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Nutrient Management for Sustainable Vegetable Cropping Systems in Western Oregon

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Contents

Introduction

This guide is for vegetable growers in western Oregon. It reflects more than 30 years of research conducted in the Willamette Valley. Soils in the Willamette Valley that are used for vegetable production are predominantly medium-textured (i.e., sandy loam, silt loam, clay loam, or silty clay loam) and have access to irrigation water. Vegetables are typically planted in fields with soils mapped as Chehalis, Cloquato, Malabon, Newburg, Willamette, or Woodburn. Rivers or wells that draw water from shallow aquifers provide most of the irrigation water. Rainfall in the Willamette Valley is sufficient in winter months to leach soluble nutrients below the rooting depth of vegetable crops. Some of the fields used for vegetable production are within the South Willamette Valley Groundwater Management Area (GWMA) designated by the Oregon Department of Environmental Quality. Vegetables are grown in rotation with agronomic crops (such as winter wheat and grass seed) and specialty crops (such as vegetable seed crops). Most of the research presented here was conducted in fields where vegetables

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were grown for processing using conventional mineral fertilizers. In recent years, organic vegetable production acreage has increased. We conducted local field trials using organic nutrient management, primarily in conjunction with smaller acreage fresh market growers.

This publication has four major sections:

- **Section 1: Sustainable soil health**
  The first section addresses some important long-term management issues related to sustainability. This section was developed in response to questions from growers, processors, and agricultural professionals. A key point of discussion in this section is the outcome of "organic" versus conventional fertilization practices on soil health and environmental quality.

- **Section 2: Soil testing and nutrient management**
  The second section synthesizes years of OSU research designed to increase the efficiency and profitability of vegetable crop production. This section describes an approach that is similar to that used in other traditional land grant university guides; it provides actionable recommendations based largely on soil test results. In this section, we also provide a critique of the reliability of various soil tests and their interpretations.

- **Section 3: Nitrogen management**
  The third section focuses on nitrogen (N) management based on factors other than preplant soil test interpretation. The efficient use of N by crops is critical from an economic and environmental perspective. This section highlights traditional components of N management and the rationale and methodology for in-season soil nitrate testing.

- **Section 4: Appendix**
  The final section of the guide provides detailed information on technical aspects of fertilizer technology and its use.

Section 1: Sustainable soil health

Soil health can be defined as the "continued capacity of soil to function as a vital living ecosystem that sustains plants, animals, and humans" (See Healthy Soil for Life at https://www.nrcs.usda.gov/wps/portal/nrcs/main/soils/health). Just as human health can be measured by certain key indicators (such as body temperature, blood pressure, and body mass index), soil health also has several measurable factors that are affected by long-term management. In this section, we discuss general principles of soil health management and how they are related to nutrient management:

- Maintaining soil organic matter
- Maintaining soil pH
- Maintaining soil biology
- Maintaining nutrient balance

In addition, energy efficiency is also discussed briefly since fertilizers are a big part of the energy budget for vegetable production.

Maintaining soil organic matter

Soil organic matter is important for all aspects of soil health: chemical, physical, and biological. Soil organic matter is an important source of nutrient supply to crops (although it is not itself a nutrient). As soil organic matter decomposes, many nutrients are made available to crops. Soil organisms rely on organic matter as an energy source.

Organic matter dynamics
Adding organic matter to soil (as compost, manure, cover crop, etc.) is the fuel that drives soil biology (Figure 1, page 3). A variety of organisms (e.g., earthworms, fungi, nematodes, millipedes, bacteria, and springtails) proliferate. Outcomes can be positive (e.g., gradual release of plant-available nutrients) or negative (e.g., pest or disease proliferation).

Total soil organic matter builds or declines slowly. At a 12-inch depth, typical Willamette Valley soil with 3 percent organic matter (by weight) contains 100,000 lb/a of organic matter (or about 50,000 lb of carbon). About 2 percent of total soil organic matter (roughly 2,000 lb/a) is lost each year in the form of carbon dioxide (a byproduct of microbial decomposition). This process of microbial decomposition of soil organic matter happens even when no fresh organic matter is supplied. Sustainable management of soil organic matter requires the continual addition of organic matter.
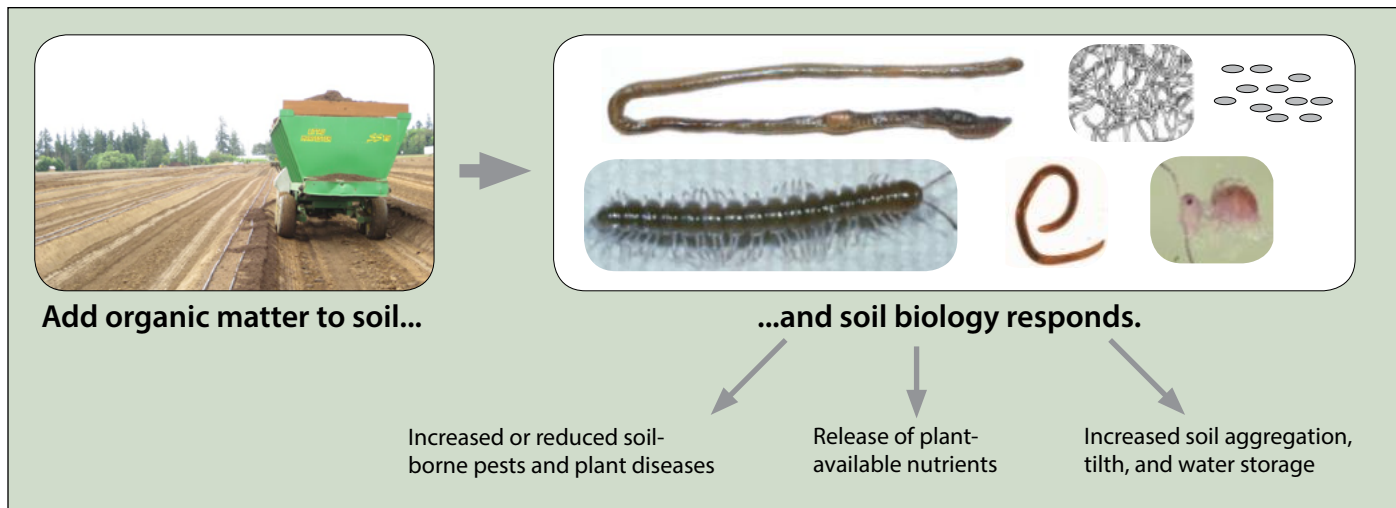
Figure 1. Adding organic matter to soil (as compost, cover crop, manure, etc.) is the fuel that drives soil biology.

Compared to total soil organic matter, a much larger percentage of fresh organic inputs are lost annually as carbon dioxide (Figure 2). However, the "new" organic matter inputs are an important source of plant available nutrients. As decomposition proceeds, nutrients are incorporated into soil organic matter or released as soluble (plant-available) forms. In general, leafy crop residues release plant-available nutrients and non-leafy crop residues, such as straw, offer little or no short-term nutrient benefit during the year they are added.

Terminology for describing soil organic matter is qualitative. Soil organic matter has a half-life from weeks to centuries, depending on the kind of carbon compounds present and how strongly it is adsorbed by clay minerals in the soil. "Fresh," "young," "new," or uncomposted organic matter has high food value for soil biota and is decomposed rapidly. Nutrients present in organic form are released (converted to mineral forms that plants can use) during the rapid decomposition process (Figure 2). The remaining organic matter is more resistant to decomposition and is described as as old, protected, or stable organic matter. In practice, it is impossible to clearly distinguish the quantity of nutrients provided by "fresh" or "stable" organic matter in soil.

Farming practices that maintain or increase soil organic matter

Soil management practices that retain topsoil in the field (reduce soil loss by wind or water) will benefit retention of soil organic matter (Table 1, page 4). Perennial sod crops or winter cover crops protect the soil from erosion and also provide organic matter inputs. Reducing tillage is another important strategy to maintain organic matter. Tillage exposes organic matter that has been protected inside soil aggregates and increases the rate of organic matter decomposition. As decomposition proceeds, soil carbon (C) is lost as gas (CO_2). The more frequent and intensive the tillage, the faster soil organic matter decomposes and is lost.

Even under ideal management practices, soil organic matter will not increase forever. The time required for a measurable increase in total soil organic matter (as determined by a soil test) can be 5 to 10 years or more following major changes in soil management. After a transition period, soil organic matter reaches a new equilibrium between addition and decomposition. At equilibrium, the rate of organic matter decomposition is approximately equal to the rate of organic matter addition.
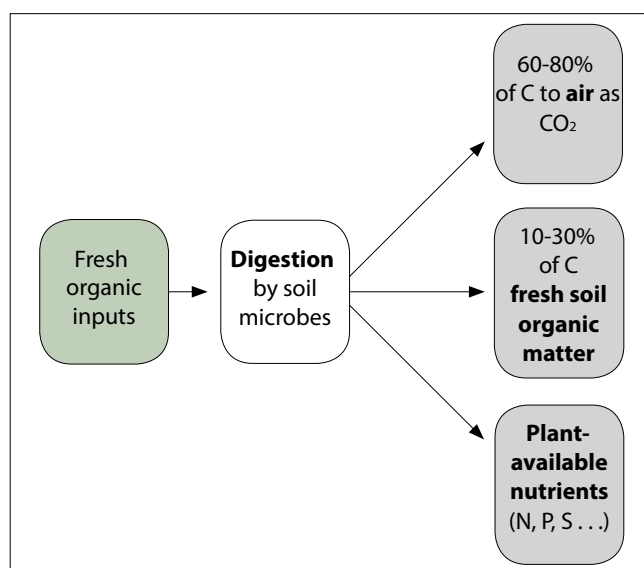

Figure 2. Fate of fresh organic inputs to soil

Table 1. Management actions that can increase soil organic matter

Practice	Examples of management actions
Increase crop biomass	Improve crop management (via soil fertility, planting density, irrigation, etc.)
Increase duration of plant growth	Plant winter cover crop; rotate to perennial grass, relay or interseeded crops[1]
Reduce tillage intensity, frequency, or depth	Consider order of tillage intensity: no-till < strip till < disc < rototill
Retain crop residues	Chop residue and leave in place instead of burning or baling

[1]Relay cropping or interseeding is the practice of planting a cover crop or a successive crop before the current crop has been harvested.

Overall benefits and drawbacks of soil organic matter buildup

It is important to consider the positive and negative aspects of increased soil organic matter (Figure 1, page 3). Increased soil organic matter almost always improves the capacity of the soil to support crop production. Benefits include improved soil tilth, increased water storage capacity, and increased biological activity. However, practices that increase soil organic matter can also intensify soil-borne pests such as slugs, symphylans, or seed corn maggots.

Some considerations for how soil buildup affects nutrient management decisions are described below.

