Perennials also greatly improve nutrient retention. For example, a four-year organic corn-soy-oat/alfalfa-alfalfa rotation leached less N than conventional corn/soy, and an organic permanent pasture lost the least N (Delate et al., 2014). A shorter (one year) perennial grass-clover phase has also reduced soluble N levels, yet also improved corn yield (Barbercheck, 2016).

In an Illinois study, all three experimental cropping strategies during a three-year transition to organic-intensive vegetable production with winter cover crops, corn-soy-wheat rotation, or undisturbed perennial sod – enhanced particulate SOM, and labile organic N. However, tomato (year 4) and edamame soybean (year 5) had significantly higher yields after perennial sod than after the other rotations treatments (Eastman et al., 2008).

## Effects of Manure, Poultry Litter, Compost, and Other Inputs on Nutrient Cycling and Soil Health

Manure nutrient contents vary widely. In 30 samples of liquid dairy manure, N content varied four-fold depending on livestock diet, manure handling and storage, and dry matter content (Spargo, 2012a). In all of these samples, only about half the N was in organic forms, the rest being ammonium N ($NH_4$-N), which can undergo 50% losses within two days after surface application. Similarly, "compost" may have nutrient analysis as low as 0.5-0.5-0.5 or as high as 4-5-2. These observations underline the importance of obtaining nutrient analysis of manure and compost.

In Minnesota, composted manure enhanced several parameters of soil health, including soil aggregation, SOM, and soil test P, compared to uncomposted manure (Sheaffer et al., 2007). Over a six-year period, composted dairy manure solids maintained higher SOM than liquid dairy manure with the same amount of N, while SOM declined with conventional N fertilizer and no manure (Sadeghpour et al., 2016). In Ohio, composted dairy manure (7.5 tons dry wt/ac-year for three years) enhanced SOM, microbial biomass and N, and bacteria-feeding nematode numbers (Briar et al., 2011). Raw or composted dairy manure incorporated in spring enhanced particulate and total SOM, potentially mineralizable nitrogen (PMN), microbial biomass-N, and free living (bacterial and fungal-feeding, omnivorous, and predatory) nematodes, and reduced plant-parasitic nematodes and soil bulk density (Nahar et al., 2003).

Annual applications of a mixed on-farm compost ("high carbon") over a five-year period in coastal Washington State resulted in higher total soil C and N, better infiltration, lower bulk density, and higher enzymatic activity and N mineralization potential, compared to annual applications of a poultry litter compost with a lower C:N ratio (Cogger et al., 2013). Crop yields were generally equivalent for the two treatments, though winter wheat yielded better after the high-carbon compost in 2011. In Missouri, active and total SOM, soil microbial biomass and activity increased with manure compost applications, reaching a plateau at 1 to 1.5X rates recommended for crop nutrition (Reinbott, 2015).

In Maine, a “conifer-based compost” (likely high C:N) enhanced soil bacterial and fungal populations, stimulated microbial utilization of “complex substrates,” and improved potato yields by 9-15%. A rapeseed green manure (probably low C:N) before the potato crop stimulated soil biological activity and reduced incidence of several stem and tuber diseases. Benefits of the compost and green manure appeared additive and complementary (Tavantzis et al., 2012). Complementary and additive benefits from manure-based amendments and cover crops have been observed in Maryland (Hooks et al., 2015), Florida and Iowa (Delate et al., 2015)

Organic grain cropping systems in Beltsville, Maryland that used poultry litter for N enhanced SOM and PMN, but accumulated excessive soil P, while the conventional system did not (Spargo, 2012a). Researchers are now using legumes for N and reducing poultry litter rates to just meet crop P needs, estimated at 32, 40, and 60 lb./ac $P_2O_5$ for 40 bu/ac soybean, 80 bu//ac wheat, and 140 bu/ac corn, respectively (Cavigelli et al., 2014, Cavigelli, 2015; Spargo, 2012a).

