Soil Nitrate Testing for Willamette Valley Vegetable Production

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A soil nitrate test measures the concentration of nitrate in the soil at a specific moment in time, including nitrate originating from organic inputs, fertilizer, and soil organic matter. This publication describes how to use soil nitrate testing to adjust nitrogen (N) application rate to meet crop N requirements. Data to support our recommendations comes from field trials conducted in the Willamette Valley for vegetable crops produced during summer months.

Quick summary

- Soil nitrate testing during the growing season is a valuable tool for fine tuning N inputs necessary for vegetable crop production. It provides an integrated assessment of nitrate supplied by all sources, including organic inputs, fertilizers, and nitrate from soil organic matter (SOM) mineralization.
- Soil nitrate accumulates as N is mineralized from this year's inputs and from SOM (Figure 3, page 4). A "Willamette Valley soil nitrate calendar" (page 3) provides a calendar-year summary of soil nitrate accumulation and loss.
- Soil nitrate tests are best suited to situations in which soil nitrate is likely to be high and there is a good possibility of reducing N inputs.
- The most important time to determine soil nitrate levels is during the first 3 to 6 weeks after seeding or transplanting, prior to the crop's rapid vegetative growth. When sidedressing N at midseason is feasible, these midseason soil test results can be used to guide sidedress N application rates (Tables 2 and 3, pages 7 and 8).

Photo: Aaron Heinrich

- Step-by-step soil sampling guidance is provided in "Soil nitrate sampling and testing instructions" (page 6).
- The "Nitrate testing questions and answers" section (page 8) addresses common questions about the use and misuse of soil nitrate tests.
- Appendices 1 (page 10) and 2 (page 14) summarize the monitoring data that support the value of soil nitrate testing for summer vegetable crops grown in the Willamette Valley.
- A quick-test method to determine soil nitrate is described in Appendix 3 (page 16).

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Understanding soil nitrate

Soil nitrate dynamics: Accumulation and loss

Nitrate accumulates in the soil via the processes of mineralization and nitrification. Nitrate loss from soil occurs via crop uptake and leaching below the root zone (Figure 1). Some of the nitrate-N lost from soil via crop N uptake is recycled back to the soil in the form of organic N.

Mineralization is the process whereby soil biota convert organic forms of N to a mineral form (ammonium). Biota then convert ammonium-N to nitrate, a process known as nitrification (the making of nitrate). Because the conversion of ammonium to nitrate proceeds more rapidly than does mineralization, accumulation of ammonium-N is short lived in soil. This is why we choose to monitor soil nitrate. Although plants are capable of taking up ammonium, most of the N absorbed by a vegetable crop is in the nitrate form.

Crop uptake is the major pathway for nitrate removal from soil during the summer growing season. Leaching occurs primarily in winter. During the summer, little nitrate leaches if irrigation management is appropriate. Some N can be lost as a gas (denitrification), but this loss is typically less than 20 lb N/acre/yr, so it is not shown in Figure 1 and is ignored in N management decisions.

The amount of nitrate present in soil changes during the year in response to the balance between nitrate addition and nitrate loss. The sidebar "Willamette Valley soil nitrate calendar" (page 3) describes soil nitrate dynamics throughout the year, from January to December.

Timing of N uptake by vegetable crops

Two or three stages of N uptake are observed during the growth cycle of vegetable crops (Figure 2):

- **Lag phase:** Slow N uptake for the first 20 to 40 days after seeding or transplanting
- **Vegetative phase:** Rapid N uptake for the next 30 to 60 days
- **Reproductive phase:** Slower N uptake near the time of harvest for a few crops such as sweet corn, squash, and potato. In these crops, N is translocated from leaves to the seeds, fruit, or tubers after flowering.

At every growth stage, N must be adequate to support growth. Very small amounts of N (less than 20 to 30 lb/acre) are required during the lag phase, while N demand is much greater during the vegetative phase.

Soil and crop management for summer vegetable crops 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). Vegetables are typically planted in fields with soils mapped as Chehalis, Cloquato, Malabon, Newburg, Willamette, or Woodburn. Vegetables are grown in rotation with agronomic crops, such as winter wheat and grass seed, and with specialty crops such as vegetable seed crops. Summer vegetable crops are irrigated, primarily with overhead sprinklers. Rainfall is sufficient in winter months to leach soluble nutrients below the rooting depth of vegetable crops.

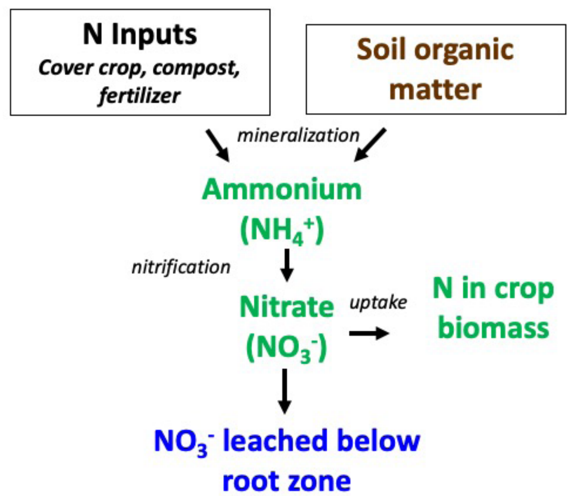


Figure 1. Nitrate accumulation and loss in soil. Nitrate accumulates as N is mineralized from this year's N inputs and from soil organic matter. In the Willamette Valley, nitrate present in soil in September is subject to winter loss via leaching.

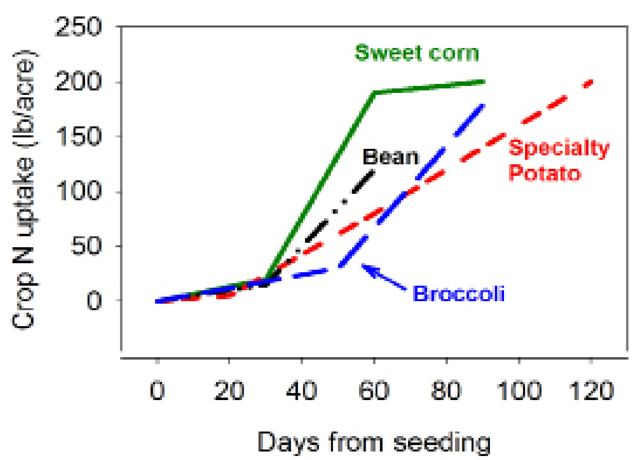


Figure 2. Timing of N uptake for four Willamette Valley vegetable crops following planting in late May or early June. Source: *Nutrient Management for Sustainable Vegetable Cropping Systems in Western Oregon*, EM 9165 (Sullivan, et al., 2017).

Willamette Valley soil nitrate calendar (January to December)

This calendar provides greater detail on the processes underlying soil nitrate management (Figure 1, page 2). It also provides additional information on soil nitrate dynamics in the spring and fall. Winter rainfall is sufficient to leach nitrate out of the soil profile during the winter months, so every calendar year begins with soil nitrate concentrations assumed to be near zero.

- February/March/April
    - ❏ Until soil temperatures exceed 60°F, nitrate accumulation from decomposition of soil organic matter (SOM) is slow. Soil NO_3-N concentrations are typically less than 10 ppm.
    - ❏ Organic fertilizers (e.g., feather meal, fish meal) are applied to overwintering vegetable crops. Soil nitrate accumulation is usually minimal because the rate of crop N uptake exceeds the rate of soil nitrate production via the mineralization process.
    - ❏ Soil nitrate monitoring is not recommended.
- May through mid-July (**"preplant"** in Figure 7, page 7)
    - ❏ Nitrate accumulates in soil via mineralization of this year's inputs and SOM.
    - ❏ Seedbed preparation breaks up soil aggregates, boosting the rate of SOM mineralization.
    - ❏ Most of the nitrate contributed by new organic inputs is produced during the first 3 to 6 weeks following application.
    - ❏ A preplant soil nitrate test is most helpful when planting occurs after June 15 and soil temperatures have warmed to 60°F for several weeks. Find interpretations for the preplant test in Table 2 (page 7).
- June/July (**"midseason"** in Figure 7 or 30 to 45 days after the crop is seeded)
    - ❏ Crop uptake of nitrate is small (less than 30 lb N/acre) between seeding and midseason.
    - ❏ Soil nitrate typically reaches a maximum value at midseason.
    - ❏ Collect soil samples for the midseason soil nitrate test.
    - ❏ Apply sidedress N fertilizer based on midseason soil nitrate test results. Find fertilizer rate guidance in Table 3 (page 8).
- July/August (**between "midseason" and "harvest"** in Figure 7)
    - ❏ As rapid crop vegetative growth continues, the rate of crop N uptake exceeds the rate of nitrate release via mineralization of organic inputs and SOM. As a result, the soil nitrate concentration declines.
    - ❏ Soil nitrate sampling is not recommended unless it is part of an intensive monitoring program in which soil nitrate is monitored every 2 to 3 weeks during the growing season.
- August/September (**"harvest"** in Figure 7)
    - ❏ Soil nitrate usually reaches its lowest concentration as harvest approaches.
    - ❏ In root, tuber, and seed crops, senescence of leaves begins before harvest. For these crops, mineralization of N from senescing crop leaves may increase soil nitrate before harvest.
    - ❏ Harvest vegetable crops. Crop residues decompose. Mineralization of high-N vegetable crop residues (e.g., brassicas) is rapid. Soil nitrate concentration increases.
    - ❏ Soil nitrate testing usually is not recommended near harvest time because mineralization of N from crop residues complicates test interpretation.
- October through January
    - ❏ Fall rains saturate the topsoil. Nitrate moves below the 12-inch soil sampling depth as water percolates downward.
    - ❏ During most years, winter rains leach nitrate below the rooting depth of winter cover crops. Accumulation of nitrate in soil (from mineralization) is insignificant when soil temperatures are below 40°F. Soil nitrate concentrations remain low until soils begin to warm in spring, regardless of N input history.
    - ❏ Soil nitrate sampling is not recommended.