Positive aspects. When total soil organic matter increases, so does the "biologically active" or "young" organic matter fraction. The biologically active organic matter fraction supplies plant-available nitrogen (N), phosphorus (P), sulfur (S), and some micronutrients. In soils that have been "built-up" by recent organic matter additions, the continual cycling of nutrients by the soil biota can effectively supply most of the nutrients required for vegetable crop production. This, therefore, reduces the need to apply expensive organic fertilizer inputs (e.g., chicken compost, feather meal, or fish fertilizers). Other benefits to soil health are also realized (Figure 1, page 3), which may improve the capacity of the crop to take up nutrients.

Negative aspects. Soils that have been "built-up" by the application of organic inputs such as compost or manure are often more susceptible to uncontrolled nutrient loss. Once plant nutrients are built up to high levels in the soil, they may remain that way for decades. Because plant-available N release from "built up" soil is primarily governed by soil temperature, too much plant-available N is usually produced by natural biological processes in late summer. Over the winter months, plant-available N that is not used by crops is subject to loss by leaching. Soils built up in phosphorus (P) will have higher risk of P loss to surface water bodies via soil erosion, runoff, or subsurface tile drains.

Crop quality is also sacrificed when the soil contains too much plant-available N late in the growing season. The risk of foliar disease and calcium (Ca) deficiency is increased with too much N. Crop maturity is often delayed. For example, indeterminate varieties of potato and tomato continue to produce vegetative growth at the expense of reproductive growth when too much N is supplied. High soil potassium (K) also may lead to crop quality problems (see "Potassium" section for more details, page 11).

Incorporation of fresh organic matter (manure or cover crop) immediately before seeding can result in poor crop stand. When high biomass cover crops are incorporated in spring, it is difficult to make a firm seedbed that ensures seed-to-soil contact. Some pests such as seed corn maggot may proliferate in response to fresh organic matter inputs. Treating seed with insecticide may be required to reduce pest damage. Both problems are reduced by waiting at least 3 to 4 weeks to seed following fresh organic matter incorporation. When spring weather is wet, fields planted to high biomass cover crops may not be ready for seeding until after June 15.

To maximize benefit and reduce nutrient loss to the environment, fertilizer rate and timing calculations must take into account the extra nutrients provided by manure, crop residues, and other organic inputs.

Maintaining soil pH

Soil pH is a key aspect of long-term soil sustainability. The pH scale is logarithmic, like the Richter scale for earthquake severity. A soil pH of 5 is ten times more acidic than a pH of 6.

Effects of nitrogen on soil acidification

Without lime application every 3 to 5 years, soil pH gradually decreases and becomes more acidic. When soil pH is too acidic for a crop, crop failure can occur. The rate of N fertilizer application is the most important factor in the rate of soil acidification. The pH of loam, silt loam, and silty clay loam soils in the Willamette

Valley decreases by about 0.1 to 0.2 pH units every year, when mineral N fertilizers are applied at the rate of 100 to 200 lb N/a per year. Higher rates of N fertilization result in a faster reduction in soil pH. Therefore, applying more N than required by the crop needlessly accelerates acidification.

Whether the N source is conventional or organic, soils are acidified by the conversion of ammonium-N to nitrate-N (nitrification process, Figure 3, page 15). Per pound of plant-available nitrogen, organic fertilizers generally do not acidify soil as rapidly as conventional nitrogen fertilizers. The organic matter and calcium minerals contained in organic fertilizers neutralize some of the acidity produced by nitrification.

Table 2 shows the relative sensitivity of vegetable crops to soil acidity. To avoid crop damage, maintain soil pH above that required for the most sensitive crop in your rotation. In a mixed vegetable crop rotation, where many vegetables may be grown, maintain soil pH near 6.5.

Determining when lime is needed and how much to apply

The periodic application of lime maintains the pH of acidic Willamette Valley soils at levels that support normal crop development. Agricultural lime is calcium carbonate. It neutralizes soil acidity via a chemical reaction:

Soil acidity (H^+) + lime (calcium carbonate; $CaCO_3$) → water (H_2O), carbon dioxide gas (CO_2), and calcium (Ca^{2+})
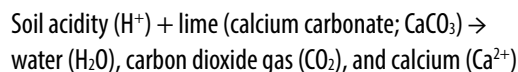
Lime is a mineral that is slightly soluble in water and not very mobile in soils. It must be tilled into the soil to achieve the desired pH in the topsoil. If lime is not incorporated into the soil, it will usually only increase pH in the top 2 or 3 inches of the soil.

Soil pH increases until all of the lime has reacted. Lime sold for agricultural use (aglime) begins reacting immediately after application to moist soils. When lime is incorporated into moist soil with tillage, it usually takes 3 to 9 months after application for the soil to reach the highest pH. Recent trials in the Willamette Valley demonstrated that most of the pH increase from fall-applied lime occurred by the following May (Heinrich and Sullivan, 2016).

Soil texture and organic matter are key determinants in how much lime is required to increase soil pH to the target level. Soils with more clay and organic matter require more lime to increase pH. Most soils used for vegetable crops in the Willamette Valley require 2 to 4 tons of lime per acre to increase pH by one unit, for example from pH 5.5 to pH 6.5. The lime requirement

Table 2. Recommended minimum pH for vegetable crops

Crop	Recommended minimum soil pH
Asparagus	6.0 to 6.5
Brassicas (broccoli, brussels sprouts, cabbage, cauliflower)[1]	6.3
Carrots	5.6
Cucurbits (cucumbers, melons, squash, pumpkins)	5.8
Garlic	6.5
Green or snap beans	5.8
Onions	6.0 to 6.5
Peas	6.0
Potatoes	5.5
Radish	6.0
Spinach	6.0 to 6.5
Sweet corn	5.8
Table beets	5.8
Turnips	5.8 to 6.0

Adapted from "Recommended minimum soil pH for Oregon crops," page 19 in OSU Extension publication *Soil Acidity in Oregon: Understanding and Using Concepts for Crop Production* (EM 9061).

[1]For brassicas grown in soils infested with *Plasmodiophora brassicae* (clubroot), liming to a higher pH is often used to control disease. See *Integrated Clubroot Management for Brassicas: Nonchemical Control Strategies* (EM 9148) for more information.

soil test is used to customize lime application rates for specific soils. See *Applying Lime to Raise Soil pH for Crop Production* (EM 9057) for more information.

Maintaining soil biology

Life in the soil is critical for nutrient cycling and plant uptake of nutrients, yet soil scientists still struggle to quantify the details of soil biology as it applies to sustainable soil management practices. In general, the same management actions that increase soil organic matter also promote beneficial soil biology in vegetable crop production. For example:

- Practice: A diverse crop rotation with at least part of the rotation in a perennial sod crop (e.g., grass seed, clover, alfalfa)
  Benefit: Better soil tilth and greater plant-available N supplied for the vegetable crops in the rotation

- Practice: Minimizing periods of bare soil during the fallow period, especially in winter
  Benefit: Improved soil tilth, reduced erosion, and greater survival of some beneficial organisms such as vesicular arbuscular mycorrhizal (VAM) fungi (See more on VAM below.)

- Practice: Longer intervals between the same vegetable crop or a crop that is subject to some of the same pests and root diseases
  Benefit: Healthy root systems that have greater capacity to take up nutrients, especially immobile nutrients like phosphorus

Vesicular arbuscular mycorrhizal (VAM) fungi

The roots of some vegetable crops, like snap beans, host VAM fungi. These fungi can be important for crop health, especially when vegetable crops are grown in soils that are marginal or deficient in zinc (Zn) or phosphorus (P). Roots hosting symbiotic VAM fungi have greater surface area for nutrient uptake. VAM fungi may also confer greater efficiency in water uptake from the soil to the host crop.

These aspects of vegetable cropping systems limit root colonization by VAM fungi:

- Not all crops host VAM. Crops in the beet family (e.g., table beets and Swiss chard), the brassica family (e.g., canola, mustard, cabbage, and broccoli), and buckwheat cover crops do not host VAM. Crops such as beans or corn that host VAM can be more susceptible to P and Zn deficiency when planted following non-host crops.

- VAM survive in the intact root systems present in no-till or cover cropped fields. Clean tillage and extended fallow periods reduce VAM propagules.

- VAM colonization of roots is reduced as soil test P increases.

Maintaining nutrient balance

Nutrient balance is an important long-term indicator of sustainability. Nutrient balance, when considered on a field level, has two major components:

Nutrient balance = **Inputs** from soil amendments, fertilizers, legumes (N only) **minus Outputs** from crop harvest

Nutrient balance does not consider nutrient flows within the field. The nutrient balance concept assumes that nutrients are not lost via other routes (leaching below the root zone or loss as a gas). These assumptions are valid for P and K, but are less valid for N. For N, loss through leaching and as a gas (ammonia) can be significant.

When the nutrient balance is negative, soil reserves of nutrients are being depleted and crop yields may suffer in the future. When the balance is positive, nutrients are accumulating. In general, nutrient accumulation is not a bad thing from a crop production perspective. However, accumulation of P is a concern from an environmental perspective. Accumulation of excess N (even in organic form) may result in higher nitrate leaching loss. Accumulation of N and K to excessive levels can compromise crop quality.

Calculations of nutrient balance are based on input records and crop yields. A constant value for nutrient removal per ton of yield is assumed. This is a good assumption for P because plant-P concentrations are relatively stable regardless of soil test P. Plant-K concentrations are more variable. Below are examples to illustrate the calculation of nutrient balance.

Example 1: A farmer fertilizes a specialty potato crop with 2 ton/a of 3-2-2 (N-P_2O_5-K_2O) organic fertilizer, resulting in an input of 80 lb P_2O_5/a and 80 lb K_2O/a. Twenty tons of tubers are removed from the field, containing 60 lb P_2O_5/a and 250 lb K_2O/a (Table 3, page 7).

Calculation—Input minus output (from crop harvest)
For P_2O_5 = 80−60 = +20
For K_2O= 80−250 = -170

Example 2: A farmer applies starter fertilizer (10-34-0) to supply 40 lb N/a and 136 lb P_2O_5/a. At harvest, a 10-ton sweet corn ear yield removed 30 lb P_2O_5/a and 60 lb K_2O/a.

Calculation—Input minus output (from crop harvest)
For P_2O_5 = 136−30 = +106
For K_2O = 0−60 = -60

Table 3. Estimates of crop removal of phosphorus and potassium via crop harvest—Units used to express removal are the same units found on fertilizer bags (P_2O_5 and K_2O).[1]

Crop	Yield ton/a	P_2O_5 lb/a	K_2O lb/a
Broccoli	8	20	110
Cabbage	30	55	230
Carrots	15	25	100
Cauliflower	6	20	60
Cucumber, slicing	10	10	40
Lettuce, Romaine	20	30	170
Onion, bulb	34	50	160
Peas, shelled, bush	2	10	20
Peppers, bell	20	30	110
Potatoes	20	60	250
Snap beans, bush	6	15	40
Spinach	12	15	120
Squash, summer	20	30	130
Squash, winter	18	20	120
Sweet corn	10	30	60
Tomato	12	10	80
Average		**27**	**113**

[1]Values listed here are based on P_2O_5 and K_2O removal unit values (lb per ton of harvested commodity) from *Nutrient Recommendations for Vegetable Crops in Michigan* (Warnke et al., 2004). Actual nutrient uptake per unit of harvested yield will depend on cultivar, harvest maturity, and dry matter content of harvested crop. Western Oregon yields were estimated based on published and unpublished sources.