On a high-P soil in North Carolina, poultry litter rates calibrated to supplement cover crop N for organic sweet corn added 35 – 100 lb. $P_2O_5$ per acre and resulted in increased dissolved P levels in runoff (Edgell et al., 2015, Osmond et al., 2014), perhaps because poor crop yields related to weed pressure reduced P utilization. Organic treatments lost less sediment and N than conventional (ibid.). Mycorrhizal association with field corn and soybean roots was higher in conventional than in organic treatments (Hu et al., 2015b), possibly because the latter utilized poultry litter and accumulated higher soil P levels.

Although potassium (K) is not considered a water pollutant, it can be lost from sandy soils through leaching, and can also build up to surplus levels in intensively managed organic systems that rely on compost and/or manure as the primary N source (Sanchez, 2009). In less intensively managed grain, forage, or hay production systems, a net drawdown in K can take place, which has also raised sustainability concerns (Mohler et al., 2009). However, in the dominant soil order of the southern United States (Ultisols), clays in the subsoil or B horizon often holds large mineral K reserves that reduce the need for K inputs in organic production in healthy soils (Kloot, 2017).

## Reduced Tillage and Organic Nutrient Management

In a six-state study (North Dakota, Iowa, Minnesota, Wisconsin, Michigan, and Pennsylvania) of organic grain production, the no-till treatment (cover crops roll-crimped ahead of corn and soybean) enhanced microbial biomass, PMN, POM, extractable K, and macro-aggregation compared to tilled organic grain production, with each parameter statistically significant at one or more sites (Delate, 2013). However, crop yields, especially corn, were sharply reduced by weeds, N limitation and/or cover crop regrowth. Reduced tillage (roll-crimping cover crops) improved soil structure and N retention in vegetable rotations in Iowa and Florida, though it also reduced yields in Iowa. Yet cover crops and compost also enhanced active and total soil organic C and N regardless of tillage (Delate et al., 2015).

Less risky strategies to reduce soil disturbance in organic systems include seeding cover crops into standing crops to eliminate post-harvest tillage (Burke et al., 2014; Ryan et al., 2015, Barbercheck, 2016); shallow tillage with rotary harrow or rotary hoe (Gallagher et al., 2006), or rotary spaders, which reduce compaction compared to plowing and disking, and can improve yields (Cogger et al., 2013).

## Plant Genetics, Soil Health, and Nutrient Management

Since the mid-20th Century, most crop varieties have been bred and selected in the context of abundant soluble nutrients from conventional fertilizer-s, and may therefore be less responsive to organic “feed the soil” nutrient management practices. Several farmer-plant breeder networks are now breeding and testing new varieties on organic farms to select for improved yield in these systems (Myers, 2015; Scott, 2015). Mandaamin Institute in Wisconsin is developing N-efficient field corn lines that derive up to half their N from N-fixing bacteria in their rhizospheres, giving competitive yields of high-protein grain, even on N-limited soils (Goldstein, 2015). Other teams are breeding dry beans and edamame soybeans and selecting rhizobia for enhanced N fixation (Heilig and Hill, 2014, Orf et al., 2015), and developing wheat varieties for improved N efficiency and N fixation by rhizosphere bacteria (Jones et al., 2011).

A new OREI funded project is breeding and evaluating cultivars of hairy vetch, crimson clover, and Austrian winter pea for regional adaptation, rapid fall establishment, winter hardiness, total biomass, N fixation, and ease of mechanical termination (Mirsky, 2015). Genetic studies of native and commercial strains of hairy vetch rhizobia in North Carolina (Hu et al., 2015a), aim to enhance N fixation in this cover crop.

Experimental lines of perennial wheat developed three times the root mass of annual wheat, enhanced labile SOM and virtually eliminated N leaching (Snapp and Swinton, 2013, Figure 7). More work is needed to improve yield and overwinter survival, but these findings illustrate the potential of perennial crops to promote tighter nutrient cycling and soil health.

