Review

In-season Soil Nitrate Testing as a Guide to Nitrogen Management for Annual Crops

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Additional index words. pre-sidedress soil nitrate test, PSNT, sidedress nitrogen, vegetable crops, field crops, cropping systems

Summary. **In-season soil nitrate testing is most useful when there is reason to believe, based on field history, that N availability may be adequate. These reasons may include soil organic matter content, applied manure, compost, legumes in the rotation, or residual N fertilizer. Soil nitrate testing is not helpful when crops are grown on sandy, low organic matter content soils that are known from experience to be N deficient. Soil nitrate testing is useful for annual crops such as vegetables or corn for which supplemental N fertilization is a concern. Soil nitrate tests must be performed at critical crop growth stages, and the results must be obtained rapidly to make important decisions about the need for N fertilization. Soil nitrate-N (NO_3-N) concentrations in the range of 25 to 30 mg·kg^{-1} (ppm) indicate sufficiency for most crops, but N fertilizer practice should be adjusted based on local extension recommendations.**

In-season soil nitrate testing is an evolving diagnostic tool that can aid in predicting the sufficiency of the soil N supply for a variety of crops. The testing procedure is often referred to as the pre-sidedress soil nitrate test (PSNT). The PSNT was originally developed in Vermont for use with field corn (*Zea mays*) to predict need for sidedressing N (Magdoff et al., 1984). Its usefulness, however, has since moved beyond corn to an increasing number of vegetable crops (Hartz et al., 2000; Heckman et al., 1995; Heckman et al., 2002). Approaches to using the PSNT or soil nitrate testing in general depend on the crop and soil system. This article will present discussions about cropping systems where soil nitrate testing has been found to be most useful.

Matching supply of N from soil with plant demand for this nutrient is one of the nutrient management challenges of crop production. Striking a balance between having too little or too much N available from soil is important to yield, crop quality, farm profitability, and the environment (Durieux et al., 1995; Guillard et al., 1999). Soil nitrate testing, when used appropriately, can provide information to improve N management in a variety of cropping systems. Nitrogen availability from soil can change rapidly, and soil testing for nitrate should be viewed as a snapshot in time of the soil's current N status which is reflective of the ability of the soil to supply available N to the crop. Crop demand for N uptake also changes during the course of the growing season. Thus, time of soil sampling is critical to the correct use and interpretation of soil nitrate test data. Appropriate use of soil nitrate testing should, therefore, be guided both by an understanding of the dynamic behavior of nitrate in soil and crop demand for nitrate uptake.

Review of factors influencing supply of nitrate in soil

When organic matter decomposes in soil, the mineral N that is released first appears in the form of ammonium. In warm soils with a favorable soil pH, ammonium-N (NH_4-N) concentrations are typically low because ammonium is rapidly converted to nitrate. Consequently, nitrate is the primary form of mineral N taken up by many crops. This explains why soil testing for NO_3-N is more useful than testing for NH_4-N to predict the sufficiency of soil mineral N supply to crops (Heckman et al., 1995; Meisinger et al., 1992). Soil testing for NO_3-N, however, unlike testing for nutrients like phosphorus (P) or potassium (K), which are relatively stable in soil, must be conducted and interpreted with consideration of the many environmental factors that can rapidly change the availability of NO_3-N.

Concentrations of soil NO_3-N are particularly susceptible to rapid change in regions of higher rainfall. Heavy rainfall can cause nitrate to leach below the depth of soil sampling or even below the root zone. When nitrate is leached from the surface layer but held in the lower profile, it remains available to deeply rooted crops, but this nitrate is not accounted for by the typical PSNT soil sampling depth. During extended periods of wet weather significant amounts of nitrate may be converted to gaseous forms of N and lost to the atmosphere by the process of denitrification.