Most N-P combination fertilizers are unbalanced. Application rates for N-P combination fertilizers are often based on supplying crop N needs. Crop biomass typically contains 5 times more N than P_2O_5, while many fertilizers contain a lower N-to-P_2O_5 ratio (e.g., 10-34-0 or 3-2-2). Conventional fertilizer salts (liquid or solid) can be blended to achieve a more suitable N-to-P_2O_5 ratio to match crop P needs. When a preplant soil test indicates sufficient P is already present, only N needs to be supplied by inputs.

Soil P buildup is usually observed when N is routinely provided by manures or composts. Most manures and composts supply about the same quantity of total N and P_2O_5. Only a few organic fertilizers (e.g., feather meal, 12-0-0) have a high N-to-P_2O_5 ratio.

Legume crops provide N for the next crop without increasing soil P. Plant-available N is manufactured by Rhizobia bacteria that grow in association with legume roots. Legumes take up P already present in the soil. Legumes do not add P to the soil, they recycle it.

Using energy efficiently

More productive crops produce more food (energy) for human or animal consumption. When fertilizer input is not needed, fertilizer application is a waste of energy and leads to an unnecessary release of carbon dioxide, a greenhouse gas.

Large inputs of fossil fuel are needed to "fix" atmospheric N into mineral forms that plants can use. It takes about 30 million BTUs to make a ton of N as ammonia (NH_3), 32 million BTUs for a ton of N as urea, and 36 million BTUs for a ton of N as UAN (urea-ammonium nitrate) fertilizer (Sawyer, 2010).

Compared to N, the energy input for phosphorus (P) and potassium (K) fertilizers is small. Phosphorus and potassium are mined from naturally occurring mineral deposits. Total energy required to fix (N) or mine (P and K), and to process, package, transport and apply nutrients in the field is estimated at 38, 15, and 12 million BTUs per ton of nutrient for N, P_2O_5, and K_2O, respectively (Gellings and Parmenter, 2004). This estimate assumes that the most efficient fossil fuel source (natural gas) is used for N fertilizer manufacture.

Section 2: Soil testing and nutrient management

Under most conditions, a complete preplant soil test every 3 to 5 years should be sufficient to determine the nutrient inputs that are required and the need for lime application. Major decisions that are based on preplant soil testing include:

- Determining the need for phosphorus, potassium, boron, and zinc applications
- Estimating lime need (using pH and lime requirement tests)

Specific situations may require additional soil tests. Preplant tests for soil nitrogen are generally not useful. See "Nitrogen management" (page 15).

The target preplant soil test values listed in Table 4 reflect the general recommendations in *Soil Test Interpretation Guide* (EC 1478) across all crops produced in western Oregon.

Nutrient-by-nutrient considerations

Organic matter

Generally, nutrient application recommendations given in OSU Extension and PNW Cooperative nutrient management guides are not adjusted based on soil organic matter content. Therefore, it is not necessary to routinely test for soil organic matter for the purpose of making nutrient management decisions.

Assessing changes in soil organic matter over time requires consistent sampling and testing protocols. Several laboratory methods are used to determine soil organic matter content. The Loss On Ignition (LOI) method is the most common method used by commercial labs to determine soil organic matter, but it is less reliable than other methods. The LOI test is an indirect test. It measures soil weight loss when soil is heated to a temperature high enough to burn off the organic matter. More reliable tests directly measure soil carbon. These methods include the Walkley-Black

Table 4. Recommended tests to monitor soil nutrient status in western Oregon vegetable crop production systems[1]

Test	Symbol	Soil test extractant/method	Adequate preplant value	Test reliability[2]
Organic matter	OM	Loss On Ignition (LOI), others	Higher is usually better	Medium
Acidity[3]	pH	1:2 soil:water	See Table 2 (page 5)	Medium
Lime requirement[3]	$CaCO_3$	SMP buffer	See OSU Lime Guide, EM 9057	Medium
Soil biology testing	—	Various	Not available	Low—experimental only
Nitrate-N	NO_3-N	KCl	25–30 ppm	Low to high[4]
Phosphorus	P	Bray P1	50 ppm	High
Potassium	K	NH_4 acetate	200 ppm	Medium
Sulfur	S	Ca phosphate	20 ppm SO_4-S	Low
Calcium	Ca	NH_4 acetate	5 meq/100g	High
Magnesium	Mg	NH_4 acetate	1.0 to 2.5 meq/100g	High
Boron	B	Hot water	0.2 to 1.0 ppm	Medium
Zinc	Zn	DTPA	0.8 to 1.5 ppm	High
Soluble salts	EC	1:2 soil:water	See Table 6 (page 12)	High

[1]See *Soil Test Interpretation Guide* (EC 1478) and crop-specific OSU Extension and PNW Cooperative nutrient management guides in the OSU Extension Catalog (https://catalog.extension.oregonstate.edu/) for more details. Interpretations shown here are based on soil samples taken from the top 12 inches.

[2]Lab tests that have high reliability are more likely to give correct management interpretations than tests with medium reliability. The sulfate-S soil test generally has low reliability and is not recommended as a reliable predictor of the need for S fertilization. The lime requirement test (SMP buffer) is more reliable when soil pH (in water) is less than 5.8.

[3]See OSU Extension liming guides in "For more Information" (page 23) for crop-specific pH recommendations. Spinach, lettuce, and the brassicas are most sensitive to low soil pH. For crop rotations that include these vegetables, maintain pH above 6.5.

[4]Preplant nitrate tests usually have low reliability. In-season soil nitrate tests have higher reliability. See "In-season soil nitrate testing" (page 19).

method and high-temperature combustion methods that detect C in CO_2 emitted from the sample. Soil organic matter is about 50 percent carbon, so a soil carbon value of 1.5 percent is equivalent to about 3 percent organic matter. For more information on these tests, see *Soil Test Interpretation Guide* (EC 1478).

Soil pH and lime requirement

Target values for soil pH are designed to prevent soil acidity damage to the most susceptible crop in the rotation. Maintaining soil pH above 6.0 is recommended for most crop rotations that include vegetables. Asparagus, brassicas, garlic, onions, and spinach are the crops most sensitive to low pH, requiring pH maintenance above 6.5 (see Table 2, page 5).

To track soil pH trends across years, measure soil pH at about the same time each year, during the fall or early spring, when N fertilizer has not been applied recently. Soil pH varies with time of year and location in the field. For example, a soil test pH value of 6.2 likely means that soil pH fluctuates between 5.9 and 6.5 over the course of the year.

The SMP lime requirement test is used to determine soil-specific lime need. If your soil already has a suitable pH for your crop rotation, you can ignore the lime requirement test results. Some labs have switched from the SMP buffer to the Sikora buffer method. The older SMP and the newer Sikora lime requirement tests have the same interpretation. The lime requirement test interpretations found in OSU Extension nutrient management guides are based on the SMP method but can be applied to soils tested using the newer Sikora buffer test. For additional lime requirement test details, see *Applying Lime to Raise Soil pH for Crop Production (Western Oregon) (*EM 9057).

In addition to the soil pH test and the lime requirement test, several other tests may provide valuable information to determine the need for liming:

- **Soil calcium (Ca) test.** Soil test Ca decreases as soil acidifies (pH drops). Tracking soil test Ca over time is an indicator of how fast the soil is acidifying and when liming might be needed again. Soil test Ca is less subject to seasonal variation than the soil pH measurement.

- **Plant tissue manganese (Mn) test.** Plant-available manganese (Mn) in soil increases as pH declines (becomes more acidic). Plant tissue Mn increases as soil pH declines. Plant tissue Mn concentrations above 100 ppm indicate the potential for soil acidity damage in lettuce, beans, and carrots (Hemphill and Jackson, 1982).

Leaf Mn is higher when plants are grown in more poorly drained soils (e.g., Dayton/Amity series) than in soils with better drainage (e.g., Willamette/Woodburn series). For more information, see *Soil Acidity in Oregon: Understanding and Using Concepts for Crop Production* (EM 9061).

In Willamette Valley soils, it is very unusual for pH to be too high (too alkaline) to support vegetable production. In fact, if results indicate a pH greater than 7, it is likely the soil sample contained unreacted lime or the laboratory made an analytical error.

Phosphorus (P)

Adequate phosphorus is essential for plant development. The phosphorus soil test, using the Bray method, is an excellent indicator of the need for P fertilization. Recent OSU research with sweet corn and snap beans confirmed that when soils test above 50 ppm (Bray test), they do not require P fertilization via any application method to achieve maximum yield (Sullivan et al., 2012; Sullivan et al., 2013; Peachey et al., 2013; Peachey and Sullivan, 2015).

The need for P by crops needs to be balanced with the environmental risk of having too much P in the soil. Phosphorus lost from the field and deposited into surface water via soil erosion, surface runoff, or tile drainage water can lead to algal blooms and fish kills. The Bray test, used to measure plant-available P in western Oregon, is a rough indicator of a soil's potential P-fertilization effect on nearby water bodies. The higher the soil test P value, the more concentrated P is likely to be in eroded soil or runoff. Almost all fields currently used for vegetable production in western Oregon have soil test P values greater than 50 ppm, which is the P fertilizer response threshold (Table 5, page 10).

Phosphorus removed with the harvested portion of the crop is small compared to N and K removal. To maintain soil test P at the current level, P fertilizer input rate must be approximately equal to P removed via harvest. About 15 to 30 lb P_2O_5/a is removed by the harvest of most vegetable crops grown in western Oregon (Table 3, page 7).

Table 5 (page 10) provides a comparison of soil test recommendations for phosphorus application in current and out-of-print OSU Extension fertilizer guides for vegetables. The out-of-print OSU Extension guides from the 1960s and 70s did not consider the issue of too much P in soil being a potential environmental problem. Phosphorus fertilizer rates recommended today are similar to those recommended historically, except when soil test P is high. For all vegetable crops, when soil test P is above 50 ppm,

Table 5. Recommended preplant application rates of phosphorus and potassium for vegetable crops in the Willamette Valley

Soil test category		Snap Bean[1]	Sweet Corn[1]	Other vegetables, as cited in out-of-print OSU Extension Fertilizer Guides[2]
Phosphorus recommendation				
	ppm P	lb P_2O_5/a		
Low	0 to 15	80 to 100	120 to 150	120 to 160
Med	16 to 50	30 to 80	60 to 120	70 to 120
High	Over 50	0	0	40 to 90[3]
Potassium recommendation				
	ppm K	lb K_2O/a		
Low	0 to 100	90 to 120	100 to 150	90 to 150
Med	101 to 200	40 to 90	50 to 100	60 to 100
High	Over 200	0	0	40 to 60

[1]OSU Extension Fertilizer Guides: Sweet Corn (EM 9010) and Snap Bean (EM 9154)

[2]Recommendations from out-of-print OSU Extension fertilizer guides: Pole Beans (FG 12); Table Beets (FG 13), Potatoes: Western Oregon (FG 19), Brassicas (FG 27), Carrot (FG 29), and Vine Crops (FG 68)

[3]For all vegetable crops, when soil test P is above 50 ppm, the current recommendation is to limit fertilizer P application to less than crop P removal. See Table 3 (page 7) for estimates of P removal by crops.

the current recommendation is to limit fertilizer P application to less than crop P removal (Table 3, page 7).