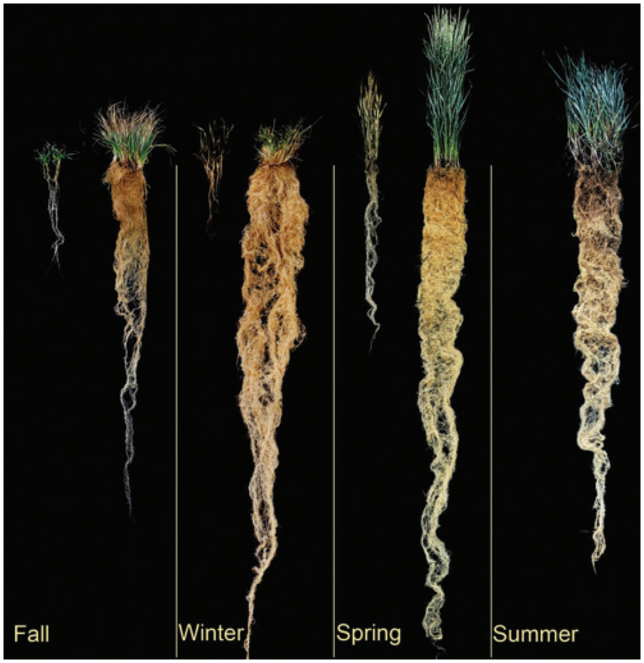

*Figure 7. Roots of perennial wheat compared with the shorter roots of annual wheat, Michigan State University*

## Nutrient Management Challenges in Semiarid Regions

Of annual cover crops tested in Montana, winter pea fixed the most N for a following wheat crop, though no annual legumes met the entire N requirement (Miller et al., 2009). Perennial legumes fix more N but may consume too much moisture to be practical in dryland production. Dryland organic wheat growers consider P their greatest nutrient issue, as neither rock phosphate, nor buckwheat or legumes increase P availability in alkaline soils. A similar limitation was encountered in Wyoming and western Nebraska, though some P amendments became more available when “combined with organic acid amendments.” (Norton et al., 2014).

In eastern Washington, a winter green manure of field pea, or an alfalfa-clover-oat-pea forage crop increased soil inorganic N and earthworm populations, and supported good yields in a following crop of spring wheat (Gallagher et al., 2006). “Increasing the frequency and intensity of perennial or winter annual legumes” during a three-year organic transition improved N fertility, weed control, and yields in organic grains (Borrelli et al., 2011). In on-farm trials, legumes intercropped into wheat showed a potential to increase grain yields 4-12% if compatible cultivar combinations are selected (Burke et al., 2014)

In Utah, a one-time application of manure compost at 22 tons/ac (dry weight) significantly improved dryland organic wheat yields, nutrient availability, and SOM for at least 16 years after application; however yield gains did not fully pay for application of purchased compost at this rate (Reeve and Creech, 2015). The team is exploring an integrated approach of cover crops, compost at lower rates, and better-adapted wheat cultivars.

## Nutrient Management and Soil Health Practices in Vegetable Crops

Organic vegetable growers tend to use compost and other organic nutrients generously to ensure that these high-value crops are not nutrient-limited. Nutrient imbalances, including excessive N, P, and/or K can result, posing risks to water resources, soil health, and produce quality. Soil and nutrient management strategies that integrate inputs with cover crops and reduced tillage (where practical) can improve soil health and production outcomes. For example, legume cover crop and chicken manure fertilizer together improved soil health over either cover crop or fertilizer alone in organic vegetable trials in Maryland (Hooks et al., 2015).

Cool-season heavy feeders with limited root systems, such as lettuce and broccoli, appear especially challenging. Modeling studies based on two years of field trials in central California indicated that about 220 lb./ac N (from green manure + applied amendments) is needed to sustain maximum broccoli yields. The model predicted that treatments with cover crops and compost would build SOM while fertilizer-only would deplete it; but that all treatments giving maximum broccoli yield can leach >180 lb. nitrate-N/ac and emit 17-42 lb./ac $N_2O$ annually (Li et al., 2009). In one field trial, a higher C:N cover crop did not effectively provide N to the broccoli (Muramoto et al., 2008). Because of its small root system and high N demand over a short period, organic broccoli needs high concentrations of PAN (R. Morse, pers. commun.), making it especially challenging to optimize yield and environmental impacts at the same time.