By the end of winter, soils in humid regions typically have low concentrations of NO_3-N (Magdoff, 1991). Mineral N is released from soil organic matter slowly in the spring when soils are cool and more rapidly as soils become warm. In general, soil nitrate tends to accumulate in spring and decrease during summer due to crop uptake. At the end of the growing season, any nitrate that remains in the soil is vulnerable to leaching during winter unless cover crops are grown to capture this nitrate.

Coarse-textured soils and soils with low organic matter content generally have lower levels of soil test NO_3-N than fine-textured soils or soils with higher organic matter content. Fields where manure has been applied or where legumes are in the crop rotation generally have higher concentrations of soil test NO_3-N (Heckman et al., 1995; Meisinger et al., 1992).

The quality of plant material, especially in terms of its carbon to nitrogen (C:N) ratio, influences the rate of decomposition and the availability of N in soil. Plant materials such as straw have a high C:N ratio and its decomposition temporarily consumes soil nitrate. Plant materials such as grass clippings have a low C:N ratio and cause soil NO_3-N concentrations to increase (Krogmann et al., 2001).

Review of demand for nitrogen by annual crops

Soil nitrate testing is most suitable for use with annual crops which accumulate N rapidly within a single

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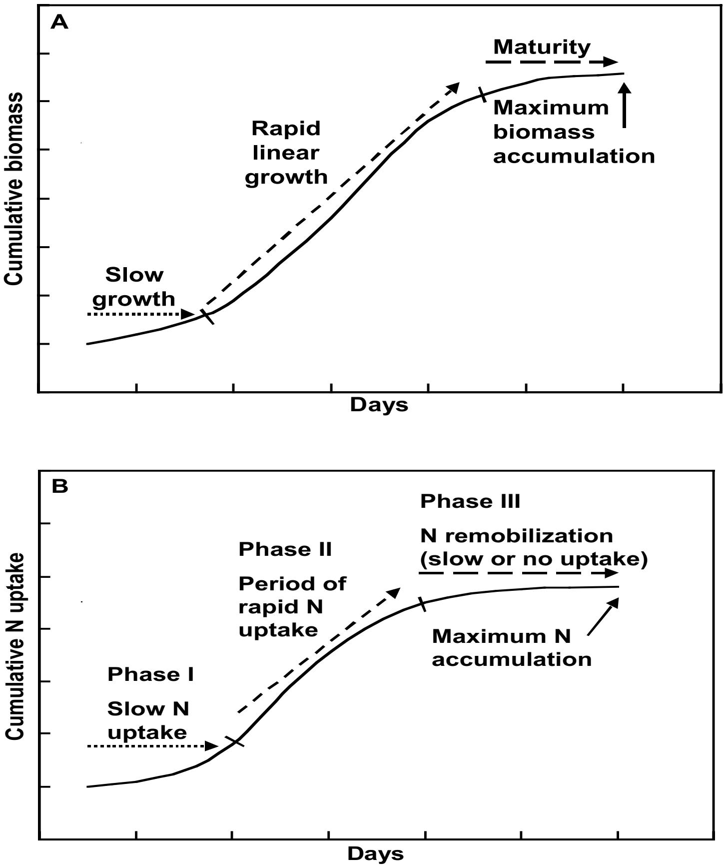

Fig. 1. Typical biomass accumulation curve (A) and N accumulation curve (B) for annual crops (adapted after Sullivan et al., 1999).

growing season. Typical patterns of biomass and N accumulation for annual crops are shown in Fig. 1. These patterns are similar suggesting that the accumulation of biomass and N are closely linked. Thus, the rate of plant growth roughly approximates the rate of plant N accumulation or plant demand for N.

In annual crops, N accumulation more closely follows the pattern of dry matter accumulation during vegetative growth than during reproductive growth and maturation. This is because in the maturing crop, N uptake slows because much of the N already in the plant is remobilized from vegetative tissues to reproductive growth (Marschner, 1995). The important point is that the pattern of N uptake by an annual crop is approximated by its pattern of growth, and that this pattern suggests the appropriate times for soil nitrate testing and N fertilization (Table 1).