Soil health: Adjusting N management to account for enhanced soil organic matter

Organic matter addition is a key soil health practice. Consistent organic inputs build SOM and a soil's capacity to provide nitrate via mineralization (Figure 3). An increase of 1 percent in SOM (e.g., from 3 to 4 percent) is equivalent to an increase of roughly 1,500 lb soil organic N per acre (0- to 12-inch depth).

The amount and timing of N inputs should be adjusted to account for nitrate mineralized from SOM. In Figure 4, the annual amount of N mineralized from SOM in the *absence* of current-season N inputs is portrayed as "nitrate from SOM mineralization." This figure shows a progression in time from a conventional system in which the crop N requirement is met by adding synthetic mineral fertilizer (System 1) to systems in which crop N requirement is satisfied via organic inputs (Systems 2–4). When "nitrate from SOM mineralization" increases over time, new inputs (compost, cover crop, and organic fertilizer) can be reduced. If inputs are not reduced as the nitrate from SOM mineralization increases, the amount of nitrate produced can exceed the crop N requirement.

Supplying all of the crop N demand via mineralization of SOM (System 5) is undesirable. Most crops take up large amounts of N for a relatively short period (4 to 8 weeks), but rapid mineralization of N from SOM will continue as long as soil is moist and warm (above 60°F). In the Willamette Valley, the excess nitrate produced via mineralization of SOM in late summer is subject to loss via leaching during fall and winter. Supplying more N than is needed for the crop can also delay crop maturity and increase crop susceptibility to disease and insect pests.

Soil nitrate monitoring

As SOM increases, the question facing growers is "by how much can inputs be reduced?" Unfortunately, measurements of total SOM do not provide reliable site-specific guidance to determine N input requirements for crop production. Likewise, crop vigor and yield are not reliable indicators of excess soil nitrate, as adequate and excessive soil nitrate levels often produce similar results.

For these reasons, testing soil nitrate during the growing season is a valuable tool. The concentration of nitrate in soil at any moment is the outcome of many simultaneous processes (Figure 1, page 2). The midseason soil nitrate test provides a site-specific "snapshot in time" of the cumulative supply of nitrate from all sources versus crop requirement.

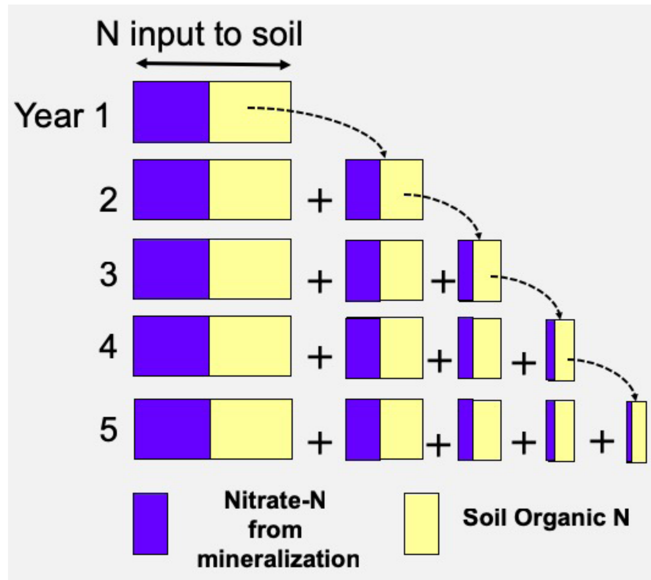


Figure 3. Consistent organic inputs build soil organic N and a soil's capacity to provide nitrate via mineralization. In this example, the same quantity of N is provided via organic inputs each year for 5 years (left side of diagram, under "N input to soil"). Each year's accumulated nitrate (from mineralization) is the sum of the blue boxes in a row. The accumulation of soil organic N is the sum of the yellow boxes in a row. Curved dashed arrows illustrate the fate of N applied in Year 1.

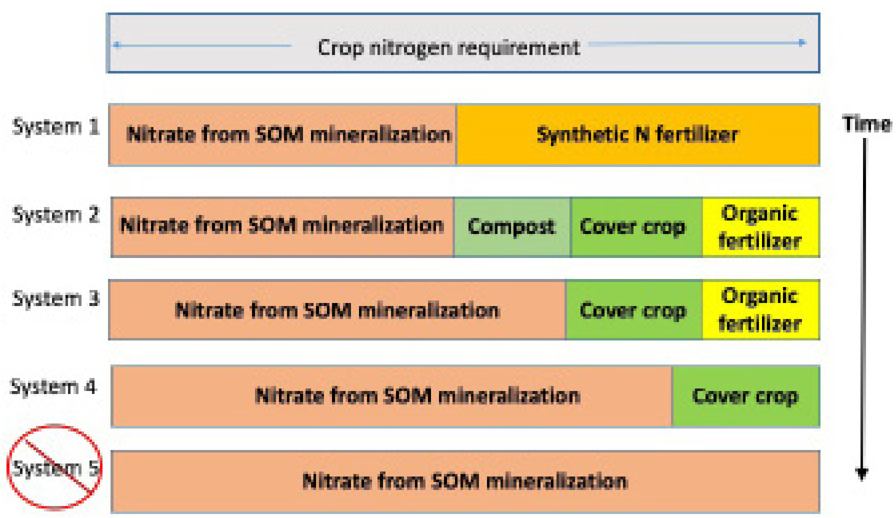


Figure 4. Effect of "soil building" (via organic matter addition) on the need for N inputs in organic systems. The long-term goal is to reach System 3 or 4, in which crops have adequate, but not excess, plant-available N supply.

When to sample soil for nitrate

- **Preplant** (sometimes useful): For seeding dates after June 15, the preplant nitrate test may provide useful information. The preplant test quantifies the nitrate contributed by early-season inputs (e.g., cover crops, composts), helping to assess the need for expensive organic fertilizer inputs (e.g., feather meal).
- **Midseason** (most useful): The midseason test provides an integrated assessment of nitrate supplied from all sources (from organic inputs and from SOM mineralization) and predicts N needed to support crop growth during the vegetative phase. See the sidebar "Validation of the midseason soil nitrate test."
- **Late-season** (least useful): Sampling soil nitrate between midseason and harvest is generally not recommended. Soil nitrate concentrations during the rapid crop N uptake phase of crop development are difficult to interpret because crop uptake and movement of nitrate below the 12-inch depth may be occurring simultaneously. Also, soil samples are more difficult to collect after row closure.
- **Postseason** (sometimes useful): Sampling after harvest, but before fall rains begin, can help you assess whether excess nitrate remains at the end of the growing season. In western Oregon, excess nitrate mostly leaches away during the winter.

The midseason soil nitrate test

Midseason is the most important time to sample for soil nitrate. Sample near the end of the lag phase (3 to 6 weeks after seeding and just prior to rapid vegetative crop growth, Figure 2, page 2).

When fertilizer can be sidedressed (in conventional systems and in some organic systems), the midseason soil nitrate test can be used to determine how much sidedress N is required. For sweet corn, the midseason test is often referred to as the "pre-sidedress nitrate test" (PSNT). In organic systems, the midseason nitrate

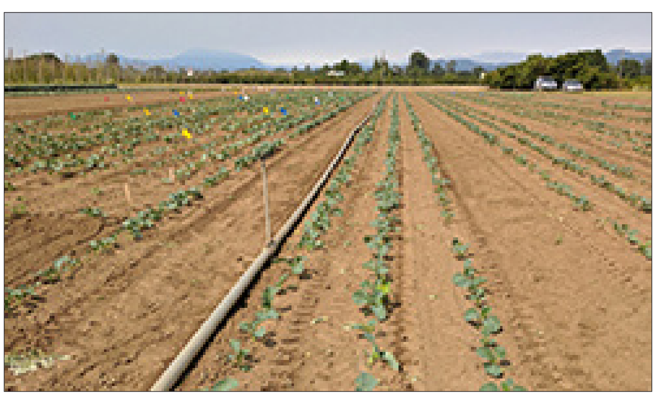


Photo: Dan M. Sullivan

Figure 5. Broccoli at midseason soil nitrate test time.