When vegetables are planted under less than optimal field conditions (e.g., cold, wet, or compacted soils in early spring), greater early season crop vigor is sometimes observed when P fertilizer is placed near the row as a starter application at seeding or transplanting. This improvement in early season plant growth can be observed even when soil test P is high (above 50 ppm by Bray test method). The P fertilizer rate required to stimulate early seedling vigor via starter application is small (< 30 lb P_2O_5/a). Starter P fertilizers (liquid or solid) are typically placed 2 inches below and 2 inches away from the row (2 × 2 placement). For additional details, see "Starter fertilizer formulations and application" in the Appendix (page 20).

"Pop-up" fertilizer application (liquid fertilizer applied at seeding close to seed, or in contact with seed) can also be used to supply P. Pop-up fertilizer formulations supply less N and K than do starter formulations because of the danger of salt and/ or ammonia damage to seedlings. Pop-up fertilizer applications of less than 10 gal/acre of 10-34-0 (supplying < 35 lb P_2O_5/a), have been used successfully by Willamette Valley farmers for sweet corn. Pop-up fertilizer applied to sweet corn seeded at moderate to high densities did not provide a yield advantage

(Peachey and Sullivan 2015). Better early corn growth was observed with a pop-up fertilizer, but it did not improve ear yield or quality.

Sulfur (S)

Sulfur is routinely applied in most western Oregon cropping systems. Sulfur movement in soil and plants is most similar to nitrogen, with some important differences. Sulfate (SO_4^{2-}) is the plant-available form of S. Like N, sulfate is an anion (a negatively charged ion); however, the sulfate anion is much less subject to leaching than nitrate. Some residual sulfate-S present in soils in the fall will carry over to the next year. Like N, an important source of S for plants comes from the mineralization of organic S present in soil organic matter and organic inputs. Soil biota transform organic S into the sulfate-S form.

Sulfur application rates are based on crop S uptake. Soil tests for S are not reliable enough to predict crop need for S when test values are low. No S fertilization is recommended when soil test S is greater than 20 ppm. A test value of 20 ppm is equivalent to about 70 lb of plant-available S in the top 12 inches of soil.

Healthy crops contain 10 to 15 times more N than S. A crop taking up 150 lb N/a will contain about 10 to 15 lb S/a. For vegetables, apply 20 to 40 lb S/a in the sulfate form in a preplant broadcast or starter fertilizer application. Fertilizers that contain

immediately available sulfate-S include the solid fertilizers ammonium sulfate (24% S), potassium sulfate (18% S), gypsum (19% S), and Sul-Po-Mag or K-mag (22% S). Composts, manures, and other organic fertilizers also supply sulfur.

Calcium (Ca) and Magnesium (Mg)

Plant-available Ca and Mg are reliably determined by a soil test (Table 4, page 8), but fertilizing with these nutrients to mitigate a deficiency is rarely recommended. Most vegetable cropping systems require a soil pH above 6. Soil pH maintenance is achieved by periodically applying lime. Calcitic limestone or aglime supplies Ca; dolomitic lime supplies both Ca and Mg. Although adding some Mg as dolomite can be beneficial, you should not use it routinely for liming. Dolomitic lime usually costs more than aglime and reacts more slowly with acidity to raise soil pH.

Toxicity from excess Ca or Mg is rare because plants do not accumulate these nutrients even when they are present in soil at levels far above that required by the crop. Soils derived from parent materials that contain high concentrations of Mg (serpentine minerals) are present in southern Oregon. These soils have unusually high amounts of Mg relative to Ca. When the ratio of Mg to Ca is greater than 1:1 (more Mg present than Ca), as determined by a soil test, do not apply additional Mg.

Calcium deficiency affects the plant during early growth but is often not recognized until later in the season. Insufficient Ca in the soil seldom causes Ca deficiencies in vegetable crops. Applying more Ca fertilizer usually won't correct the deficiency. Instead, the best response to a plant Ca deficiency is to modify other crop management practices. For example, blossom-end rot of tomato is a symptom of a plant Ca deficiency, but it is almost always caused by uneven soil moisture combined with a susceptible cultivar, excessive vegetative growth, and unusually hot or cold temperatures when fruit is young. To reduce blossom-end rot, plant resistant varieties, manage irrigation to provide even soil moisture, and avoid excess N application.

Crop Mg deficiencies are rarely seen on vegetables in the Willamette Valley. However, a few scenarios might trigger crop Mg deficiency:

- When soil test K is very high, crop K uptake is usually elevated and crop Mg uptake is reduced. Fields where manure or compost has been applied frequently often have very high soil test K (above 500 ppm).

- When calcium carbonate lime has been applied and soil pH is greater than 6.5, crop Mg deficiency is more likely.

Composts, manures, and most organic fertilizers supply both Ca and Mg. Calcium sulfate (gypsum; $CaSO_4$) supplies additional Ca without affecting soil pH. Magnesium sulfate (Epsom salts; 9% Mg) or K-Mag (10% Mg) can supply additional Mg without affecting soil pH.

When soil test Mg is low in a preplant soil test or when field history suggests the possibility of an Mg deficiency, apply 10 to 20 lb Mg/a in starter fertilizer band.

Potassium (K)

Plant-available K is determined by the same soil test used for Ca and Mg. Generally speaking, plants respond with good yields when soil test K is greater than 100 ppm K in the top 12 inches of soil. Few soils with soil test K >150 ppm in the top 12 inches of soil are K deficient. The target soil K maintenance value of 200 ppm K (Table 5, page 10) is higher than vegetable crops generally require but allows for some soil test variability. The test to measure soil K has medium reliability in predicting crop response to additional fertilization.

Potassium fertilizer rates do not need to equal crop K uptake. Much of the K accumulated by the crop will be returned to the field as crop residue. In the case of sweet corn, more than half of the K in the aboveground portion of the plants will be found in crop residue.

Fertilizer K recommendations, based on a preplant soil test (0 to 12 inches), are shown in Table 5 (page 10). Few trials have been conducted in the Willamette Valley to evaluate vegetable crop response to K application. In general, when soil test K is less than 100 ppm, an application of K fertilizer equal to about half of the projected crop K uptake will provide for plant needs. When soil test K is 100 to 200 ppm, apply about a third of the projected crop K uptake.

Very high soil test K (above 500 ppm) is unusual unless high rates of animal manure or compost have been applied for many years. When present at excessive levels in soil, plants usually respond by accumulating K in plant tissue, sometimes at the expense of the plants' use of Ca and Mg.

Potassium fertilizers are a major source of added salt in starter fertilizer formulations, which limits the amount of K that can be applied via starter fertilizer. See "Starter fertilizer formulations and application" in the Appendix (page 20) for more information.

Potassium chloride (KCl; 0-0-60) is the most common mineral K fertilizer used. KCl is very soluble

in water and is plant-available at application. Avoid root damage by limiting KCl application rates when banding a starter fertilizer near the row.

At times in organic cropping systems, manures and composts are the sole N input. Under these conditions, it is likely that more K is provided than vegetable crops require. When soil test K is high, legume cover crops can supply plant-available N without supplying additional K.

Calcium, magnesium, potassium ratios, and "cation saturation"

Crop uptake of cations is determined primarily by genetic factors and not by the relative concentrations of exchangeable K, Ca, and Mg present in the soil. For example, plants take up much more K than Ca although exchangeable K is much lower in soil than Ca. Some soil test reports from private laboratories show additional values for K:Mg, K:Ca, or Ca:Mg ratios, or for estimated K, Mg, Ca "saturation" of estimated cation exchange capacity (CEC). Interpretations for cation ratios and cation saturation percentages are not supported by research conducted at OSU.

Soluble salts (EC)

Electrical conductivity (EC) is a measure of soluble salts. The higher the EC, the more soluble salt is present in the soil solution. Soils in western Oregon are flushed annually by winter rainfall. Salts are leached below the rooting depth, and, for that reason, soils used for vegetable production do not generally require testing for soluble salt accumulation.

Vegetable crops differ in their tolerance to soluble salts (Table 6). Onions, beans, carrots, and lettuce are among the most sensitive. Plant damage occurs when

Table 6. Relative susceptibility of vegetables to injury from excess soluble salt
Crops listed from most sensitive to salt (top row) to most tolerant to soluble salts (bottom row)

Crop	Expected crop yield reduction from soluble salt in soil[1]		
	No yield reduction	10% yield reduction	25% yield reduction
	Electrical conductivity (EC) of soil extract, dS/m[2]		
Turnip	0.9	2.0	3.7
Carrot	1.0	1.7	2.8
Bean	1.0	1.5	2.3
Radish	1.2	2.0	3.1
Onion	1.2	1.8	2.8
Lettuce	1.3	2.1	3.2
Pepper	1.5	2.2	3.3
Potato	1.7	2.5	3.8
Corn, sweet	1.7	2.5	3.8
Celery	1.8	3.4	5.8
Cabbage	1.8	2.8	4.4
Spinach	2.0	3.3	5.3
Tomato	2.5	3.5	5.0
Cucumber	2.5	3.3	4.4
Broccoli	2.8	3.9	5.5
Squash, scallop	3.2	3.8	4.8
Beet, red	4.0	5.1	6.8
Squash, zucchini	4.7	5.8	7.4

Adapted from: Ayers and Westcot (1985)

[1]Example: For lettuce, when soil EC (as determined by saturated paste method) exceeds 1.3, expect yield reduction. The expected yield reduction is 10 percent when EC = 2.1 and 25 percent when EC = 3.2. Keep in mind that crop yield reduction from excess soluble salts also depends on growth stage, soil temperature, soil moisture, and other factors.

[2]EC measured using the saturated paste extract method. For the same soil sample, EC test values for the 1:2 (soil:water) method (PNW laboratories) are approximately half the value determined by the saturated paste method.

excessive soluble salt reduces water uptake by roots. Seedlings are most susceptible to salt damage.