In organic vegetable rotations in Iowa (high fertility soil, temperate climate) and Florida (low fertility sandy soil, subtropical climate), composted animal manure (applied at 100 lb. total N/ac annually), cover crops (vetch + rye in Iowa, sunnhemp in Florida), and reduced till (cover crops roll-crimped ahead of vegetables) each improved active and total organic C and N) in an additive manner (Delate et al, 2015). Reduced tillage improved soil structure, stimulated microbial respiration, and improved N retention (less leaching), but reduced sweet corn and tomato yields in Iowa. In Florida, summer squash and pac choi performed well in roll-crimped cover crops (Delate et al, 2015). Even in tilled treatments, cover crops + compost enhanced SOM and N fertility over a four-year period, and the cover crops reduced N leaching.

In Virginia and Georgia, organic summer squash (direct-seeded), pepper and broccoli (transplanted) grown no-till after flail-mowed cover crops gave yields equivalent to conventional till organic crops in most site-years. Reduced yields of no-till pepper and broccoli (each one site-year) appeared related to nutrient limitation, as weed levels were low (Morse et al., 2007). However, severe yield losses in summer squash and broccoli transplanted no-till into rolled or flail-mowed cover crops were reported in coastal Washington State (Fortuna et al., 2014).

Taken together, these findings suggest that no-till vegetable planting into roll-crimped or mowed cover crops may be most workable in the southern half of the US, where warmer temperatures promote rapid N mineralization and longer growing seasons facilitate vegetable production after a cover crop grown to maturity.

In a five-year organic vegetable rotation in Washington State, annual applications of a mixed on-farm compost improved soil organic C and N and tilth compared to poultry litter compost with a lower C:N ratio (Cogger et al., 2013). Broccoli, winter squash, and lettuce yields were generally similar in the two treatments, although poultry litter gave higher yields in two out of 25 comparisons. Use of the rotary spader in lieu of plow-disk consistently reduced compaction and improved vegetable yield in five comparisons.

Soil texture can affect the need for applied N. In Wisconsin, potatoes grown on a sandy soil with irrigation and with legume plowdown as their only source of N yielded up to 300 cwt/ac (similar to conventional yields), whereas a second trial on a heavier soil with legume plowdown with added manure and organic N fertilizer yielded about 200 cwt/ac (Rouse and Jansky, 2005).

The high tunnel environment presents additional nutrient management and soil health challenges, as higher temperatures and season extension accelerate SOM oxidation, and excluding rainfall can lead to salt buildup in the soil. Higher soil temperatures during spring and fall result in increased soil biological activity, microbial biomass, and bacteria-feeding nematode populations in high tunnel versus field soils in Ohio (Briar et al., 2011). Higher tomato yields in the high tunnel in the fourth year of a vegetable rotation were attributed in part to higher soil PAN levels. The challenge is to replenish soil organic C and N without building up excessive P, K, other nutrients, and salts.

## Nutrient Management and Soil Health Practices in Organic Fruit Crops

Several organic tree fruit studies illustrate the need to take nutrient inputs and nutrient dynamics into account in orchard floor management. In Utah, young orchard fruit trees with in-row straw or living (alyssum) mulch and legume (birdsfoot trefoil) alleys mowed and blown into crop rows showed tree growth equal to the in-row weed mat, tillage, or herbicide (conventional) treatments. Increased growth of tree roots into legume alleys as well as N delivered via mow-and-blow apparently compensated for higher within-row weed pressure (Reeve, 2012). In addition, the trefoil treatment enhanced soil organic C, total N, and microbial biomass and activity, and reduced bulk density compared to the tilled treatment (Reeve, 2014).

In Oregon, sweet cherry orchards, living orchard floor cover maintained higher SOM, available P, N mineralization, and activity of several microbial enzymes than either applied organic amendments or landscape fabric (Figure 8). Bare fallow maintained with herbicides resulted in the lowest levels of these soil health indicators (Azarenko et al., 2009).

*Figure 8. Living orchard floor, USDA ARS*

Researchers in Davis, California compared organic pears grown without added fertilizer and with in-row mowing versus trees fertilized with feather meal or manure, with or without in-row landscape fabric, wood chip, or NOP-allowed herbicides. Fertilized treatments, especially feather meal, increased soil nitrate-N and slightly increased foliar N, while the wood chip + manure treatment raised soil P, K, and SOM, yet all treatments gave similarly high fruit yields over the three years of the study (Ingalls, 2012). Considering materials costs and weed management labor, the project team concluded that the unfertilized, mowed treatment was most economical, but cautioned that some fertility inputs will eventually be needed to sustain yields.