Validation of the midseason soil nitrate test

The midseason soil nitrate test is a valid predictive tool for broccoli, sweet corn, and table beets in the Willamette Valley. Replicated field experiments were conducted to correlate soil nitrate test values with crop yield response. A range of midseason soil nitrate concentrations was achieved at each experimental site via preplant N input treatments (organic fertilizers, composts, or cover crop residues). Figure 6 shows the findings of these field experiments using "relative" crop yield, which was determined as:

Relative crop yield (% of maximum yield) =
(treatment yield/maximum yield) x 100

"Treatment yield" is crop yield with prescribed preplant N inputs, and "maximum yield" (for a specific site in a specific year) was determined by applying high rates of urea or a rapidly mineralized organic fertilizer (e.g., feather meal) so that plant-available nitrogen supply did not limit yield.

Data from the field validation trials show that crop yield was near maximum when soil nitrate-N was 30 ppm at midseason (Figure 6). When midseason nitrate-N was less than 30 ppm, yield was reduced by insufficient N. These trials were conducted in different years by different researchers using different soil amendment treatments. The similarity in crop response across all of these studies suggests that midseason soil nitrate testing is a powerful tool to assess N sufficiency.

See Appendix 1 (page 10) for a more detailed discussion.

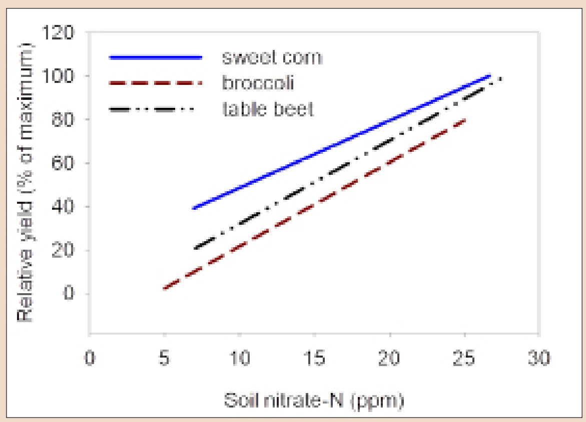


Figure 6. Midseason soil nitrate and relative crop yield for three vegetable crops. These crop response relationships demonstrate the predictive value of the midseason test. For all three crops, crop yield reaches a maximum when soil nitrate-N is approximately 30 ppm. Details of these calibration data are provided in Appendix 1 (page 10).

test can also highlight differences among fields in the amount of N mineralized from SOM.

The predictive value of the midseason nitrate test has two components:

- The test measures nitrate-N already in the soil at the time of sampling.
- It also gives an indication of the likely N mineralization amount for the remainder of the growing season. In summer, typical rates of nitrate accumulation from mineralization of SOM (0- to 12-inch depth) are 1 to 2 lb N/acre/day. So, in the 30 days following a midseason nitrate test, an additional 30 to 60 lb/acre of nitrate-N is typically produced.

  A single midseason test is useful, but sampling at 2- or 3-week intervals after seeding can be even more informative. Consider using this more intensive approach on a few fields. For example, you might want to intensively monitor a field with a novel crop rotation or novel fertilization practice. Or, monitor a few fields that are representative of fertilizer and crop management practices. See Appendix 2 (page 14) for case studies using this monitoring protocol.

Soil nitrate sampling and testing instructions

1. Choose representative areas of the field for sampling. Avoid irregular areas, such as low areas or field entrances. If you plan to sample repeatedly during the growing season, consider marking or georeferencing sample areas in the field. Additional instructions are given in *A Guide to Collecting Soil Samples for Farms and Gardens*, EC 628 (Fery and Murphy, 2013).
2. Collect the soil sample away from fertilizer bands. When fertilizer bands are not present, sample within 6 to 12 inches of the row. The goal is to sample soil that is, or will be, colonized by roots.
3. Sample soil to a depth of 12 inches. Collect a composite sample of 15 to 20 cores.
4. Thoroughly mix the soil cores in a clean container. Transfer about a cup of soil to a zippered polyethylene bag or a soil sample bag provided by the laboratory.
5. Keep samples cool by placing them in an insulated container with blue ice. Test results are likely to change if soil is warmed.
6. Send the sample immediately to a soil testing laboratory to be analyzed for nitrate-N (NO_3-N). To avoid shipping delays over the weekend, do not ship samples on Thursday or Friday.
7. Make sure you know which units the laboratory uses to report test results. All laboratories determine nitrate concentration in soil in units of ppm, but some labs report soil nitrate data in units of lb/acre. If your soil test report shows lb/acre, ask the lab for the conversion factor used in their report. Most laboratories in the Pacific Northwest assume that 1 ppm NO_3-N = 4 lb NO_3-N/acre when the soil sampling depth is 12 inches. See the sidebar "Soil nitrate units" for more information.
8. Keep records of test results, including relevant crop management information (e.g., sampling date, crop growth stage, previous crop).

Soil nitrate units

What is soil "nitrate-N"? Soil nitrate-N (NO_3-N) is the quantity of N present in the soil in the nitrate form (as NO_3). In this publication, we speak of testing soil for nitrate, but we express the concentration of N in units of NO_3-N. Soil NO_3-N is the common reporting unit used by commercial soil testing laboratories.

Tables in this publication express nitrate-N concentration in ppm. What is ppm? How can I convert ppm to lb/acre? In this publication, we use parts per million (ppm) for soil nitrate test interpretation (e.g., Tables 2 and 3). Because the nitrate test measures all of the nitrate present in soil at the time of sampling, nitrate data can also be expressed in units of lb/acre.

1 ppm NO_3-N = 3.5 lb NO_3-N/acre for our recommended sampling depth (12 inches) and a typical soil bulk density for loamy Willamette Valley soils (1.3 g/cm^3 or 81 lb/ft^3). Table 1 shows example equivalent values for ppm and lb/acre.

The math used to calculate the conversion factor is:

43,560 ft^3/acre (volume of an acre of soil, 12 inches deep) x 81 lb/ft^3 (density of soil) = 3.5 million lb soil/acre

Note that it is not appropriate to convert soil test values for other nutrients, such as phosphorus (P) and potassium (K), from ppm to lb/acre. Soil tests for these nutrients are index values and do not represent all of the plant-available P or K present in the soil.

Table 1. Soil nitrate-N test unit equivalencies.[1]

Soil NO_3-N test value	
ppm (mg/kg)	**lb/acre-ft**
10	35
20	70
30	105

[1]Conversion factor: lb/acre-ft soil = ppm x 3.5. Based on a sampling depth of 12 inches and typical soil bulk density for silt loam and silty clay loam soils in the Willamette Valley (1.3 g/cm^3).

Interpreting preplant and midseason nitrate test results

Figure 7 represents three nitrate monitoring scenarios for vegetable crops seeded in late May/early June.

- The "adequate" line shows a field for which soil nitrate is sufficient at midseason (near 30 ppm). Nitrate is depleted during rapid vegetative growth (between midseason and harvest).
- The "excess" line represents a field for which nitrate is present in excess of crop need at midseason. Considerable nitrate remains after harvest and is subject to winter leaching.
- The "deficient" line represents a field for which soil nitrate remains low throughout the season, limiting crop production.

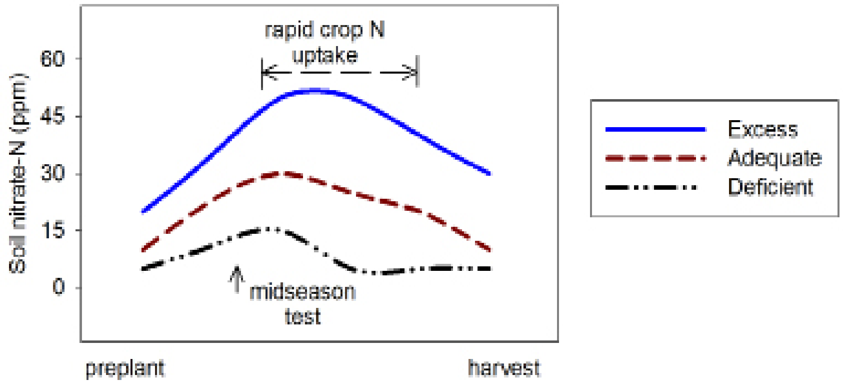


Figure 7. Scenarios for deficient, adequate, and excess soil nitrate (0- to 12-inch depth) during the production of a summer vegetable crop. The most important time to sample is during the first 3 to 6 weeks after seeding or transplanting. Nitrate dynamics for the full year are discussed in the sidebar "Willamette Valley soil nitrate calendar" (page 3).

Intepretation of preplant and midseason results is discussed below. Tables 2 and 3 show recommended plant-available N (PAN) inputs, based on preplant or midseason soil test results. PAN input refers to N fertilizer input.