Soil testing laboratories in the Pacific Northwest commonly determine EC using a 1:2 (soil:water) method. Table 6 (page 12) is based on a different EC measurement method (saturated paste). Because these methods differ, the EC values listed in Table 6 should be viewed as relative values. For the same soil sample, EC test values for the 1:2 (soil:water) method (PNW laboratories) are approximately half the value determined by the saturated paste method.

Situations where excessive salts might damage vegetable crops grown in western Oregon include the following:

- Injury from soluble salts can be caused by applying too much fertilizer N and K close to the seed. Minimize the risk of salt injury by placing starter fertilizer applications no closer than 2 inches from the seed, and by limiting rates of N and K application. See "Starter fertilizer formulations and application" in the Appendix (page 20) for details. Phosphorus is much less soluble in soil, so it is not a concern for salt damage.

- Soluble salts may accumulate in the soil when vegetables are grown under cover in high tunnels. With a roof to keep out the rain, salts are not leached from the root zone during the winter. Removing the tunnel roof during the winter may be necessary when soil tests show excess salt accumulation.

- Composts or organic fertilizers may contain high concentrations of salt. To minimize risk, apply organic fertilizers by broadcasting, not banding. Carefully monitor the application rate and EC of fields to which such fertilizers are applied.

- Vegetables grown with fertigation under drip irrigation may be at risk of salt damage. Salts accumulate at the edge or wetting front of an irrigated zone. Minimize this risk by limiting the rate of fertilizer applied and monitoring salt accumulation near plant roots.

Because salts accumulate and move in soil, in-season testing (rather than a preplant test) will better reveal the conditions under which the crop is growing. You can use handheld EC meters to assess salt accumulation during the growing season. The meter must be calibrated frequently to ensure accurate results. Use of a portable meter is recommended as a supplement to, and not a substitute for, laboratory testing.

Table 7. Nutrient concentration in youngest mature leaves of vegetable crops that indicate possible deficiency[1]

Nutrient	Possible nutrient deficiency (ppm)
Boron (B)	< 30
Copper (Cu)	< 6
Iron (Fe)	< 40
Maganese (Mn)	< 25
Zinc (Zn)	< 25

[1]Concentrations listed here are in the middle of the critical concentration ranges given in the literature. For example, minimum concentrations of Zn listed for most vegetable crops in plant analysis handbooks range from 20 to 30 ppm. (Adapted from: Mills et al., 1996)

Micronutrients

Micronutrient fertilizers are not routinely required for vegetable production in western Oregon. These nutrients are required in very small amounts, hence their designation as "micro" nutrients. There is a real danger of crop damage from applying too much of a micronutrient. Use soil testing and plant tissue analyses as the basis for your decision to add micronutrients. Willamette Valley soils that are managed organically almost always have adequate micronutrients present to support crop production.

Plant tissue tests are commonly used to diagnose micronutrient deficiencies. See Table 7 for general guidelines for interpreting plant tissue tests. For all crops, the youngest mature leaf from the top of the shoot is submitted for analysis. Interpret values in Table 7 with caution—they reflect professional judgment and are not supported by extensive experimental data. Exact values that signal nutrient deficiency vary across crops.

Zinc (Zn), Copper (Cu), Manganese (Mn), and Iron (Fe)

Because Willamette Valley soils are acidic and contain relatively high amounts of organic matter, metal micronutrients such as Mn, Zn, Cu, and Fe are usually adequate for vegetable crop production. Soil organic matter is the primary reservoir for micronutrients. As soil pH declines (becomes more acidic), these micronutrients become more plant-available.

Sensitivity to micronutrient deficiency varies considerably among vegetable crops (Martens and Westermann, 1991). For example, sweet corn, snap beans, and onion are among the most sensitive of the vegetable crops to zinc deficiency. By comparison, asparagus, peas, and carrots are unlikely to show zinc deficiency.

Soil test labs working under OSU guidelines use a chelate extractant acid (abbreviated as DTPA) to measure metal micronutrients. See *Soil Test Interpretation Guide* (EC 1478) for details. Other micronutrient extractions (e.g., Mehlich 3 extractant) offered by some soil test laboratories have not been correlated to crop response in western Oregon, so interpretation of these tests is not provided here.

Zinc (Zn). Sweet corn is among the crops most sensitive to zinc deficiency. *The Sweet Corn (Western Oregon) Nutrient Management Guide* (EM 9010) recommends:

- On soils testing low for Zn (DTPA soil test below 0.8 to 1.0 ppm), apply 3 to 4 lb Zn/a in a band or 10 lb Zn/a via a broadcast application. The higher broadcast rate usually supplies adequate zinc for 2 to 3 years after application.

- In gravelly soils derived from volcanic ash, such as the Sifton series in the Stayton area, apply zinc at higher rates. In Sifton, Salem, and other dark-colored soils, a Zn application is recommended when soil test Zn is below 1.5 ppm.

The reduced plant-availability of Zn in Sifton soils may be due to their volcanic ash content. The explicit mechanism responsible for reduced Zn availability on these soils has not been identified.

Copper (Cu). Spinach, lettuce, and onion are the vegetable crops most sensitive to Cu deficiency (Martens and Westermann, 1991). Deficiencies of Cu were observed in 'Danvers' onion fields in the Lake Labish area, near Keizer, Oregon in the 1980s (McAndrew, 1983). Before the lake was drained for cropping, the soils had accumulated more than 10 percent organic matter. Soils on old lakebeds are among the sites most susceptible to Cu deficiency. Since the 1980s, copper sulfate has been applied routinely to some Lake Labish fields. As a result, onions produced in these fields now have elevated leaf tissue copper concentrations and potentially reduced yields due to copper excess. For most crops, leaf tissue Cu concentrations of 20 to 50 ppm are considered "high." Cu levels greater than 50 ppm may indicate toxicity (Schulte and Kelling, 1992).

Manganese (Mn) and Iron (Fe). Deficiencies of Mn and Fe in replicated trials in western Oregon have not been identified. Manganese deficiency is most likely to occur in sandy soils that have been limed to a pH near 7. Iron deficiency is extremely unlikely.

Boron (B)

Laboratories working under OSU guidelines use a hot water extraction method to estimate plant-available boron. This method does not measure soil B in soil organic matter. Additional B, not measured by a soil test, is released in the field as organic matter and decomposed by soil biota.

Neither soil testing nor plant tissue testing for B is highly predictive of crop response to B fertilization. Adequate B in the most recently, fully expanded leaves of vegetable plants is 25 to 40 ppm for most crops (Mills et al., 1996).

Crops vary considerably in B requirement. Generally speaking, vegetables in the beet family (table beets), the brassica family (cauliflower, broccoli, cabbage, turnip), and celery are most sensitive to B deficiency (Martens and Westermann, 1991). By contrast, spinach, tomato, asparagus, snap bean, cucumber, sweet corn, peas, and potatoes have a low to moderate B requirement and are less sensitive to B deficiency.

Boron deficiency is most common on sandy, low organic matter soils that have been limed above pH 6.5. Plants that are water stressed or have damaged root systems from pest attack are more likely to show B deficiency. Too much B can be toxic to crops.

One important purpose of soil testing is to identify fields that are already high in B. The soil B test is regarded as effective in identifying B excess. It is less reliable in identifying B deficiency. Boron is potentially toxic to sensitive crops like beans when soil test B levels are above 2 ppm.

Most often, B toxicity is the result of the uneven application of boron fertilizer. Applying B evenly via broadcast application will minimize the risk of toxicity. Solubor (sodium octoborate) is the most common B fertilizer used for broadcast application. Do not apply B in starter fertilizer mixes because of the danger of B toxicity.

Boron response of vegetable crops in western Oregon has not been evaluated recently by OSU. Older OSU Extension fertilizer guides (based on research conducted before 1980) recommended preplant broadcast B application at 1 to 3 lb/a for crops that are sensitive to B deficiency (e.g. cauliflower, broccoli, cabbage) and 0.5 to 1 lb/a for other crops.

Foliar applications of B fertilizers will damage some crops. Recommended foliar applied B rates (0.1 to 0.3 lb/a) are much lower than preplant broadcast rates.

In western Oregon, the response of table beet to B fertilization was thoroughly studied on a Willamette

soil (Hemphill et al., 1982). The incidence of beet canker (a symptom of B deficiency) was reduced by increasing N fertilizer rate or by applying B fertilizer. The presence of visible beet canker did not correlate with B concentration in leaves.

Section 3: Nitrogen management

Nitrogen (N) is the most difficult nutrient to manage in Willamette Valley vegetable production systems. Crops in almost every field respond to nitrogen fertilizer or other N inputs. The pathways for N cycling are complicated. Figure 3 shows only some of the most important pathways:

1. Soil biota transform organic N contained in soil and organic inputs into plant-available ammonium-N and nitrate-N (mineral N).

2. Fertilizers contribute additional mineral N.

3. Crops take up mineral N from the soil.

4. Some N is removed with crop harvest, and some is returned to the field in organic form (crop residue).

5. Crop residue adds organic N to the soil. The cycle begins again from the top of the diagram.

6. The most important pathway for N loss from the field is via leaching of water soluble nitrate-N. Because both soil and nitrate have net negative charge, the nitrate does not "stick" to soil. Nitrate is free to move down through the soil with drainage water.

We also need to consider that the pathways shown in Figure 3 do not operate at the same speed. Biological processes in the N cycle speed up when soil is warm and moist, and slow when soil is cold or dry. Nitrogen from urea or ammonium-N fertilizers converts to nitrate-N after a few weeks in the soil via microbial activity. Conversion of soil organic N to ammonium N is slower. A key part of the nitrogen challenge for western Oregon vegetable cropping systems is that much of the nitrate remaining in the soil profile in early September moves below the rooting depth by the following spring and eventually enters groundwater. Fall-planted cereal cover crops have been shown to reduce but not eliminate the over-winter nitrate loss (Feaga et al., 2010). The following sections provide recommendations for N rate, timing, and placement for mineral and organic N inputs. The goal is to provide a reliable supply of N for crop production while protecting groundwater quality.
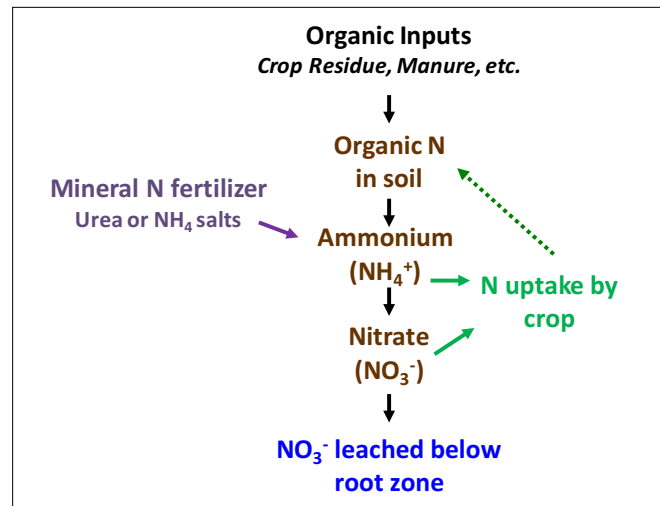

Figure 3. The nitrogen management challenge: The N cycle is "leaky".