A more detailed description of the pattern of cumulative N uptake over the growing season shows that it follows a sigmoid or "S" curve that may be divided into three phases (Fig. 1B). A key time for soil nitrate testing is when a crop nears the end of the first phase and is about to enter the second phase of N uptake.

During the first growth phase, early plant growth and N uptake are relatively slow (Fig. 1). The use of a starter fertilizer at time of planting typically can satisfy this early demand for N uptake.

In the second growth phase (Fig. 1), there is a period of rapid N uptake, which corresponds with rapid vegetative growth. Demand for N during this growth phase is the highest of the growing season. As much as 50 to 85% of the total N uptake for the growing season is taken up during this growth phase (Karlen et al., 1988; Sullivan et al., 1999). Producers can anticipate this growth phase by becoming familiar with the growth pattern of a particular annual crop. Any needed N fertilizer should be applied in advance of this growth phase to ensure that N is not limiting. The value of soil nitrate testing performed before the second growth stage is that the soil NO_3-N concentration can be used to predict whether the supply of N from soil is adequate to meet the demands of the second growth phase. Another consideration with regards to N fertilization is that the enlarging crop canopy may make later applications of N fertilizer difficult.

In the third growth phase (Fig. 1B), vegetative growth (stems, leaves etc.) has largely ended while reproductive structures (seed, fruit, tubers) are in development. As the crop approaches maturity, N is remobilized within the plant from vegetative to reproductive tissues. Nitrogen uptake from soil is slow. Applying N fertilizer during this final growth phase is seldom effective for increasing crop yields. Late applications of N may also slow maturation and reduce crop quality. A possible exception where late N fertilization may be useful is on an indeterminate fruiting crop such as tomato (*Lycopersicon esculentum*).

Time of sampling for soil nitrate testing

The dynamic nature of soil nitrate concentrations and the changes in N demand during crop growth are key considerations in the effective use of soil nitrate testing. In general, soil sampling should be performed just prior to the period of rapid N uptake by the crop (Magdoff, 1991). This allows the many environmental factors that influence soil NO_3-N concentration to operate as long as possible before the start of the crop growth period with the highest requirement for N uptake and before making a decision about N fertilization.

For certain crops, soil nitrate tests may be performed at other times (Hartz et al., 2000). For example, multiple sidedressings of N fertilizer are often recommended for the production of vegetable crops such as celery (*Apium graveolens*), peppers (*Capsicum annuum*), and tomatoes. In each case the decision as to whether any of these sidedressings are needed can be based on the results of a current soil nitrate test. However, if an earlier application of sidedress N was placed in a small zone (e.g., band), rather than uniformly over the field, then this may make the following soil sampling and soil nitrate test interpretation difficult or impossible.

Where to use soil nitrate tests

Time, labor, and costs of conducting soil nitrate tests limit the number of field sites that can be tested. Efforts should, therefore, be directed towards fields/cropping systems where soil nitrate testing can provide useful information. To prioritize fields for testing, one should consider the following.

Soil type. In humid regions, soils with a sandy texture or low organic matter content can be expected to have low soil NO_3-N concentrations. There is little useful information to be gained by performing soil nitrate tests on such soils, because crop need for N fertilizer is already predictable. It is generally better to focus efforts in soil nitrate testing on soils that have relatively high organic matter contents. In arid regions, however, where N is less likely to leach, it may be useful to test soils for elevated concentrations of NO_3-N regardless of soil texture or organic matter content.

MANURE OR COMPOST. Fields that have received recent applications of manure, compost, or other N rich amendments are good candidates for soil nitrate tests. The soils in these fields will likely have elevated concentrations of NO_3-N. Questions remain, however, whether soil N availability will be adequate for crop production. This represents the classic example of where soil nitrate testing is especially useful in predicting whether or not supplemental N fertilizer is needed.