In Tables 2 and 3, vegetable crops are grouped by recommended PAN input using "book values" published by Gaskell, et al. (2007). Squash is representative of crops with the lowest N input need, sweet corn represents crops with an intermediate N input need, and broccoli represents crops with a high N input need. See Table 4 (page 8) for other crops in each group. Keep in mind that these are rough estimates of crop PAN input needs and are most useful when used for relative comparison (e.g., broccoli needs more N than snap bean). Within the same vegetable crop, factors such as plant population, variety, and irrigation system efficiency affect site-specific PAN input requirements.

Recommendations apply to crops fertilized with either mineral fertilizers (e.g., urea) or organic fertilizer. For mineral N fertilizer, PAN input = total N input. For organic fertilizers, PAN is equal to the plant-available portion of the total organic N input. To calculate PAN from organic fertilizers, use the worksheet provided in PNW 646 (Collins, et al., 2013) or the OSU organic fertilizer and cover crop calculator (http://smallfarms.oregonstate.edu/calculator).

Preplant soil nitrate test interpretation

Because preplant soil nitrate-N often is very low (below 10 ppm) in May, and sometimes in early June, the preplant test is most useful when crops are seeded or transplanted after mid-June. See Table 2 for interpretation of results.

Additional N mineralization takes place between preplant and midseason, increasing soil nitrate. When the preplant test is less than 15 ppm, we recommend retesting at midseason to more accurately assess site-specific soil nitrate supply.

Table 2. Interpretation for preplant soil nitrate test (0- to 12-inch depth).

		Crop[1]		
		Low N need (squash)	Medium N need (sweet corn)	High N need (broccoli)
Soil nitrate-N (ppm)	Interpretation	Recommended PAN input (lb/acre)[2]		
Above 25	Little chance of crop response to additional PAN	0	0	0
15 to 25	Borderline adequate PAN	0 to 30	0 to 50	0 to 75
Below 15	Typical PAN input required. Retest soil in 4 to 6 weeks for greater recommendation accuracy and use Table 3 (page 8) to interpret results.	60 to 100	100 to 150	150 to 200

[1]Crops are grouped into three categories for the purpose of PAN input recommendations (low, medium, and high). See Table 4 (page 8) for additional vegetable crops in each category.
[2]Recommended PAN input = recommended mineral N fertilizer (e.g., urea) rate. In organic systems, PAN is the portion of input N that is converted to nitrate via mineralization.

Table 3. Interpretation for midseason soil nitrate test (0- to 12-inch depth).

Soil nitrate-N (ppm)	Interpretation	Crop[1] Low N need (squash)	Medium N need (sweet corn)	High N need (broccoli)
		Recommended PAN input (lb/acre)[2]		
Above 40	More PAN than the crop can use	0	0	0
30 to 40	Little chance of crop response to additional PAN	0	0	0
20 to 30	Borderline adequate PAN	30	50	70
10 to 20	Typical PAN input required	60	100	140
Below 10	Very low N mineralized, high need for PAN	100	150	200

[1]Crops are grouped into three categories for the purpose of making PAN input recommendations (low, medium, and high). See Table 4 for additional vegetable crops in each category.
[2]Recommended PAN input = recommended mineral N fertilizer (e.g., urea) rate. In organic systems, PAN is the portion of input N that is converted to nitrate via mineralization.

Midseason soil nitrate test interpretation

The midseason soil nitrate test more accurately evaluates soil nitrate supply versus crop N demand than does the preplant test. This is why Table 3 is more detailed than Table 2.

Nitrate testing questions and answers

In which situations is soil nitrate testing during the growing season most useful?

Preplant and midseason soil nitrate tests are most useful when soil nitrate is likely to be high and there is a good possibility of reducing N fertilizer inputs below the typical recommendation. The following are some common scenarios:

- Organic soil amendments have been applied in the early spring or have been applied routinely for several years, as in organic production systems.
- Leafy greens or brassicas are seeded or transplanted in July–August for fall harvest.
- A high biomass legume cover crop was incorporated before seeding.
- Mineral fertilizer or an organic fertilizer that rapidly releases PAN (e.g., feather meal) can be sidedressed.

Soil nitrate testing is *least* likely to be helpful when crops are planted in early spring (before May 1) or when nitrate is leached during the growing season. Very sandy soils (e.g., loamy sand or sandy loam soil textures) with low soil water-holding capacity have a high risk of leaching. Leaching can occur on any soil when irrigation is excessive or irrigation water distribution is not uniform.

Table 4. Relative PAN input need for vegetable crops.

Relative PAN input need[1] Low	Medium	High
Baby greens	Carrot	**Broccoli**
Snap bean	**Corn, sweet**	Cabbage
Cucumber	Garlic	Cauliflower
Radish	Lettuce	Celery
Spinach	Melon	Potato
Squash	Onion	
Table beet	Pepper	
	Tomato	

Adapted from Gaskell, et al. (2007).
[1]Crops in bold are the example crops in Tables 2 and 3.

Preplant soil nitrate tests are likely to be misleading when applied irrigation exceeds evapotranspiration during the first month after seeding. If early-season irrigation is likely to leach some of the nitrate below the top foot of soil, midseason nitrate testing is strongly preferred.

Are in-season soil nitrate tests useful when crops are grown in high tunnels?

When crops are grown in hoop houses that exclude rainfall, soil nitrate is not leached during the winter. The best time for soil nitrate sampling is after the soil has been thoroughly mixed by tillage. When drip irrigation is used, soil nitrate test results are more variable because nitrate moves laterally and concentrates at the edges of the wetting front.

Do the midseason N sufficiency values (25 to 30 ppm) reported here for sweet corn, table beets, and broccoli apply to other crops?

Reported midseason soil nitrate sufficiency values for a variety of vegetable crops grown in other regions have generally been between 25 and 30 ppm (Lazicki and Geisseler, 2017; Heckman, 2002). It is likely that a 30-ppm sufficiency threshold applies to other vegetable crops. A value of 30 ppm nitrate-N represents approximately 105 lb N/acre present in the soil. Nitrate present in the soil in midseason substitutes 1 for 1 with N supplied by mineral N fertilizer.

What are the options for additional N application when midseason soil nitrate is low in organic cropping systems?

High-N organic fertilizers containing more than 6 percent total N (dry weight basis) mineralize N rapidly and can supply PAN at sidedress time. Most of the PAN release from high-N organic fertilizers occurs during the first 3 to 6 weeks following application (Hartz and Johnstone, 2006; Gale, et al., 2006). Liquids can be applied by fertigation (Miles, et al., 2010). Solid fertilizers (e.g., feather meal) can be applied beside the row and lightly cultivated to incorporate. When the field is sprinkler irrigated, or when rainfall is expected soon after application (e.g., March in the Willamette Valley), it is not always essential to incorporate a fast-acting organic fertilizer via tillage.

Are soil nitrate quick tests a good substitute for testing soil samples by an analytical laboratory? Which quick tests are recommended?

A quick test using nitrate-sensitive test strips has been developed and validated for use with vegetable crops in California (Hartz, et al., 1994; Lazicki and Geisseler, 2017). This quick test is accurate when performed routinely by a trained person, but using it exclusively is not recommended. Instead, quick test results should be validated by periodically sending duplicate samples to a commercial lab. See Appendix 3 (page 16) for more information.

My midseason soil nitrate test was 50 ppm NO_3-N. What might be the cause of the high soil nitrate values?

Soil nitrate can originate from this year's inputs (fertilizer, cover crop residue, irrigation water, etc.) or from the mineralization of SOM. Check records of N inputs applied this year. A long-term record of soil nitrate values on your fields will indicate how often the field exhibits high soil nitrate levels. If a field routinely has high soil nitrate values, and this year's N inputs were minimal, then it is likely that the high soil N values come from the natural process of mineralization of SOM.

When preplant soil nitrate-N is high (above 25 ppm; 0–12 inches), is starter fertilizer application warranted?

Starter fertilizer containing N is often applied beside the row at seeding, where emerging crop roots can access it. Applying a low rate of starter fertilizer, supplying about 30 lb PAN/acre, is a reasonable practice. Crops sometimes respond to starter even when the soil nitrate level is high. Likely, this is because the starter fertilizer concentrates N near the roots, while soil nitrate is more evenly distributed in the soil.

Is it likely that I am getting nitrate from irrigation water?

Willamette River water is routinely low in nitrate. Well water is sometimes high in nitrate, especially if the well is distant from a river and is located in a groundwater management area (GWMA). It is not unusual for wells in a GWMA to have N concentrations of 5 to 10 ppm NO_3-N. Water from a well testing at 10 ppm NO_3-N supplies 27 lb NO_3-N per acre-foot.

Can plant tissue tests for N evaluate the supply of N in the soil?

Plant tissue tests tell you whether the plant currently has enough N. They do ***not*** indicate whether the reserve supply of nitrate in the soil is sufficient for the future. Consider this analogy from driving a car: plant tissue testing tells your current location, but it does not tell you how much gas is in the tank.