In Arkansas, apple trees mulched with “municipal green compost” showed the greatest growth, followed by wood chip mulch, “mow-and blow,” and shredded paper mulch in that order (Rom, 2012). The paper controlled weeds but created anaerobic and alkaline soil conditions and tied up N. Green compost and woodchip improved soil organic matter and biological activity, but the green compost delivered 3 to 5 times the desired amount of N to the trees, while mow-and-blow delivered too little, and wood chip was close to optimum.

Blueberries require an acidic soil (pH ~5.0), and an Oregon blueberry crop grew better in soil amended with plant-based compost (yard waste) than a more alkaline manure-bedding compost (Strik et al., 2011, 2015). Acidifying compost to pH ~ 5.5 (requiring 6-12 lb. elemental sulfur per ton) further improved growth. Weed mat maintained lower soil pH and higher PAN than sawdust mulch, but reduced fruit firmness as well as Ca and Mg availability. The low rate of N as fish emulsion (25 lb./ac) gave better yields and substantially greater root development than the 50 lb./ac rate (Strik et al., 2011, Valenzuela et al, 2014). In organic blackberry production, weed mat with drip fertigation enhanced nutrient uptake, growth, and yield compared to a hand-weeded treatment (Strik et al., 2014). In Florida, rabbiteye blueberries grew and yielded better when mulched with pine straw or pine bark than with weed mat or no mulch (Krewer et al., 2009). Some labor was required to replenish pine mulches and remove weeds, but the weed mat treatment required the most weed control labor during the six-year study.

In a California study, organic strawberries grown in sandy soil responded better to N provided during the growing season than to pre-plant organic fertilizer (from which much of the N was lost to leaching), whereas on a heavier soil during a drier-than-normal winter, preplant applications of about 75 lb. N/ac appeared optimal (Gliessman et al., 2009). In-season fertigation required care to ensure proper delivery of liquid organic fertilizers via the drip tubing. The research team is working to develop improved organic N management guidelines integrating cover crops and organic fertilizers (Gaskell et al., 2009). Broccoli residues and organic amendments incorporated just before strawberry planting in November mineralized N rapidly, while the strawberry crop did not take up much N until the following May-September; leaving some 250 lb./ac soluble N prone to leaching by winter rains (Muramoto et al., 2015).

The University of Florida has undertaken a study of organic strawberry production, including nutrient management with a summer legume cover crop (sun hemp or mixed summer legumes) and reduced rates of organic N fertilizer (Chase, 2015).

## Minimizing $N_2O$ Emissions in Organic Systems

In addition to nitrate leaching, high soil soluble N levels can lead to release of nitrous oxide ($N_2O$) into the atmosphere. A product of biological reduction of nitrate (denitrification), $N_2O$ is a powerful greenhouse gas (GHG) that comprises over 50% of agriculture-related GHG emissions in carbon dioxide ($CO_2$) equivalents (Carpenter-Boggs et al., 2016). Agricultural soils account for 69% of US $N_2O$ emissions, and manure management for another 5% (Cogger et al., 2014).

Because one ton of $N_2O$ exerts the climate impact of ~300 tons of $CO_2$, sustainable nutrient management must strive to avoid the conditions that promote denitrification. These include high levels of soil $NO_3^-$-N and labile (readily-decomposable) organic C combined with high soil moisture levels and limited oxygen (Baas et al., 2015; Li et al, 2009). Thus, $N_2O$ emissions often take place after heavy rains (Baas et al., 2015, Carpenter-Boggs et al., 2016), during seasons when precipitation exceeds evapotranspiration (Muramoto et al., 2015; Cavigelli, 2010), during snow-melt (Thies, 2007), or after incorporation of succulent green manures (Grossman, 2012,Shennan and Muramoto, 2016) or amendments such as poultry litter that provide abundant labile C and N (Baas et al., 2015, Li et al., 2009). Irrigation tailwater ponds and drainage ditches can be substantial sources of $N_2O$ emissions and nitrate leaching (Jackson et al., 2008).