PREPLANT BROADCAST N. Fields that received broadcast applications of N fertilizer at time of planting may also be appropriate for soil nitrate testing (Binford et al., 1992; Rozas et al., 2000). The interpretation of soil nitrate tests in this instance may depend on the amount of rainfall received since the time of applying the broadcast N. When rainfall has been below normal, it is generally safe to assume that much of the N that had been broadcast is still available to the growing crop. However, when rainfall has been above normal, there is a concern about leaching and denitrification, and about whether enough N is still present to grow the crop. Soil nitrate tests can assess the current soil N status giving consideration to the N contribution from the applied fertilizer and the influence of N transformations including mineralization, immobilization, or denitrification. In consideration of numerous environmental influences, soil nitrate testing can be helpful in predicting if there is a need for additional N application.

DOUBLE CROPPING. When cabbage (*Brassica oleracea* Capitata Group) and other vegetables are grown as a fall crop following the harvest of early season vegetables, such as sweet corn (*Zea mays*), peas (*Pisum sativum*), snap bean (*Phaseolus vulgaris*), or lettuce (*Lactuca sativa*), in some cases enough carryover N from the early crop is available to grow the fall crop (Heckman et al., 2002). Soil nitrate testing can be used to measure both the carryover N and the release of N from the incorporation of the previous crop's residue.

LEGUME COVER CROPS. When N-fixing crops are grown in the rotation and plowed down, soil nitrate testing can be used to predict if sufficient N has become available for the production of the nonlegume crop that follows (Meisinger et al., 1992).

ORGANIC SYSTEMS. Organic growers are challenged to provide optimal N fertility to crops from hard-to-quantify natural sources of N. The organic philosophy is to feed the soil rather than feed the crop during the growing season with sidedress N fertilizer. The function of soil nitrate testing in organic systems is not, therefore, to determine whether sidedress N fertilizer is needed. Rather, its function is to learn about the performance of the current organic fertility program that is in place and if that program needs adjustment for future growing seasons. Soil nitrate testing might help to indicate when excessive rates of N-containing materials have been applied which upon mineralization has the potential to leach N.

Procedures for soil nitrate testing

In general, sample after crop es-

Table 1. Suggested times for soil sampling for use of in-season soil nitrate tests on various crops.

Crop	Scientific name	Time of soil sampling
Field corn Sweet corn	*Zea mays*	When plants are 15 to 25 cm (6 to 10 inches) tall.
Cabbage Cauliflower Broccoli Brussels sprouts	*Brassica oleracea*	2 weeks after transplanting.
Celery	*Apium graveolens*	2 weeks after transplanting. Sample again in about 3 to 4 weeks.
Lettuce	*Lactuca sativa*	2 weeks after transplanting or after thinning if direct seeded (2- to 4-leaf stage).
Endive and escarole	*Cichorium endivia*	
Beets	*Beta vulgaris*	After thinning (2- to 4-leaf stages).
Turnip	*Brassica rapa*	
Rutabaga	*Brassica napus*	
Pumpkin	*Cucurbita pepo*	When vines are 15 cm (6 inches) long.
Winter squash	*Cucurbita maxima*	
Cucumber	*Cucumis sativus*	
Muskmelon	*Cucumis melo*	
Spinach	*Spinacia oleracea*	At 2- to 4-leaf stages. Sample again after cutting.
Irish potato	*Solanum tuberosum*	When vines are 15 cm (6 inches) long.
Pepper	*Capsicum annuum*	At first fruit set. Sample again 3 to 4 weeks later.
Tomato	*Lycopersicon esculentum*	
Eggplant	*Solanum melongena*	