Appendix 1. Soil Nitrate Testing for Broccoli, Sweet Corn, and Table Beet

Midseason soil nitrate test for broccoli

Question

What is the relationship between midseason soil nitrate and measures of broccoli crop performance (marketable yield and crop N uptake)?

Methods

Soil nitrate was monitored at the OSU Lewis Brown farm (Corvallis, OR) on a Chehalis silt loam soil. During the summer before winter cover crop establishment, the field was fallow (no crop).

Winter cover crop treatments were oat (*Avena sativa*), phacelia (*Phacelia tanacetifolia*), or common vetch (*Vicia sativa*), seeded in the fall prior to growing broccoli. Cover crops were flail-mowed and then incorporated. Broccoli was transplanted in early June, about 30 days after cover crop incorporation. See references (page 11) for additional details. The cover crop–broccoli rotation experiment was conducted in adjacent fields in 2006–2007 and 2007–2008.

Soil nitrate in the top 12 inches of soil was measured 63 to 67 days after cover crop incorporation and about 30 days after transplanting. Soil samples were collected between rows.

Results

Soil nitrate data reported here came from plots that did not receive preplant organic fertilizer application beyond the cover crop incorporation.

Plant-available N was less than required for maximum yield for all of the unfertilized treatments. Midseason soil nitrate-N values were very low (below 10 ppm) following an oat or phacelia cover crop. Soil nitrate-N values were highest following common vetch (up to 25 ppm).

Aboveground plant N uptake at harvest (Figure 8a) increased linearly with midseason soil nitrate-N values. A 1 ppm increase in midseason soil nitrate-N resulted in a crop N uptake increase of 5 lb/acre at harvest.

Marketable head yield also increased linearly with midseason soil nitrate-N (Figure 8b). Very poor yields (less than 40 percent of maximum) were measured when soil nitrate-N was less than 15 ppm. With 15 to 25 ppm nitrate-N at midseason, head yield was 50 to 80 percent of the maximum yield measured with organic fertilizer application (Figure 8c).

In both years of the trial, the winter fallow (no cover crop) treatment achieved maximum head yield (6 ton/acre) with a preplant feather meal input of 180 to 270 lb N/acre.

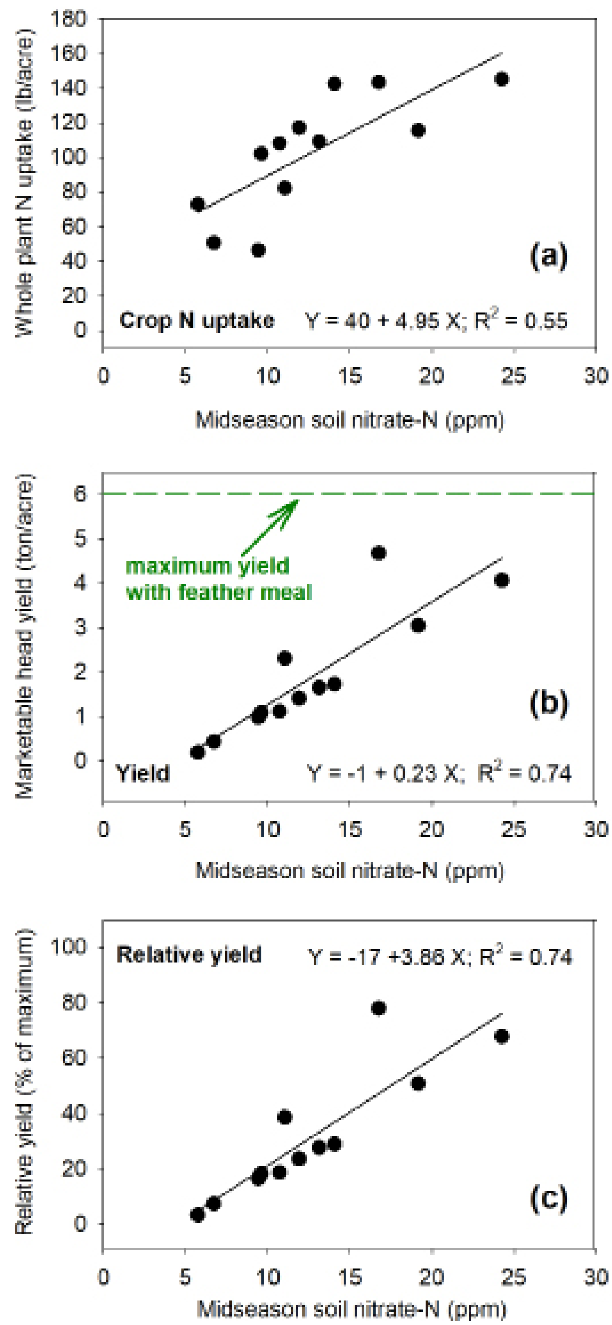


Figure 8. Relationship between midseason soil nitrate and (a) whole-plant (aboveground) broccoli N uptake, (b) marketable head yield, and (c) relative head yield. The midseason soil nitrate sample (0 to 12 inches) was collected approximately 65 days after winter cover crop incorporation. Chehalis soil, OSU Lewis Brown Farm. Adapted from Garrett (2009) and Luna, et al. (2018).

Conclusion

Approximately 30 ppm of soil NO_3-N at midseason in the top 12 inches of soil was required for maximum yield. The results presented in this case study confirm the predictive value of the midseason nitrate test for broccoli.

References (broccoli)

Garrett, A. 2009. Improving nitrogen management with cover crops in organic broccoli production. M.S. thesis. Oregon State University. http://hdl.handle.net/1957/12109

Luna, J., D. Sullivan, A. Garrett, and L. Xue. 2018. Cover crop nitrogen contribution to organic broccoli production. Renewable Agriculture and Food Systems 1–10. doi:10.1017/S1742170518000236

Sullivan, D. and N. Andrews. 2012. Case Study 3: Replacing organic fertilizer N with plant-available nitrogen from cover crops. In *Estimating Plant-available Nitrogen Release from Cover Crops* (pp. 12–13). PNW 636, Oregon State University. https://catalog.extension.oregonstate.edu/pnw636

Preplant and midseason soil nitrate test for sweet corn

Question

What is the relationship between preplant or midseason soil nitrate and measures of sweet corn performance (ear yield and crop N uptake)?

Methods

Soil nitrate was monitored at the OSU North Willamette Experiment Station on a Willamette soil. Soil testing showed 2.4 percent organic matter in the top 12 inches of soil. Before these trials, the field was not cropped the previous summer, nor cover cropped the previous winter.

Organic amendments were applied to replicated field plots in early May. Organic amendment treatments included poultry litter, municipal yard debris compost, dairy solids from a mechanical separator, and rabbit manure. Both composted and uncomposted organic amendments were included in the trial. Urea (with no organic amendment applied) was sidedressed at rates of 0 to 200 lb N/acre to determine crop yield response to N. See references (page 12) for additional details.

Preplant soil nitrate samples (0 to 12 inches) were collected just prior to seeding 'Jubilee' sweet corn in early June. Midseason soil nitrate samples (0 to 12 inches) were collected when corn had 4 to 6 true leaves, about 30 days after seeding. The midseason sample timing was based on guidance provided for the pre-sidedress nitrate test (PSNT). Both preplant and midseason samples were collected between crop rows.

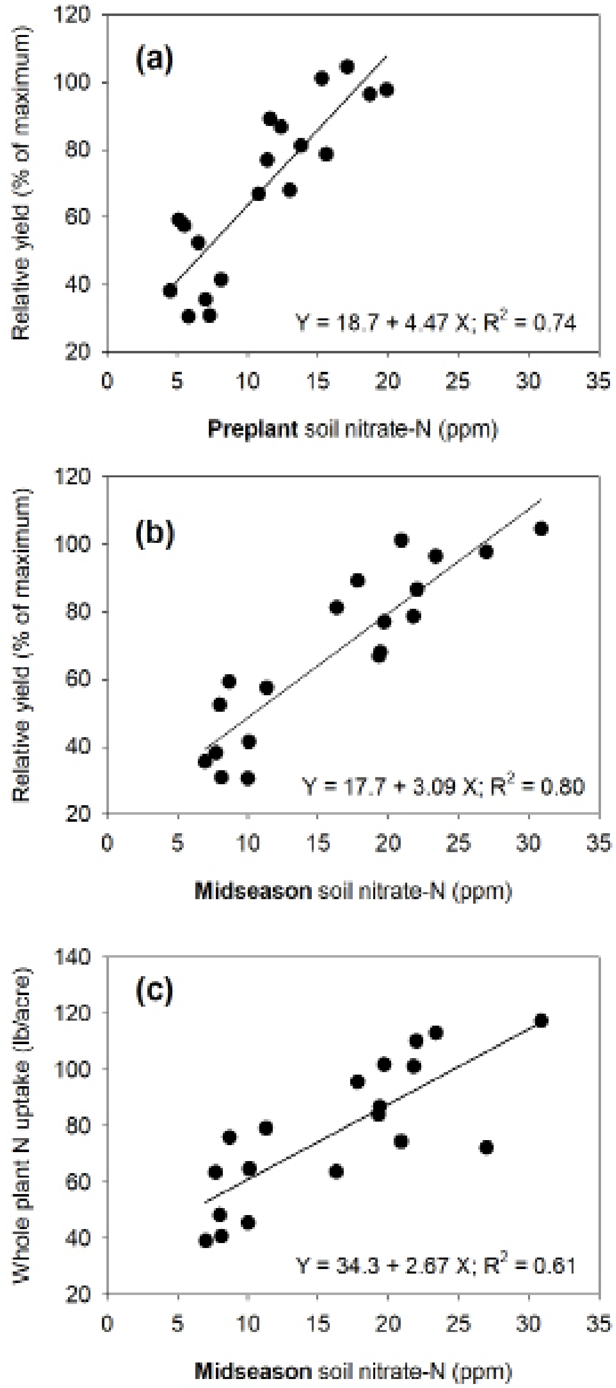


Figure 9. (a) Preplant soil nitrate and relative ear yield of sweet corn at harvest; (b) midseason soil nitrate and relative ear yield at harvest; (c) midseason soil nitrate and whole-plant N uptake at harvest. Willamette soil, Aurora, OR, 2002 and 2003. Source: Gale (2005), Gale, et al. (2006).