$N_2O$ can be released during microbial nitrification (oxidation of $NH_4$-N) and denitrification (Cogger et al., 2014), and is therefore related to total soluble N. Thus, optimum N management would meet crop needs through timely release of plant-available N (PAN) in the rhizosphere, yet maintain low bulk soil soluble N levels (Jackson and Bowles, 2013). Compared to conventional fertilizers, most organic N sources do not push soil soluble N levels as high, but release PAN over an extended period (Carpenter-Boggs et al., 2016). In several studies, compost-fertilized organic systems emitted less $N_2O$ than conventional systems (Reinbott, 2015; Cavigelli, 2010), and either conventional no-till or organic reduced-till systems emitted about half as much $N_2O$ as conventional tilled (Hu et al., 2015b). Labile and total organic C was higher in organic systems, but $N_2O$ emissions were more directly related to soluble N regardless of source. The presence of mycorrhizal fungi reduced $N_2O$ emissions from organic soils but not from conventionally managed soils with high N inputs (Hu et al., 2015b).

In Michigan, an organic corn-soy-wheat rotation that received pelleted poultry litter (4.5% N, C:N ~7) at 2,900 – 4,400 lb./ac annually emitted five times as much total $N_2O$ over three years as conventionally fertilized corn-soy rotations (Baas et al., 2015). Brief, intense bursts of $N_2O$ (~1 lb./ac-day) from the poultry litter treatment were related to a combination of abundant labile organic C and N, heavy rain events, and soil disturbance associated with mechanical weed control. In California, application of sufficient N to meet the needs of an organic broccoli crop could potentially release 17-42 lb./ac $N_2O$ per cropping cycle (Li et al., 2009). $N_2O$ spikes have also followed incorporation of hairy vetch or sugar beet residue into moist soil, or manure applications to winter wheat (Bhowmik et al., 2015b; Cavigelli, 2010). In a soy-spelt-corn rotation in Pennsylvania, elevated soluble soil N and $N_2O$ spikes associated with rain events were observed when hairy vetch + triticale was planted after spelt harvest and incorporated before corn planting, but lower soluble N levels and no $N_2O$ spikes occurred when timothy + red clover were frost-seeded into the spelt and incorporated before corn (Barbercheck, 2016).

$N_2O$ emissions increased with increasing applications of animal manures in organic crop rotations in Maryland (Yarwood, 2016). Emissions were similar for surface applied or subsurface-injected poultry litter, and were increased when roll-crimped rye + vetch maintained higher moisture levels near the soil surface. Large populations of the nitrifying and denitrifying microbes involved in $N_2O$ emissions were found near the soil surface and in association with plant roots.

Efforts to mitigate $N_2O$ emissions from agricultural soils must begin with accurate detection and monitoring, a daunting task because soil $N_2O$ emissions often occur in brief, intense pulses that can spike and subside over a matter of minutes (Cogger et al., 2014). Continuous in-field monitoring to capture $N_2O$ emission spikes after rainfall, irrigation, freeze-thaw, tillage, or amendment applications has helped clarify the extent of the problem and contributing factors (Carpenter-Boggs et al., 2016; Cogger et al., 2014; Hu et al., 2015b).

Microbial gene markers for nitrifying and denitrifying bacteria show promise as an indicator for risk of $N_2O$ emissions. In organic vegetable crops, genes for bacterial $NH_4$-N oxidation decreased in compost-amended plots and increased after freeze-thaw cycles (Bhowmik et al., 2015a), while denitrifier genes increased in wet soil (80% water filled pore space), especially when sugar beet residues were tilled in (Bhowmik et al., 2015b).

One notable finding by a Brazilian research team is that a legume green manure crop planted in soil with high pre-existing soluble N levels can emit considerable $N_2O$ *while it is growing,* accounting for 30% of total emissions from planting through plowdown and decomposition (Alves, 2014). $N_2O$ emissions from the legume were double those from a fallow control, while a sorghum green manure slightly reduced $N_2O$ emissions.