Nitrogen rate

For major crops, OSU researchers conducted field trials to determine optimum N fertilizer application rates. You can find the latest N fertilizer rate recommendations in *Sweet Corn (Western Oregon) Nutrient Management Guide* (EM 9010), *Nutrient Management for Onions in the Pacific Northwest* (PNW 546), and *Snap Bean (Western Oregon) Nutrient Management Guide* (EM 9154).

For other vegetable crops, N rate recommendations are based on a much smaller database of university field response studies. Table 8 (page 16) shows values for total N uptake in the crop at harvest. Crop N uptake is not a fertilizer recommendation. Instead, it reflects uptake of N from all sources, including fertilizer, N mineralized from soil organic matter and other N inputs, and from irrigation water. Crop N uptake data demonstrates the relative capacity of different crops to utilize N.

Nitrogen needs of other vegetable crops are reported in other land grant university guides. For example, relative N need for California vegetable crops is estimated by Gaskell, et al. (2007) as:

- "Low" for baby greens, bean, cucumber, radish, spinach, and squash

- "Medium" for carrot, sweet corn, garlic, lettuce, melons, onion, pepper, and tomato

- "High" for broccoli, cabbage, cauliflower, celery, and potato

Prescriptions for N fertilizer rate given in books and in Extension publications from other regions may not

Table 8. Approximate amount of N removed by harvest and recycling of N in the field via crop residues
Crops listed in order of relative crop N uptake (low to high)[1]

Crop	Yield (fresh weight)	Nitrogen Partitioning at Harvest**			
		Total N in the crop	N removed by harvest	N returned in crop residue	Data source
	ton/a	lb/a	lb/a	lb/a	
Onions	20 to 35	100 to 150	60 to 120	20 to 40	PNW 546
Snap beans	6 to 8	100 to 150	35 to 50	60 to 90	EM 9154
Sweet corn	8 to 15	150 to 200	80 to 120	60 to 120	EM 9010
Specialty potato	15 to 25	150 to 250	80 to 130	40 to 100	McQueen, 2007
Broccoli	5 to 6	200 to 300	50 to 90	150 to 250	PNW 513
Cauliflower	5 to 10	200 to 300	50 to 90	150 to 250	PNW 513

[1]Nitrogen Partitioning at Harvest: Values listed in each column (total N in the crop, N removed by harvest, and N returned in crop residue) are not additive. Not all of these parameters were determined in every field trial. Therefore, they must be considered as independent measurements. The value given for "total N in the crop" is based on a greater number of field measurements, so confidence in these values is greater. Values given for "harvested N" and "crop residue N" were more variable across field trials.

be reliable. Reliance on local data, especially in-season soil nitrate-N from your fields is the best way to refine N application rate.

Nitrogen timing

Two or three stages of N uptake are found during the growth cycle of vegetable crops (Figure 4):

- Lag phase—slow N uptake for the first 20 to 30 days after seeding or transplanting

- Vegetative phase—rapid N uptake for a period of the next 30 to 60 days

- Reproductive phase—Slower N uptake near the time of harvest for a few crops like sweet corn, squash, and potato; in these crops, N is translocated from leaves to the fruit after flowering.

At every growth stage, N must be adequate to support growth. Very small amounts of N (less than 20 to 30 lb N/a) are needed for the lag phase, while N demand is much greater in the vegetative phase (Table 9, page 17). Crops that have a reproductive phase have reduced N requirements after flowering because N is translocated from leaves to the developing seeds/fruit.

In general, N fertilizer is utilized most efficiently by a crop when fertilizer application is delayed until a few weeks prior to the rapid phase of crop N uptake. When mineral N fertilizer is applied a long time before rapid crop N uptake begins, more N is potentially "lost" via leaching, incorporation into organic form (immobilization), or as a gas (volatilization). Nitrogen applied as the crop nears the end of its rapid uptake phase is mostly wasted.
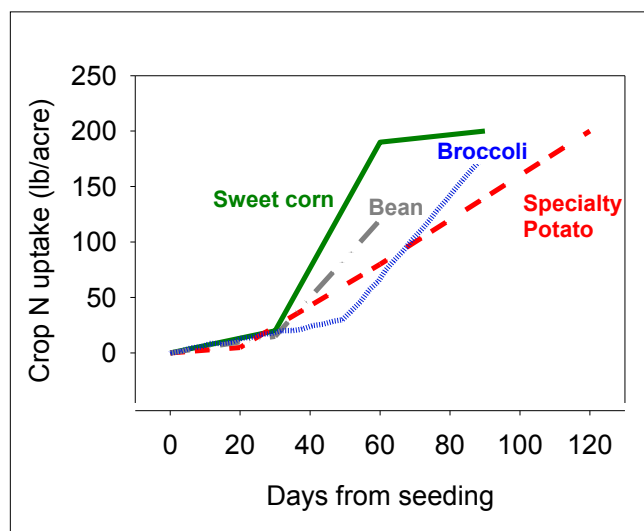

Figure 4. Timing of crop N uptake for four Willamette vegetable crops following a planting in late May or early June.

Using mineral fertilizers to supply N

Conventional N fertilizers are salts containing urea, NH_4 and/or NO_3. All have performed similarly when broadcast-applied in research trials. Some crops (e.g., beans) are sensitive to banded urea application. In general, ammonium-based fertilizers like ammonium sulfate (24-0-0-24S) or ammonium phosphates (11-52-0 or 10-34-0) are less likely to cause seedling injury compared to urea, when applied in fertilizer bands.

"Enhanced efficiency" (EEF) additives for urea and/or ammonium-based fertilizers were evaluated from 2013 to 2015 in OSU field trials with sweet corn (Sullivan et al., 2013, 2014, and 2015). The EEF

Table 9. Amount and rate of crop N uptake during the "rapid" (vegetative) phase of crop N uptake[1]

Crop	Growth stages	Days elapsed	Crop N uptake	Range in N uptake rate	Average N uptake rate
	Start & end of rapid N uptake		lb/a	lb/a/day	lb/a/day
Sweet corn	4 to 6 leaf to silking	30	170	4 to 8	5.7
Specialty potato	Tuber bulking	60	120	1.5 to 2.5	2.0
Snap bean	2nd trifoliate leaf to harvest	30	105	2 to 4	3.5
Broccoli	4 to 6 leaf to harvest	45	160	2 to 6	3.6

[1]Data in Table 9 and Figure 4 (page 16) come from the same field research trials in the Willamette Valley: sweet corn (EM 9010); specialty potato: McQueen (2007); snap bean (EM 9154), broccoli (PNW 513). Values given for average N uptake rate correspond to linear crop N uptake slopes shown in Figure 4. Range in N uptake rate was computed from crop N uptake data using a sigmoid equation, as described in *Nitrogen Uptake and Utilization by Pacific Northwest Crops* (PNW 513).

fertilizers contained proprietary polymer coatings, urease inhibitors, or nitrification inhibitors. Major findings:

1. In field trials, EEF fertilizers did not increase economic return from sweet corn when compared to conventional urea fertilizers.

2. EEF products prevented the conversion of NH_4-N to leachable NO_3-N for up to 4 weeks following application.

3. Measured gaseous ammonia loss from surface-applied urea in field trials was insignificant, and so EEF products that reduce ammonia loss from urea (urease inhibitors) were not useful.

See "Enhanced efficiency additives for urea and ammonium-N fertilizers" in the Appendix (page 22) for more information.

Nitrogen fertilizer placement

Mineral fertilizers:

Applying 20 to 40 lb N/a as a 2 × 2-inch starter placement is usually beneficial. Starter N is most beneficial early in the season (April and May) when soil is cool and soil test nitrate-N is low. Crops planted after June 1 in soils with NO_3-N above 15 ppm are less likely to benefit from starter N. High rates of starter N application risk salt damage to seedlings. See "Starter fertilizer formulations and application" in the Appendix (page 20) for details. Sidedress applications, made just prior to the rapid N uptake phase of crop development, can be delivered via irrigation water, placement near the row, or by broadcast application over the top of the crop canopy. Broadcasting dry fertilizers over the top of the crop canopy is less desirable on crops like corn. The dry fertilizer can be caught in the whorls of emerging corn leaves, resulting in foliar damage.

Gaseous ammonia-N loss following broadcast application of urea was measured in Willamette Valley field trials. (Sullivan and Heinrich, 2014 and 2015). Less than 5 percent of N applied was lost as ammonia gas under "worst case" conditions (broadcast urea left on the soil surface for a week without irrigation). See "Enhanced efficiency additives for urea and ammonium-N fertilizers" in the Appendix (page 22) for additional details.

Organic fertilizers

Band placement options are limited for organic fertilizers. Most organic fertilizers can only be applied preplant as a broadcast application. Some pelleted formulations of chicken or fish fertilizer can be surface banded beside the row. Pelleted fish and chicken and feather meal fertilizers decompose quickly and provide most of the plant-available N in the first 4 weeks after application.

Estimating N supplied from inputs, crop residues, and soil organic matter

Management of N from organic sources is challenging. Table 10 (page 18) summarizes expected N release dynamics from contrasting classes of organic matter. Some organic matter sources are inputs (e.g., manure or compost), while some are recycled in place (e.g., crop residues and soil organic matter). Legume cover crops provide N input as the result of the activity of Rhizobia bacteria that are hosted by legume roots.

Manures, composts, and other organic materials vary in the amount and timing of N release via N mineralization (Table 10). The amount of N released depends on N concentration and decomposition rate. Organic materials with total N concentrations below 1.5 percent total N (in dry matter) release little or no plant-available N in the first growing season after application. Plant-available N released from organic

materials containing more than 1.5 percent N in dry matter is predicted by the OSU Organic Fertilizer and Cover Crop Calculator (smallfarms.oregonstate.edu/calculator). Typically, organic materials with the highest N concentration (e.g., specialty organic fertilizers) also have the highest rates of decomposition and plant-available N release in soil.

Composted organic materials are more resistant to decomposition, and they release plant-available N more slowly than fresh organic materials. Although sold as "compost," dry-stacked chicken manure decomposes and releases plant-available N more quickly than real compost.

Even if you do not add organic fertilizers, you still need to account for N released from high N crop residues such as legumes or vegetable crop residues from prior summer plantings.

See these publications for detailed information about organic inputs used for organic vegetable production:

- *Estimating Plant-Available N Release from Cover Crops* (PNW 636)
- *Fertilizing with Manure and Other Organic Amendments* (PNW 533)
- *Soil Fertility in Organic Systems: A Guide for Gardeners and Small Acreage Farmers* (PNW 646)

Plant-available N release from soil organic matter

Total soil organic matter is measured by routine soil testing. Only 2 to 3 percent of total soil organic matter is mineralized each year. Large quantities of N are stored in soil organic matter. A Willamette Valley soil with 3 percent organic matter in the top 12 inches, contains 5,000 to 6,000 lb/a total N. If 2 to 3 percent of soil total N is mineralized, 100 to 180 lb NO_3-N/a is made available per year ($5,000 \times 0.02 = 100$ lb/a; $6000 \times 0.03 = 180$ lb/a).