Corn ears were harvested in early September. Maximum ear yield was determined from corn ear yield response to urea. For each soil amendment, relative yield was determined as:

Relative crop yield (%) = (treatment yield/maximum yield with urea) x 100

Results

Soil nitrate was a good predictor of ear yield and whole-plant N uptake. More than 60 percent of the variation in crop yield or N uptake was attributed to soil nitrate values (R^2 values > 0.6 for all lines in Figure 9, page 11).

Soil nitrate increased between preplant and midseason sampling dates. The greater range in soil nitrate values at midseason reflected additional N mineralized from the preplant soil amendments.

Ear yield was maximized when soil nitrate-N was 18 ppm at preplant and 27 ppm at midseason. The midseason soil nitrate test was a more sensitive predictor of crop response to N than was the preplant test. At preplant, ear yield increased by 4.5 percent with each 1 ppm soil nitrate-N (Figure 9a). At midseason, ear yield increased by 3.1 percent with each 1 ppm soil nitrate-N (Figure 9b). This shows that the range between deficient and adequate soil nitrate values is greater at midseason than at preplant.

Aboveground plant N uptake at harvest increased linearly with midseason soil nitrate values. A 1 ppm increase in midseason soil nitrate-N resulted in a crop N uptake increase of 2.7 lb/acre at harvest (Figure 9c).

Conclusion

These trials demonstrated that "adequate" values for midseason soil nitrate-N (27 ppm) under Willamette Valley conditions are similar to published values for silage corn in our region and for sweet corn in other regions.

In this example, there were about 30 days between preplant soil amendment application and seeding. This case study shows that a preplant test can indicate the need for additional N inputs when sufficient time (about 30 days) elapses between incorporation of compost, cover crop residue, or other soil amendment and the preplant soil nitrate sampling date.

References (sweet corn)

Gale, E. 2005. Estimating plant-available nitrogen release from manures, composts, and crop residues. M.S. thesis. Oregon State University. http://ir.library.oregonstate.edu/concern/graduate_thesis_or_dissertations/4t64gq41z

Gale, E., D. Sullivan, C. Cogger, A. Bary, D. Hemphill, and E. Myhre. 2006. Estimating plant available nitrogen release from manures, composts, and specialty products. Journal of Environmental Quality 35:2321–2332.

Photo: Dan M. Sullivan

Figure 10. Table beet response to N inputs (cover crop and/or feather meal). The zero N control plot (no winter cover crop, no preplant fertilization with feather meal) is in the foreground. Canby, OR, 2009.

Midseason soil nitrate test for table beet

Question

What is the relationship between midseason soil nitrate and table beet yield?

Methods

Soil nitrate was monitored in a field trial conducted in an organic production field in the northern Willamette Valley in 2008–2009. The field had been in conventional mixed vegetable production for many years and farmed organically for several years. Soil was Canderly sandy loam.

The field trial had four winter cover crop treatments, with each treatment replicated four times within the field. Feather meal was broadcast at 0 or 100 lb N/acre and incorporated just prior to seeding. Soil nitrate samples (0- to 12-inch depth) were collected on May 18, about 5 weeks after cover crop incorporation and about 2 weeks after seeding. Beets were harvested to determine fresh weight yield on August 6.

Results

Aboveground cover crop biomass contained 94 to 164 lb N/acre (Table 5, page 13). Cover crop N concentration was 2.7 to 3.6 percent. Winter cover crops containing common vetch supplied PAN for the summer beet crop (Table 6, page 13, and Figure 10).

Beets responded to N inputs. Beet yield at harvest increased linearly with soil nitrate measured early in the growing season (Figure 11, page 13). The equation describing the relationship between relative yield of beets and soil nitrate was similar to that determined in field trials with broccoli and sweet corn (Figures 8 and 9).

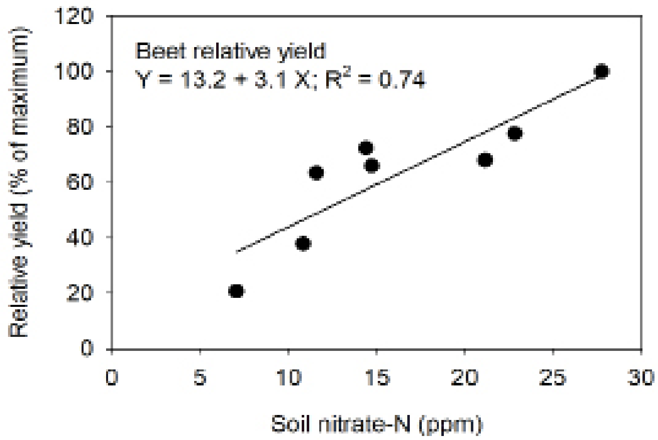


Figure 11. Soil nitrate (sampled on May 18; 0- to 12-inch depth) and relative yield of table beet at harvest. Canby, OR, 2009.

Table 5. Winter cover crop biomass and cover crop N uptake.

Winter cover crop[1]	Cover crop biomass (lb/acre)[2]	Cover crop N uptake (lb/acre)
Fallow (no cover crop)	—	—
Common vetch + phacelia	2,670	94
Common vetch + cereal rye	4,950	135
Common vetch	4,450	164

Data from table beet field trial, Canby, OR, 2009.
[1]Cover crop was seeded September 12, 2008. Common vetch = *Vicia sativa*; phacelia = *Phacelia tanacetifolia*; cereal rye = *Secale cereale*.
[2]Cover crop biomass was measured at termination, April 9, 2009.

Table 6. Soil nitrate and table beet yield response to winter cover crop and preplant feather meal application.

Winter cover crop[1]	Feather meal N rate (lb/acre)	Soil nitrate-N (May 18) (ppm)[2]	Beet root yield (Aug. 6) (lb/plot)	Relative beet yield (% of max)
Fallow (no cover crop)	0	7	4	21
	100	15	14	66
Common vetch + phacelia	0	12	13	64
	100	23	16	78
Common vetch + cereal rye	0	11	8	38
	100	21	14	68
Common vetch	0	14	15	72
	100	28	21	100

Data from table beet field trial, Canby, OR. 2009.
[1]Cover crop was seeded September 12, 2008 and killed April 9, 2009. Common vetch = *Vicia sativa*; phacelia = *Phacelia tanacetifolia*; cereal rye = *Secale cereale*.
[2]Beets were at four- to six-leaf growth stage on June 11.

Appendix 2. Soil Nitrate Monitoring Following Winter Legume Cover Crop

Situation

Growers want to know how much N a winter legume cover crop contributes and whether additional inputs of organic fertilizer are required to meet crop demand.

Questions

- How much PAN does a winter cover crop provide for a summer vegetable crop?
- Following a winter cover crop, is soil nitrate sufficient at midseason to meet crop demand?

Method

Soil nitrate was monitored following a winter cover crop in four organic production fields in the northern Willamette Valley in 2008–2009. Cover crop treatments (no cover crop or common vetch) were replicated four times in small plots within each field. The vetch was seeded in the fall, killed the following April to early May, and incorporated by tillage (Figure 12).

In the spring, growers did *not* apply organic fertilizers to the test plots. Summer crops were seeded or transplanted in late May. Summer crops were winter squash/pumpkins at Farm M and Farm P, lettuce at Farm X, and summer squash at Farm W.

Soil nitrate was monitored by sampling the 0- to 12-inch depth at a distance of 4 to 8 inches from the row from mid-May through July.

Results

How much PAN does a winter cover crop provide for a summer vegetable crop?

Across farms, soil nitrate was 5 to 20 ppm NO_3-N greater following a vetch cover crop than following winter fallow. This increase was equivalent to approximately 20 to 70 lb NO_3-N/acre. Most of the nitrate mineralized from the cover crop was detected in the soil by early June.

Was soil nitrate sufficient to meet crop needs?