Researchers are refining the Denitrification-Decomposition (DNDC) computer-based model (http://www.dndc.sr.unh.edu/) to estimate $N_2O$ and total GHG impacts related to different cover crops (Drinkwater and Walter, 2014) and the transition from conventional to organic dairy farming (Varner and Li, 2014). Pennsylvania State University is evaluating $N_2O$ emissions from full-till and reduced-till systems in a 3-year organic grain rotation with manure additions to meet crop P requirements (lower rates) or N requirements (higher rates) (Kemanian, 2015). Washington State University is developing an Organic Farming Footprint model (OFFOOT, http://csanr.wsu.edu/organic-farming-footprints/) to estimate $N_2O$ and other GHG impacts of various organic systems (Carpenter-Boggs et al., 2016). University of Illinois is working with producers to develop modules for organic systems for GoCrop (http://gocrop.com/), a comprehensive nutrient management tool (Wander, 2015). Their goal is to improve existing PAN and $N_2O$ emissions calculators by accounting for cover crops, manure composition, soil moisture, and the feedback effects of improving soil health during organic management.

## Base Cation Saturation Ratio: Is Cation Balancing Important?

Two USDA funded research teams have undertaken farmer-participatory research into the “base cation saturation ratio” (BCSR) approach to soil nutrient management, used by many organic producers across the US. BCSR aims for an “optimum” balance with calcium (Ca) occupying about 65-80% of the soil’s cation exchange capacity or CEC, magnesium (Mg) 10-20%, potassium (K) 2-5%, sodium (Na) 0.5-3%, and acidity (hydrogen) up to 10%. Practitioners believe that optimum BCSR promotes better soil tilth, biological activity, and overall soil health, enhances crop nutrition and resistance to pests, and reduces weed pressure.

A University of Wisconsin team compared the effects of conventional, standard organic, and BCSR (organic with gypsum to bring Ca base saturation into range) treatments on foliar nutrients and susceptibility to European corn borer (ECB) in field corn. The BCSR increased foliar sulfur (S), iron (Fe) and copper (Cu), but had little effect on foliar Ca, Mg, and K levels. BCSR accelerated ECB growth early in the season, but reduced pest growth and feeding later, apparently through complex interactions among fertility treatment, mycorrhizal fungi, crop, and pests (Murrell and Cullen, 2014; Murrell and Cullen, 2015; Murrell et al., 2015).

An Ohio State University team has initiated a multi-site study in collaboration with organic producers to compare BCSR to other organic approaches. Parameters to be measured include crop yield and quality, soil biological activity and food web function, soil aggregation and other physical properties, weed seed banks and pest levels (Doohan, 2015).

An earlier OFRF-funded field study (five on-farm sites in Virginia) and literature review did not show any clear soil quality, crop yield, or weed management benefits to adjusting soil cation levels that depart from the "optimum" BCSR to a moderate degree (Schonbeck, 2000). When lime is required for acidic soils, selection of lime type (dolomitic or calcitic) based on relative Ca and Mg levels may be justified, especially if plant Ca or Mg deficiency symptoms are observed.

## Questions for Further Research in Organic Nutrient Management

More research into organic soil and nutrient management is needed for the Southern region, where warm rainy climates and highly weathered, low-fertility soils accentuate soil quality and crop nutrition challenges. Long hot growing seasons and mild winters expand options for crop rotation and cover cropping, but also accelerate SOM oxidation, which can compromise soil nutrient cycling. and intensify weed growth, which competes with crops for nutrients and moisture. An unmet need exists for practical soil and nutrient management information and decision tools for organic farmers across the South, including:

- Optimum cover crops, mixtures, and management practices for nutrient retention and delivery, SOM, and soil health in the Southern region.
- Optimum use of manure and compost for crop nutrition, soil, and environmental health.
- Practical strategies for organic reduced tillage systems.
- Estimates of PAN release from soil organic matter, cover crop residues, and amendments in Southern climates and soils.
- Practical guidelines to manage soil food web function for soil health and crop nutrition.