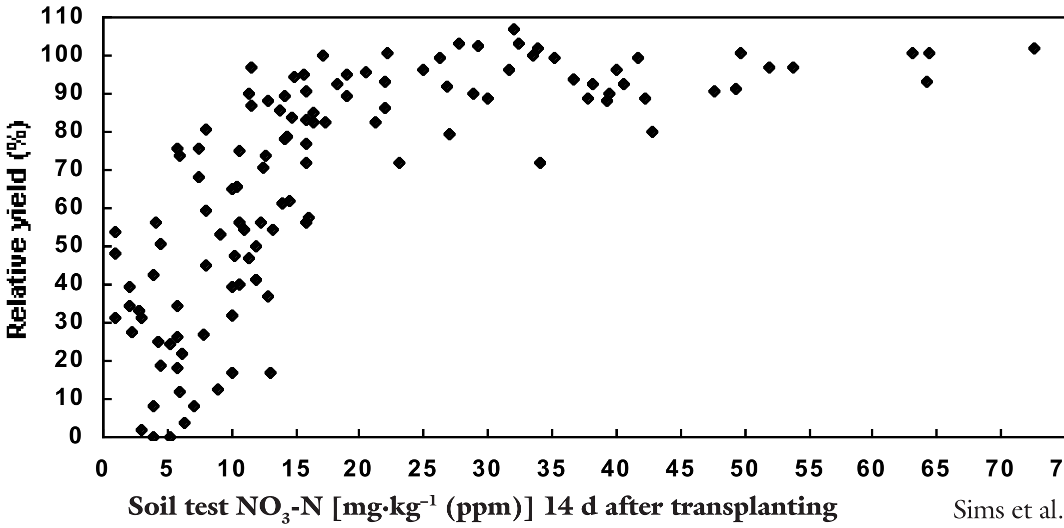

Fig. 2. Relative yield of marketable cabbage heads as a function of soil nitrate (NO_3-N) concentration in surface 30 cm (12 inches) of soil sampled at 14 d after transplanting.

tablishment and just before the crop begins to grow and take up N rapidly. Some suggested sampling times are given in Table 1. Soil cores should be taken from the 0 to 30 cm (12 inches) depth, which is deeper than for a traditional soil fertility test. The deeper sampling helps to capture nitrate that is moving below the surface layer. Sampling below 30 cm may be justified in some regions, but it is generally not considered to be worth the added effort and cost associated with deeper sampling (Binford and Hansen, 2000).

Areas having different soil types or management histories must be sampled and treated separately. Collect 15 to 20 soil cores from the area to be sampled and probe from the row center away from any starter fertilizer band. For vegetable crops grown where all N fertilizer was broadcast and incorporated in the bed and covered with plastic mulch, sample from the bed by probing through the plastic. Thoroughly mix the soil and save about a cupful to carryout the analysis for NO_3-N.

Microbial activity can rapidly change the concentration of NO_3-N in warm, moist soil samples; therefore, the soil samples must be dried immediately after sample collection. The samples can be dried by spreading the soil in a thin layer on a sheet of plastic overnight. A microwave oven may also be used to dry soil samples more rapidly. One of several commercially available soil nitrate test kits can be used to determine the soil NO_3-N concentration in parts per million (Griffin et al., 1995; Roth et al., 1992), or the samples can be sent by express mail to a university or commercial soil testing laboratory. An alternative soil nitrate test method is the quick test procedure developed by Hartz et al., (2000) which has the advantage of being employed in the field on moist soil samples.

Interpretation of soil nitrate test results

The interpretation of soil nitrate tests is based on the findings of soil test calibration research conducted with a variety of crops grown in many regions of the U.S. By far, the largest body of calibration data is for field corn collected from many states. These data have consistently shown that in humid regions soil NO_3-N concentrations of 25 mg·kg^{-1} indicate N sufficiency for field corn (Binford and Hansen, 2000). Researchers in some midwestern and eastern states found that even lower concentrations (20 to 24 mg·kg^{-1} NO_3-N) may be sufficient for field corn (Blackmer et al., 1989; Evanylo and Alley, 1997; Fox et al., 1989; Heckman et al., 1996; Klausner et al., 1993; Rozas et al., 2000; Sims et al., 1995).