Sampling more than once during the growing season allowed growers to assess the balance between N inputs and crop need.

At all farms monitored, soil NO_3-N following a legume cover crop was above 30 ppm NO_3-N at midseason and sufficient to meet crop demand without application of supplemental fertilizer.

- **Farms M and P (winter squash**, Figure 13): The accumulation of nitrate in May/June and consumption in July reflects a reasonable balance between nitrate supply and crop uptake.

Photo: Nick Andrews

Figure 12. Common vetch cover crop in April at time of tillage to kill and incorporate it.

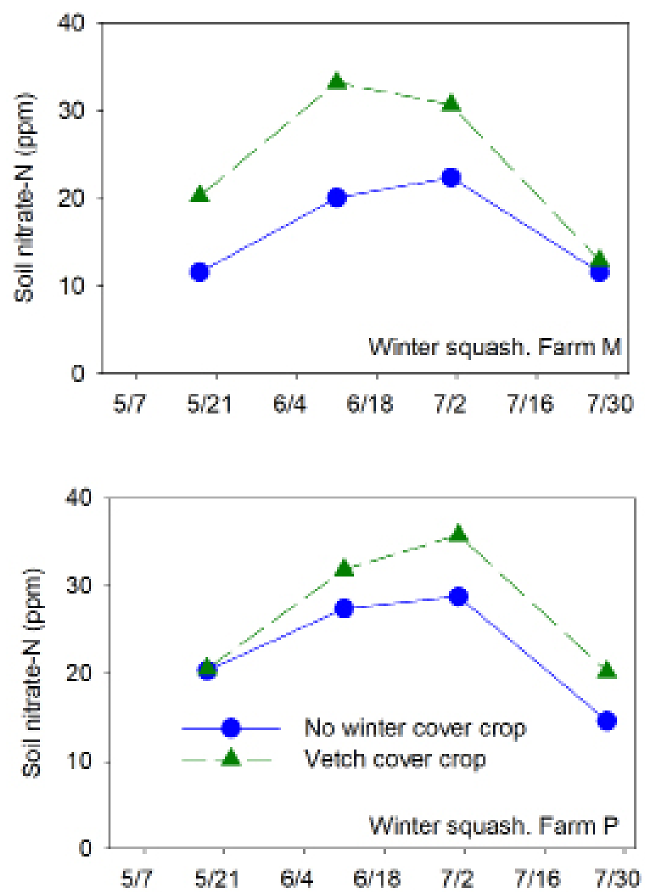


Figure 13. Soil nitrate in two organic winter squash fields in the northern Willamette Valley. A squash crop was planted following winter fallow (no winter cover crop) or following a common vetch winter cover crop. Source: N. Andrews, unpublished data, 2009.

- **Farm X (lettuce,** Figure 14, top): Two crops of lettuce were produced during the time in which soil nitrate was monitored. Soil nitrate continued to increase during July, indicating a surplus of nitrate relative to crop requirement.
- **Farm W (summer squash,** Figure 14, bottom): Soil NO_3-N was very high in mid-June and early July, approximately 60 ppm without a winter cover crop and near 100 ppm with a cover crop. Mineralization of nitrate-N from SOM provided more than enough nitrate to support crop production, even with no winter legume cover crop in the rotation. In this situation, a non-legume cover crop (e.g., cereal) would be more suitable than the legume cover crop. A non-legume cover crop can take up some of the excess nitrate that would otherwise be leached. This case study demonstrates the utility of in-season soil nitrate testing in assessing soil N mineralization amounts in fields that have been "built up" with applications of organic inputs for many years. This case study outcome is similar to that described in "System 5" in Figure 4 (page 4).

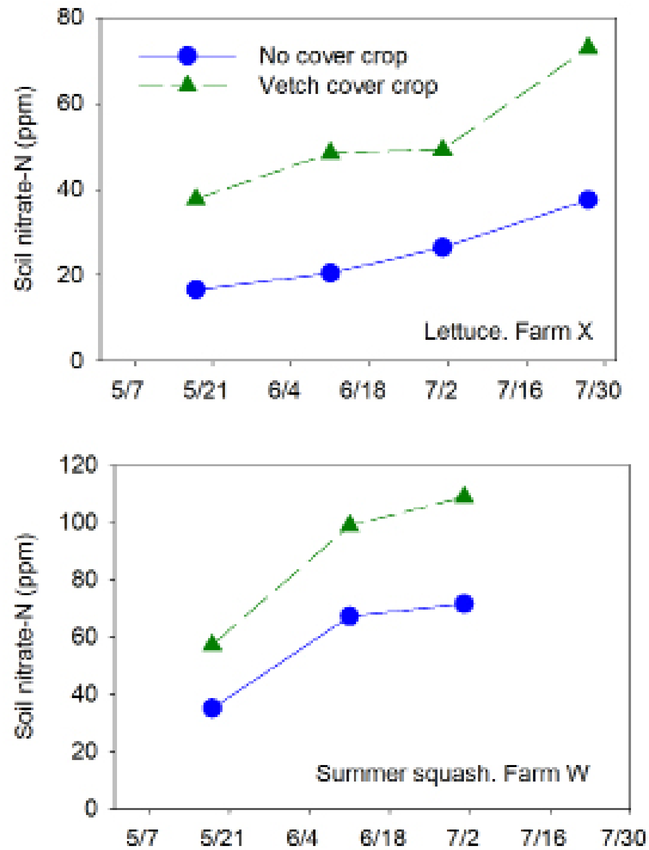


Figure 14. Soil nitrate in a lettuce field (top) and a summer squash field (bottom) following winter fallow (no winter cover crop) or a common vetch winter cover crop. Source: N. Andrews, unpublished data, 2009.

Appendix 3. Quick Test to Determine Nitrate in Soil

This quick test (QT) method, developed by the University of California-Davis, has reasonable accuracy compared to laboratory nitrate testing (Hartz, et al., 1994; Lazicki and Geisseler, 2017).

Method overview

Nitrate is extracted from a moist soil sample with a calcium chloride ($CaCl_2$) solution. Soil is added by volume (no scale required). Nitrate (ppm; mg NO_3/L) is determined in the soil extract solution using nitrate-sensitive test strips. The value for NO_3 (as nitrate) in the soil extract is converted to NO_3-N (nitrate-N) on a dry soil basis (ppm; mg/kg) based on estimated soil texture and soil moisture (Table 7, page 17).

Advantages and limitations

Compared to a traditional laboratory test, the QT is less expensive and quicker. Test results can be obtained within hours of soil sample collection. This method is not as accurate as a laboratory test. However, when performed properly, QT test results correlate well with laboratory results.

It is important to regularly validate QT results by comparison with test values from a soil testing laboratory. From a single composite sample, analyze one subsample with the QT method and then submit a subsample for laboratory analysis. We recommend validating your QT results with laboratory analyses until you gain confidence in the accuracy of the QT method. Thereafter, periodically check QT results with lab results.

QT test strips lose sensitivity in detecting nitrate with time and temperature. Store test strips under refrigeration and use them before the manufacturer's expiration date.

Procedure (Figure 15)

In a clean container, make the extraction solution by dissolving approximately 6 grams of calcium chloride (about 1 teaspoon) in 1 gallon of distilled water. The calcium will help to settle out suspended clay particles.

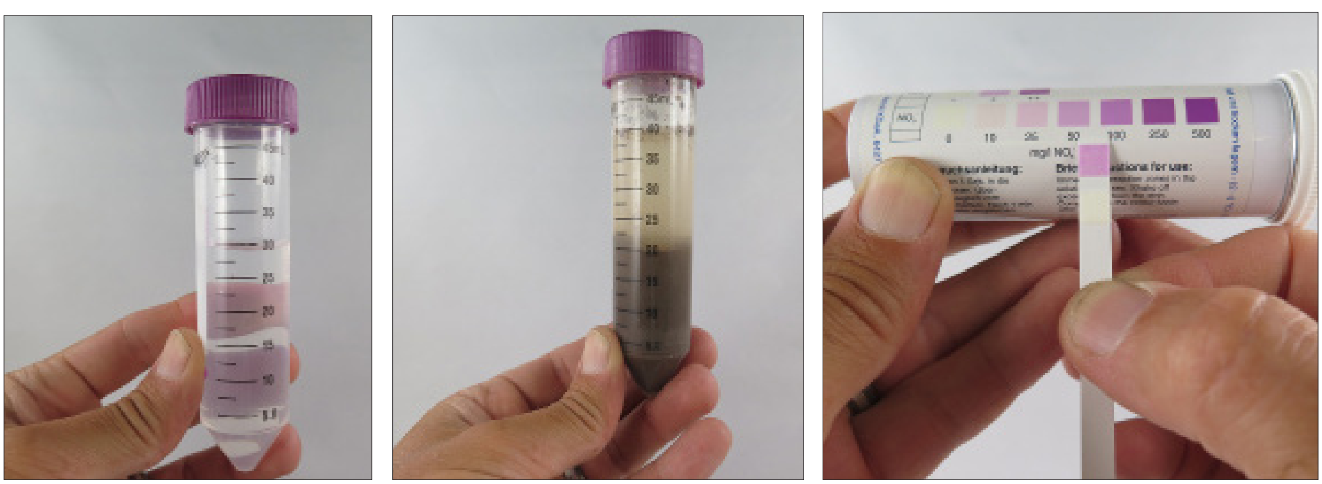
Fill a volumetrically marked tube or cylinder to the 30 mL level with the extracting solution. Any volumetrically marked tube or cylinder will work, but 50-mL plastic centrifuge tubes are convenient and reusable.