Nitrogen mineralization is a biological process; soil temperature is the primary driver for the mineralization process. Soil organic N is mineralized slowly whenever the soil is above freezing. The rate of N mineralization increases exponentially with temperature. It roughly doubles when soil temperature increases from 50°F to 70°F. In summer, Willamette Valley vegetable growers can expect N mineralization from soil organic matter of roughly 100 lb N/a (Figure 5, page 19). Nitrogen fertilizer recommendations given in OSU Extension guides already account for typical plant-available N provided by mineralization of soil organic matter. (Note: Estimates for N mineralization are not listed explicitly in OSU Extension Guides.) The experimental method used to determine appropriate N fertilizer rates (N rate trials in the field) indirectly accounted for typical N mineralization amounts.

Table 10. Rates of decomposition and cumulative plant-available N release from contrasting classes of organic matter

Class of organic matter	Total N	Rate of decomposition	Cumulative PAN released		
			4 weeks	10 weeks	One year
	--% dry matter--		-----------------------% of total N-----------------------		
Inputs to field					
Specialty organic fertilizer —feather meal, fish etc.	6 to 12%	Very rapid	60+ %	75+ %	near 100%
Legume cover crop	3 to 5%	Very rapid	20 to 40%	40 to 60%	50%+
Fresh poultry manure	3 to 5%	Rapid	20 to 40%	40 to 60%	50%+
Other manures	2 to 3%	Moderate	0 to 15%	15 to 30%	30%+
Composts	1 to 3%	Slow	0 to 5%	5 to 10%	5 to 10%
Recycled in field					
Fresh leafy green crop residue—Brassica or potato residues	3 to 5%	Very rapid	20 to 40%	40 to 60%	50%+
Cereal cover crop (jointing)	1.5 to 3%	Very rapid	5 to 20%	15 to 30%	30%+
Cereal cover crop (heading)	1.0 to 1.5%	Moderate	< 0%	-10 to 10%	0 to 20%
Total soil organic matter		Very slow. Years to centuries			2 to 3%

Nitrogen input rates lower than those given in OSU Extension nutrient management guides are logical for fields with a significant history of organic N inputs. These guides do not account for the "extra" N mineralized in soils that have been cover cropped with legumes in the current year, or where organic fertilizers, manure, or compost have been used routinely in the past 3 to 5 years. In-season soil nitrate testing can provide feedback on whether adequate N is provided by organic inputs and soil N mineralization.

Soil nitrate testing

In-field monitoring of nitrate-N during the growing season is the best strategy to evaluate the N supply delivered to the crop. The soil is generally tested only for nitrate because soil ammonium-N concentrations are typically low (< 5 ppm). Ammonium-N is converted rapidly to nitrate-N (Figure 3, page 15), so an accumulation of ammonium-N in soil usually happens only when soil is dry or when a N fertilizer or organic input has been applied just prior to sampling. It typically takes urea-N about a week to transform to nitrate-N in summer and about 2 to 3 weeks in spring or fall.

The interpretation of soil nitrate test results varies with the time of sampling. Below we discuss interpretations for preplant, in-season, and late season tests.

Preplant soil nitrate testing in early spring is generally not useful. Soil nitrate values are usually low in March and April because nitrate is lost over the winter through leaching, and cooler soil temperatures limit N-mineralization rate.

Nitrogen mineralized from plowdown of legume cover crop can be measured reliably by a preplant soil nitrate test. Our research showed that most of the plant-available N from a legume cover crop killed in mid-April could be measured by soil testing a month later.

Preplant soil nitrate testing is most useful when seeding or planting takes place after June 1 because soil has been warm long enough for nitrate-N to accumulate. The preplant test can be especially helpful in adjusting fertilizer rates for July plantings of brassicas and leafy vegetables on organic farms.

In-season soil nitrate testing

An in-season soil nitrate test is the most accurate way to adjust the N fertilizer application rate to meet site-specific requirements. The in-season test is taken prior to the rapid phase of N uptake by the crop (Figure 4, page 16).
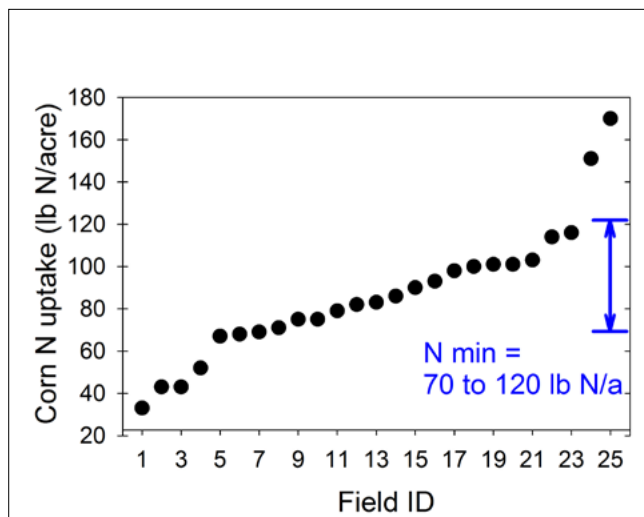

Figure 5. Aboveground N uptake by sweet corn grown without N fertilizer addition. The N present in the crop originated from mineralization of soil organic matter. Biomass samples to determine crop N uptake were collected at 1,200 growing degree days after seeding. Twenty-five fields were sampled over a 3-year period. (Data from Peachey and Sullivan, 2011; Sullivan et al., 2012; Sullivan et al., 2013)

A mixture of sources contributes to the nitrate measured by an in-season soil nitrate test and can include:

- Preplant N inputs (broadcast fertilizer, compost, or manure)
- Nitrogen produced by the decomposition of soil organic matter (mineralization)
- Nitrogen provided by irrigation water

The in-season soil nitrate test provides a more reliable estimate of N sufficiency for crops than do preplant estimates (credits), such as those provided by the OSU Fertilizer and Cover Crop Calculator or by fixed N credits for "previous legume crop" found in some older OSU Extension guides. Table 11 (page 20) shows the interpretation of an in-season soil nitrate test for sweet corn. Research has not been performed on all vegetable crops to validate crop-by-crop soil nitrate test interpretations. However, in general, when soil nitrate-N exceeds 25 to 30 ppm (0- to 12-inch depth) just prior to the start of rapid crop vegetative growth, then 0 to 70 lb of sidedress N fertilizer will meet crop N needs. Our confidence in the nitrate test is based on the fact that nitrate present in the soil acts the same as fertilizer in satisfying crop N need. A soil nitrate test value of 25 ppm nitrate-N is equivalent to about 90 lb nitrate-N/a in a 12-inch soil depth.

The *Sweet Corn Nutrient Management Guide* (EM 9010) includes soil sampling instructions for an in-season soil nitrate test, the "Pre-Sidedress Nitrate

Table 11. Sidedress N rate for sweet corn in the Willamette Valley, based on soil samples collected when corn has 4 to 6 leaves[1]

PSNT soil test value (0–12 inches)[2]		Recommended sidedress N fertilizer rate
soil test NO$_3$-N (lb/a)	soil test NO$_3$-N (ppm)	lb N/a
10	3	165
50	14	125
90	26	85
140+	40	40

[1]Adapted from *Sweet Corn (Western Oregon) Nutrient Management Guide* (EM 9010)

[2]Values given in the same row for PSNT soil test value are equivalent. For example, a soil test value of 50 lb N/a is approximately equivalent to 14 ppm in a 12-inch depth of soil (assumed soil bulk density = 1.3 g/cm^3 or 81 lb/cubic foot).

Test" (PSNT). Recommendations for the PSNT (Table 11) are based on soil nitrate determined when corn has 4 to 6 leaves. The reliability of the PSNT was recently verified for newer corn hybrids (Peachey and Sullivan, 2011; Sullivan et al., 2012).

Late-season soil nitrate sampling

The goal of late-season soil nitrate testing is to identify fields where more N was supplied than could be utilized by the crop. A late season test has value for new cropping situations, such as a transition from conventional to organic. Late-season soil nitrate interpretations have not been specifically developed for vegetable crops. For most crops, soil nitrate should be less than 10 to 15 ppm (0-to 12-inch soil depth) near the time of crop harvest. Higher soil nitrate test values in late summer or fall suggest the potential for N loss over winter via leaching.

Excellent crop yields can be associated with very low soil nitrate-N values (< 5 ppm) near harvest. To be useful in assessing crop N use efficiency, soil samples must be collected before the crop starts to shed lower leaves. For crops like potato, samples taken as vines begin to die will usually contain some nitrate mineralized from dead or senescing vines, confounding test interpretation. Soil sampling below 1-foot depth is usually not useful. In our research trials, where late season soil profile nitrate was measured to a 5-foot depth, most of the nitrate-N was present in the top 0- to 12-inch depth sample. To be a valid assessment, soil samples must be collected in the fall prior to heavy rains. Typically, in western Oregon, this means sampling before October 15.

Section 4: Appendix

This appendix provides details on:

1. Starter fertilizer formulations and application
2. Enhanced efficiency additives for urea and ammonium-N fertilizers

Starter fertilizer formulations and application

A 2 × 2 starter fertilizer application is the placement of nutrients 2 inches below seed and 2 inches to the side of the seed row. This is an effective placement method for most seeded vegetable crops. The benefits of this fertilizer application technique include:

- Improved uptake of nutrients such as phosphorus (P) and zinc (Zn) that have limited solubility in soil

- Greater crop yields than broadcast applications, when used to correct P or Zn deficiency

- Stimulation of seedling or transplant growth under less than ideal soil conditions (such as cold, wet, and compacted soils that can restrict nutrient mobility in soil, and limit root system development)

- Earlier and/or more uniform crop maturity

Better early season growth does not always translate into increased crop yield or quality.

Delivery of P is the main reason for choosing starter fertilizer application, although most growers and dealers also include nitrogen (N), potassium (K), sulfur (S), and occasionally micronutrients in the mix. The fertilizer dealer will mix simple fertilizer salts in prescribed ratios to create starter fertilizer blends.

Direct measurement of N mineralization rates on organic or transitional organic fields

Research Questions:

1. How much nitrate-N is released by mineralization, and when is it available for plant uptake?

2. Can soil organic matter percentage or total N percentage predict the amount of plant-available N provided via mineralization?

Methods: Soil from a depth of 0 to 8 inches was collected from six commercial fields. The soil was collected prior to the application of fertilizer or compost to exclude current-season N inputs. None of the fields had significant N inputs from cover crops. Soils used in this study contained an average of 4 percent organic matter (range = 2 to 5 percent). Soil nitrogen mineralization measurements were made with a "buried bag" method. All of the soil-filled bags were installed at the OSU Vegetable Research Farm on June 14. Buried bags were harvested every 3 weeks to measure accumulated soil nitrate-N, from June 14 to Sept 6, 2016.