More research and development is needed to help organic producers co-manage soil health, crop nutrition, and water quality for a wide range of crops. While several excellent tests and decision tools are available for conventional field corn, and some can be adapted for organic corn, such tools are not available for most organic crops. Specific research needs include:

- N management for crops with high N requirements that are difficult to meet without increasing environmental risks, such as broccoli, cauliflower, and celery.
- N management for crops with limited root systems that do not access nutrients throughout the soil profile, such as salad greens.
- N management for crops whose N demand occurs weeks or months after peak PAN from a preceding legume or pre-plant fertilizer, such as fall-planted strawberry.
- Adaptation of existing decision tools and development of new tools for organic nutrient management for the full range of crops, crop rotations, and agricultural regions.
- Further exploration of the roles of soil organisms, soil and plant enzymes, and plant genetic expression in soil C-N-P dynamics, plant nutrition, and environmental impacts.

- Identifying conditions and practices that enhance crop nutrition and protect water quality and climate through tight nutrient cycling for a wide range of crops and agricultural regions.

Additional plant breeding and public cultivar development in and for sustainable organic systems is a high priority. Key traits for soil health and nutrient management may include:

- Adaptation to local or regional climates, soil types, and soil biota.
- High biomass production to provide good yields and add substantial residues to the soil.
- N use efficiency – high yields and quality (e.g., protein) where bulk soil PAN is low.
- Deep, extensive root systems that enhance nutrient uptake and build organic matter and biological activity throughout the soil profile.
- Enhanced expression of key plant enzymes for nutrient uptake and utilization.
- Enhanced symbiotic associations with N-fixing rhizobia (legumes), mycorrhizae (most crops), and other endophytic microbes that support crop nutrition.
- Enhanced association with beneficial rhizosphere micro-organisms that promote tight nutrient cycling, crop nutrition, soil C sequestration, or plant disease suppression.

Additional research is needed to evaluate and calibrate the many proposed indices of soil health and nutrient cycling, such as: “active,” “slow,” and “passive” SOM, particulate organic matter (POM), total and labile organic N, potentially mineralizable N (PMN), amino-sugar N (Illinois Soil Nitrogen Test), active and total soil microbial biomass, microbial respiration, fungal: bacterial ratio, nematode community abundance and diversity, and specific organisms or enzymes considered markers for key nutrient cycling processes. While some of these measures have been promoted as tools for farmers to assess soil health and fertility, interpretation can be tricky, and further clarification is warranted. For example:

- When does a “high” microbial respiration rate indicate a vibrant soil food web, and when does it raise a red flag that SOM may be degrading too rapidly?
- Does a high labile N, PMN or ISNT value foretell high crop yield, increased risk of N leaching or denitrification, or both?
- How can these indices be used to optimize N applications for yield, soil health, and environmental outcomes?

- Do enzyme markers that indicate tight, efficient nutrient cycling in tomato production in California (Jackson and Bowles, 2013) also apply to other crops and regions, such as corn in Iowa or wheat in Maine?
- How can the new SOM, soil N, and soil food web indices be developed into practical, reliable field tests that farmers can use to monitor soil health and fertility?
- Is a given tool widely applicable or specific to a particular region or cropping system?

There is a need for the scientific evaluation of the large and growing number of organic, biological, and natural mineral amendments marketed to organic producers and claimed to enhance soil biological activity, suppress crop diseases, support crop nutrition, improve yield and quality, and/or build SOM and overall soil health. Examples include biochar, humates, rock dusts with 50 or more trace elements, and various microbial inoculants. Many of these products have been approved by NOP, but relatively few have been evaluated in replicated, controlled trials. Product efficacy may vary with soil type and condition, and the pre-existing soil microbial community. The direct and environmental costs must also be considered. Organic producers need reliable information to help them distinguish useful products from ineffective ones, and to determine whether a specific product is likely to benefit their particular soils and cropping systems.

Finally, more research is needed on organic management of nutrients other than N and P. While surplus K, S, or micronutrients have not emerged as water quality or GHG issues, over-application can add unnecessary production expenses, and could upset nutritional balance for crops, livestock, or the soil food web. In addition, nutrient drawdown in “extensive” low-input systems such as hayfields and dryland cereal grains can threaten soil fertility and system viability over the long run. Producers need practical strategies to maintain optimum P, K, S, and other nutrient levels in these systems.

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# Notes

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