Soil nitrate test calibration research conducted on other crops such as sweet corn, celery, lettuce, cabbage, peppers, pumpkin (*Cucurbita pepo*), winter squash (*Cucurbita maxima*), and sugar beets (*Beta vulgaris*) suggests that sufficient soil N is available to grow these crops when the soil nitrate test is between or above 25 to 30 mg·kg^{-1} NO_3-N (Binford, et al., 1996; Hartz et al., 2000; Heckman et al., 1995; Heckman et al., 2002; Howell, 1999; Howell, 2002). In some cases even lower concentrations (Hartz et al., 2000) were considered sufficient, but until additional research has been conducted 25 to 30 mg·kg^{-1} NO_3-N should be used as the generally recommended sufficiency level. In vegetable crops that set fruit, such as peppers, pumpkin, and winter squash, the application of sidedress N when the soil NO_3-N concentration is greater than 30 mg·kg^{-1} may cause crop yields to decrease (Howell, 1999; Howell, 2002).

Research is also needed to extend this interpretation of soil nitrate testing to additional crops, but the fact that the 25 mg·kg^{-1} NO_3-N level (or lower) has been found sufficient for all crops so far examined suggests that this level may be interpreted with cau-

Table 2. Interpretation of in-season soil nitrate nitrogen (NO_3-N) tests for annual crops grown in humid regions and recommendations for N fertilizer application.

Soil test NO_3-N [mg·kg^{-1} (ppm)]	Interpretation
<20	Very likely N deficient, sidedress N is recommended.
20–24	May be sufficient for some crops. A low rate of sidedress N may be applied to ensure that N is sufficient.
25–30	Sufficient N is available for most crops. Sidedress N is usually not recommended.
>30	Sidedress N is not recommended.
>50	Excessive. Indicates excessive application of manure, compost, or other sources of N.

tion as sufficient for the production of similar crops. A typical display of soil test calibration data is shown in Fig. 2 for cabbage. A summary of suggested soil nitrate test interpretations for humid regions is given in Table 2.

Few studies of in-season soil nitrate testing have been conducted in semiarid regions. In the semiarid environment of Colorado and where soils are not tile drained or subject to leaching, a soil NO_3-N concentration of 15 mg•kg^{-1} NO_3-N was identified as sufficient for field corn (Spellman et al., 1996). It was suggested that when a deep rooting crop, such as corn, is grown in regions of low rainfall, the uptake of nitrate from below the 30 cm sampling depth may influence the soil nitrate test interpretation. A recent study (Krusekopf et al., 2002) conducted in a semiarid region of California similarly found that fields with soil NO_3-N concentrations greater than 16 mg•kg^{-1} were sufficient for production of processing tomato. These studies suggest that in-season soil nitrate testing is a useful practice in semiarid regions but that sufficiency levels may be lower than for humid regions.

No soil test or system of providing N recommendations is always on target. Research on the PSNT, however, indicates that soil nitrate testing is about 85% accurate in making correct predictions as to whether applications of sidedress N are needed (Fox et al., 1989; Heckman et al., 1995; Heckman et al., 2002; Jemison and Lytle, 1996; Klausner et al., 1993). The success of soil nitrate testing in improving N management in several crops has lead to grower interest in extending the practice to other crops where research data are lacking. Experiences of growers in use of soil nitrate testing with tomato, winter squash, pumpkin, peppers, and muskmelon (*Cucumis melo*) crops have been satisfactory (Heckman, unpublished data on tomato from 2000 and 2001; Howell, 1999; Howell, 2002). In regions where soil nitrate testing research has been conducted, local Extension recommendations should be followed. Soil nitrate testing is not universally recommended for all crops and soils, but it is a useful tool when employed with knowledge and understanding of the N-cycle and the impacts of weather conditions on soil N availability.

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