Results: Plant-available nitrate-N released via mineralization varied considerably among soils (Figure 6). Cumulative N mineralized in 12 weeks averaged 103 lb N/a, ranging from 60 to 128 lb N/a. The rate of nitrate-N accumulation was linear over time. N mineralization was not strongly related to cropping history or to years in organic production.

Conclusions:

1. Across soils, cumulative N mineralization ranged from 1.1 to 2.6 percent of the total N present in soil. Nitrogen mineralized steadily from soil organic matter throughout the measurement period.

2. Soil total N percentage or soil organic matter percentage did not predict cumulative N mineralized. Therefore, we recommend that growers use in-season soil nitrate testing to refine N input rates.
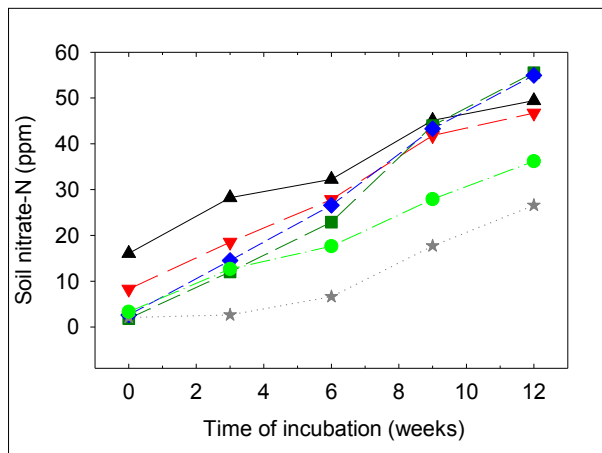
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Figure 6. Production of soil nitrate-N (plant-available N) from mineralization of soil organic matter in six organically managed soils. Soil collected from 0- to 8-inch depth.

Figure 7. Method for measurement of N mineralization in soil samples collected from organic fields (2016). Buried bags filled with soil before installation (top). Bags installed into an auger hole before backfilling (middle). Bags placed in row with corn so that natural shading of soil surface is present during the growing season (bottom). Photos: Aaron Heinrich, ©Oregon State University.

When choosing a starter fertilizer formulation, consider that:

- The combination of N and P in starter formulations improves early season vigor of many crops.

- If including K, it must be added at low rates. High rates of K can result in stand loss from salt damage when applied via starter.

- If including S in a starter, it must be a sulfate form. Elemental S does not convert to plant-available sulfate quickly enough to include in a starter mix.

- Under most western Oregon conditions, Zn is the only micronutrient useful in a starter. The acidic soil conditions here promote the solubility (and so, plant availability) of the other metal micronutrients. Include copper (Cu), manganese (Mn), and iron (Fe) only if a preplant soil test indicates a deficiency.

- Do not include boron (B) in starter fertilizer mixes; the risk of B toxicity is real. It is much safer to apply B as a spray (e.g., Solubor).

Balance between N and P in starter

Ammonium phosphate salts are widely available in the Willamette Valley in dry form (11-52-0 or 11-48-0) or liquid form (10-34-0). These formulations are not ideal starter fertilizers from the standpoint of N-to-P_2O_5 ratio. Usually, growers target a desired N rate in starter of 20 to 60 lb N/a. Our research showed that the phosphate (P_2O_5) fertilizer rate needed to achieve the best starter crop response was less than 30 lb P_2O_5/a (Peachey et al., 2013; Sullivan et al., 2012 and 2013). When 20 to 60 lb N/a is supplied via ammonium phosphate fertilizers, too much P_2O_5 is supplied.

We recommend that dealers and growers work together to reduce N-to-P_2O_5 ratios in starter fertilizer applications and limit banded P rates to less than 30 lb P_2O_5/a. The exception would be if soil test values are below the crop response threshold of 50 ppm for vegetable crops. Excess starter fertilizer P is not harmful to seedlings, but it is a wasted nutrient input. When ammonium phosphates are the only starter fertilizer product available, apply less N via starter and more N via sidedress application later in the season.

Avoid salt injury from starter

Starter fertilizer application can injure seedlings if N and K are applied in excess. The P and S anions in fertilizer blends supply very little soluble salt. When evaluating blends, you can ignore them for salt injury potential. As a general guideline, apply less than 90

lb N + K_2O/a in a starter band located 2 inches from the seed. When placing fertilizer 1 inch from the seed, reduce the application rate to 40 lb N + K_2O/a. Splitting the application and applying banded fertilizer on both sides of the row further reduces the risk of salt injury.

Ammonia (NH_3) toxicity from the application of dry urea (46-0-0) or liquid urea-ammonium nitrate (32-0-0) in starter fertilizer bands can also kill or injure seedlings. As urea converts to ammonium, some ammonia can be produced in the soil solution. This is especially true for sandy soils that have been limed to pH 6.5. Beans are especially sensitive to urea in starter fertilizers. For beans, avoid urea application altogether or limit the urea-N rate to less than 30 lb N/a.

Polymer-coated or sulfur-coated dry urea fertilizer products are less likely to damage seedlings than uncoated urea. Some coated fertilizer prills will be cracked during fertilizer handling and application. Prills with broken or cracked coatings affect seedlings in the same way as uncoated urea.

Caution is advised in using fertilizers in starter blends containing thiosulfate because of the potential for seedling toxicity. The thiosulfate anion is toxic to some seedlings, especially when applied close to the seed in dry soil. Ammonium thiosulfate (12-0-0-26S) is a liquid fertilizer with high solubility that supplies N and S in liquid blends. Other thiosulfate salts (Ca, Mg, or K) are sometimes used in blended liquid fertilizers. Insufficient research has been done in western Oregon to permit reliable recommendations for safe rates of thiosulfate applied as a starter fertilizer. Growers report the successful use of thiosulfate in starter blends.

Enhanced efficiency additives for urea and ammonium-N fertilizers

Enhanced efficiency N fertilizers (EEFs) contain additives or coatings that slow the N-cycling processes. These products inhibit the conversion of ammonium-N to nitrate-N (nitrification) or the conversion of urea to ammonium-N (urea hydrolysis). If there is a high potential for N loss as gaseous ammonia or via leaching below the rooting depth, these products are effective tools in improving N fertilizer efficiency use by crops. Product efficacy claims made by distributors are largely based on trials conducted in the Midwest. In western Oregon, sweet corn is the only vegetable crop that has been investigated for response to the enhanced efficiency N fertilizer products.

Historic findings

OSU researchers evaluated nitrification inhibitors N-Serve (nitrapyrin) in 1978, DCD (dicyandiamide)

in 1986, and Nutrisphere-N (maleic-itaconic acid copolymer) in 2009 and found them not to be beneficial. Find details in Sweet Corn *(Western Oregon) Nutrient Management Guide* (EM 9010).

More recent findings

Nitrogen fertilizer additives were evaluated in field and laboratory incubation trials (Sullivan et al., 2013, 2014, and 2015). Products evaluated included Instinct (encapsulated formulation of nitrapyrin), AgroTain Plus (dicyandiamide plus the urease inhibitor NBPT) and ESN, a polymer-coated urea product. These products control N release by slowing the rate of conversion of urea to ammonium (urease inhibition) or by slowing the rate of conversion of ammonium-N to nitrate-N (nitrification inhibition). Polymer-coated products retain the urea inside the prill, protecting it from immediate conversion to ammonium and nitrate-N.

In field trials, EEF products did not increase sweet corn ear yield or ear quality, or reduce soil nitrate-N present at the end of the growing season in comparison to urea.

Laboratory incubation trials showed that EEF products retained more of the applied urea-N in NH_4 form during the first 4 weeks after incorporation into moist soil at 72°F. After 6 weeks of soil incubation, there was no difference in the nitrate-N present in soil regardless of additives or coatings. Therefore, the "slow" or "controlled" release products tested reduced the rate of nitrification only for a short period after application. None of the tested products matched the rate of N demand of a sweet corn crop. All of the products tested released nitrate-N faster than it could be used by the crop.

Additional field trials were conducted to evaluate the efficacy of AgroTain Plus, a product that contains an inhibitor of the soil urease enzyme (Sullivan et al., 2014 and 2015). Treated or untreated urea was broadcast on the surface of warm, moist, sandy loam or loam soils in June or July. This scenario is considered a "worst case" with a high potential for gaseous ammonia loss from urea. Fertilizer prills were left on the soil surface for at least a week before irrigating. Despite these conditions, gaseous ammonia loss from these soils was insignificant (less than 5 percent of applied N) in both years of testing. Based on these trials, the additional cost of urease inhibitors is not likely to be cost-efficient under western Oregon conditions.

For more information

OSU Extension and PNW Cooperative publications

Applying Lime to Raise Soil pH for Crop Production (Western Oregon) (EM 9057)
https://catalog.extension.oregonstate.edu/em9057

Estimating Plant-Available Nitrogen Release from Cover Crops (PNW 636)
https://catalog.extension.oregonstate.edu/pnw636

Fertilizing with Manure and Other Organic Amendments (PNW 533)
https://catalog.extension.oregonstate.edu/pnw533

Integrated Clubroot Management for Brassicas: Nonchemical Control Strategies (EM 9148)
https://catalog.extension.oregonstate.edu/em9148

Nitrogen Uptake and Utilization by Pacific Northwest Crops (PNW 513)
https://catalog.extension.oregonstate.edu/pnw513

Nutrient Management for Onions in the Pacific Northwest (PNW 546)
https://catalog.extension.oregonstate.edu/pnw546

Snap Bean (Western Oregon) Nutrient Management Guide (EM 9154)
https://catalog.extension.oregonstate.edu/em9154

Soil Acidity in Oregon: Understanding and Using Concepts for Crop Production (EM 9061)
https://catalog.extension.oregonstate.edu/em9061

Soil Fertility in Organic Systems: A Guide for Gardeners and Small Acreage Farmers (PNW 646)
https://catalog.extension.oregonstate.edu/pnw646

Soil Test Interpretation Guide (EC 1478)
https://catalog.extension.oregonstate.edu/ec1478

Sweet Corn (Western Oregon) Nutrient Management Guide (EM 9010)
https://catalog.extension.oregonstate.edu/em9010

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Additional resources

Reports to the Oregon Processed Vegetable Commission are available by searching at this page:
http://horticulture.oregonstate.edu/content/oregon-processed-vegetable-commission-0

For more information on historic research findings (from 1970s and before) on fertility requirements of Oregon vegetable crops, please refer to archived publications by T.L. Jackson, et al. at:
http://ir.library.oregonstate.edu/xmlui/bitstream/handle/1957/60627/Vegetable_Nutrient_Management_TL_Jackson_Bibliography.pdf