Add well-mixed soil to the tube until the solution rises to 40 mL. Cap tightly and shake vigorously until all soil clods are broken down and dispersed. For moist clay soils that may be difficult to blend, pinch off small pieces of each soil core to get a representative sample.

Let the samples sit until a clear solution appears at the top of the tube. This may take a few minutes for a sandy soil or up to an hour for a clay soil.

Insert a nitrate test strip into the clear zone of the solution at the top of the tube. Shake off excess solution and wait 60 seconds. The strip color will continue to darken with time. Make the nitrate determination between 60 and 70 seconds after dipping the strip.

Compare the color that has developed on the test strip with the color chart provided by the manufacturer. If the strip color is between two color samples on the chart, choose an intermediate nitrate value. When in doubt, be conservative and choose a lower rather than a higher value for nitrate from the color chart.



Photos: Aaron Heinrich

Figure 15. Nitrate Quick Test method steps. Left: A centrifuge tube containing 30 mL calcium chloride solution. Middle: Soil added to bring volume to 40 mL and allowed to settle. Right: determination of nitrate present in clear solution near the top of the tube using test strip.

Obtaining the required materials

Purchase the following items online. An internet search will identify vendors.

- Nitrate test strips (many brand names; example: "EM Quant")
- Centrifuge tubes (50 mL) can be purchased from many vendors in packages containing as few as 10 tubes.
- Calcium chloride ($CaCl_2$) can be purchased from laboratory supply companies or home canning supply stores. To make sure that a new source of calcium chloride is not contaminated with nitrate, test a pure $CaCl_2$ solution (no soil).

Quick test unit conversions

Not all nitrate test strips use the same units. Nitrate test strips may be calibrated in units of nitrate in solution (mg NO_3/L) or in units of nitrate-N in solution (mg NO_3-N/L). Table 7 assumes that your quick test data is in units of nitrate-N (mg NO_3-N/L). To convert ppm nitrate to ppm nitrate-N, multiply by 0.226. For test strips that are calibrated in units of ppm nitrate-N, this conversion (ppm NO_3 to ppm NO_3-N) is not necessary.

Use Table 7 to estimate nitrate-N in dry soil. The correction factors listed in Table 7 allow for differences in soil moisture at the time of testing and for soil texture. Use "moist soil" correction factors in Table 7 for quick tests performed using "as-is" soil at field moisture. Use "dry soil" correction factors in Table 7 when soil is air dried prior to the quick test.

Table 7. Correction factors for the nitrate quick test.

	To correct nitrate-N in the QT centrifuge tube solution to ppm nitrate-N in dry soil, **divide by the factors show below**	
Soil texture	**Moist soil**	**Dry soil**
Sand	0.52	0.59
Loam	0.45	0.54
Clay	0.38	0.50

Example

You added calcium chloride solution and moist soil to a centrifuge tube as shown in Figure 15. After moist soil was added, the solution level reached the 40 mL mark on the tube. On the color strip, which is calibrated in units of ppm nitrate, you measured a value of 50 mg NO_3/L in solution (in the centrifuge tube). A test strip reading of 50 mg NO_3/L corresponds to 11 mg NO_3-N/L in solution (50 mg NO_3/L * 0.226). For test strips that are calibrated in units of ppm nitrate-N, this conversion (ppm NO_3 to ppm NO_3-N) is not necessary.

Soil texture was loam, so divide by the correction factor (0.45 in Table 7):

ppm NO_3-N (mg/kg) in dry soil = [11 mg NO_3-N/L)/0.45 (correction factor)] = 24 ppm

Find the interpretation for 24 ppm soil test NO_3-N in this publication in Table 2 (preplant, page 7) or Table 3 (midseason, page 8).

For more information

Andrews, N., D. Sullivan, K. Pool, and J. Julian. 2010. Organic fertilizer and cover crop calculator. http://smallfarms.oregonstate.edu/calculator

Bary, A., C. Cogger, and D. Sullivan. 2016. *Fertilizing with Manure and Other Organic Amendments*. PNW 533, Washington State University. https://pubs.wsu.edu

Collins, D., C. Miles, C. Cogger, and R. Koenig. 2013. *Soil Fertility in Organic Systems: A Guide for Gardeners and Small Acreage Farmers*. PNW 646, Washington State University. https://pubs.wsu.edu

Fery, M. and E. Murphy. 2013. *A Guide to Collecting Soil Samples for Farms and Gardens*. EC 628, Oregon State University. https://catalog.extension.oregonstate.edu/ec628

Gale, E. 2005. Estimating plant-available nitrogen release from manures, composts, and crop residues. M.S. thesis. Oregon State University. http://ir.library.oregonstate.edu/concern/graduate_thesis_or_dissertations/4t64gq41z

Gale, E., D. Sullivan, C. Cogger, A. Bary, D. Hemphill, and E. Myhre. 2006. Estimating plant available nitrogen release from manures, composts, and specialty products. Journal of Environmental Quality 35:2321–2332.

Garrett, A. 2009. Improving nitrogen management with cover crops in organic broccoli production. M.S. thesis. Oregon State University. http://hdl.handle.net/1957/12109

Gaskell, M., R. Smith, J. Mitchell, S. Koike, C. Fouche, T. Hartz, W. Horwath, and L. Jackson. 2007. *Soil Fertility Management for Organic Crops*. Publication 7249, University of California Division of Agriculture and Natural Resources. http://anrcatalog.ucdavis.edu/pdf/7249.pdf

Hart, J., D. Sullivan, J. Myers, and R. Peachey. 2010. *Nutrient Management for Sweet Corn (Western Oregon)*. EM 9010-E, Oregon State University. http://hdl.handle.net/1957/19064

Hartz, T. and P. Johnstone. 2006. Nitrogen availability from high-nitrogen-containing organic fertilizers. HortTechnology 16:39–42.

Hartz, T., R. Smith, K. Schulbach, and M. LeStrange. 1994. On-farm nitrogen tests improve fertilizer efficiency, protect groundwater. California Agriculture 48:29–32.

Heckman, J. 2002. In-season soil nitrate testing as a guide to nitrogen management for annual crops. HortTechnology 12:706–710.

Heinrich, A., D. Sullivan, and E. Peachey. 2016. *Snap Bean—Western Oregon, Nutrient Management Guide*. EM 9154, Oregon State University. https://catalog.extension.oregonstate.edu/em9154

Lazicki, P. and D. Geisseler. 2017. Soil nitrate testing supports nitrogen management in irrigated annual crops. California Agriculture 71:90–95. https://doi.org/10.3733/ca.2016a0027

Luna, J., D. Sullivan, A. Garrett, and L. Xue. 2018. Cover crop nitrogen contribution to organic broccoli production. Renewable Agriculture and Food Systems 1–10. doi:10.1017/S1742170518000236

Miles, C., J. Rosen, E. Maynard, and T. Coolong. 2010. Fertigation in organic vegetable production systems. eOrganic and eXtension. http://www.extension.org/pages/29712/fertigation-in-organic-vegetable-production-systems

Rosen, C. and R. Eliason. 2005. *Nutrient Management for Commercial Fruit and Vegetable Crops in Minnesota*. Publication BU-05886, University of Minnesota. http://hdl.handle.net/11299/197955

Sullivan, D. and N. Andrews. 2012. *Estimating Plant-available Nitrogen Release from Cover Crops*. PNW 636, Oregon State University. https://catalog.extension.oregonstate.edu/pnw636

Sullivan, D., E. Peachey, A. Heinrich, and L. Brewer. 2017. *Nutrient Management for Sustainable Vegetable Cropping Systems in Western Oregon*. EM 9165, Oregon State University. https://catalog.extension.oregonstate.edu/em9165

Research reports to Oregon Processed Vegetable Commission (most recent listed first)

Reports are available on the Oregon Processed Vegetable Commission website: https://horticulture.oregonstate.edu/oregon-vegetables/oregon-processed-vegetable-commission

Heinrich, A. and D. Sullivan. 2016. Providing organic nutrient management guidance to processed vegetable growers.

Heinrich, A., D. Sullivan, and E. Peachey. 2013. Improving fertilizer P and N use efficiency in sweet corn.

Sullivan, D., A. Heinrich, and E. Peachey. 2012. Predicting phosphorus and nitrogen needs in sweet corn.

Peachey, E. and D. Sullivan. 2011. Predicting N fertilizer needs in sweet corn: Comparing preplant Nmin and pre-sidedress tests to improve predictability.

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