Chapter 7. Nutrient Testing, Analysis, and Assessment

Douglas Beegle
Department of Crop and Soil Sciences, Penn State University

Table of Contents

Soil testing 153
Components of a soil testing program 153
Soil sampling 153
Understanding soil variability 153
Nutrient variability under conventional tillage 154
Nutrient variability under no-tillage and reduced tillage 155
Variability in pH under no-tillage 155
Collecting a representative soil sample 157
Sampling depths 157
Sampling patterns: random 158
Sampling patterns: grid sampling 158
Soil fertility maps 159
Sampling on the basis of known or suspected variability 160
Soil laboratory analysis 161
Understanding soil test extractants 161
Using soil test procedures recommended for your region 162
Soil test interpretation 164
The soil test-yield response relationship 164
Soil testing interpretation categories 165
Defining the terms used for interpretation categories 165
Predicting potential environmental impact from nutrients 167
Soil test recommendations 168
Developing fertilizer recommen-dations 168
Fertilizing the soil vs. fertilizing the crop 169
Assessing soil acidity 171
Soil pH and lime requirement 171
Assessing soil N levels 172
Introduction 172
The Pre-sidedress Soil Nitrate test 173
Test-based recommen-dations for N 174
Chlorophyll meter N test 175
Late Season Stalk Nitrate Test 176
Assessing soil P levels for environmental management 177
The critical source area approach 177
The Phosphorus Index 178
Using the P Index in nutrient management planning 180

Plant analysis 180
Purpose of plant analysis 180
Elements analyzed 180
Sampling plant tissue for elemental analysis 181
Sampling in different situations 181
When and what to sample 181
Multiple sampling for diagnosing nutritional problems 182
Interpreting plant analysis data 183
Introduction 183
Critical levels and sufficiency ranges 183
Using plant analysis data to determine timing of nutrient addition, and nutrient use efficiency 184
Using plant analysis data with soil test results 184
References cited 186

Soil testing

Components of a soil testing program

A soil testing program can be divided into four main components: sample collection, laboratory analysis, interpretation of results, and the recommendations for nutrient application. This chapter describes these four components. It is important to understand all these components to maximize the effectiveness of soil testing.

Two types of soil tests are run routinely. Soil tests for properties such as pH and CEC are direct measures or estimates of soil properties that affect the fertility of the soil. Other soil tests (for example, those for P, K, Ca, Mg, and micronutrients) use extractants to assess the amount of each nutrient that is related to the plant-availability of that nutrient.

Soil testing is also being used in environmental management to reduce non-point source pollution from agriculture. Use of P soil tests in the Phosphorus Index is an example of this and is discussed in this chapter.

Soil sampling

Understanding soil variability

The largest source of error in soil testing usually results from not obtaining representative samples. Frequently, these sampling errors are due to the inherent variability of soils. This variability can be either natural or man-made.

- *Natural variability* in nutrient levels is due to ongoing soil forming processes and is characterized by soil properties such as soil texture, mineralogy, depth, drainage, slope, aspect, and landscape location. For example, there are often major differences in nutrient concentrations with depth due to horizonation of the soil profile. Sandy-textured soils have a lower cation exchange capacity (CEC) and will hold fewer cations such as calcium (Ca), magnesium (Mg), and potassium (K). Low nitrogen (N) concentrations, due to denitrification, may be found in low lying, wet soils.

- *Man-made variability* in nutrient levels is usually due to farming practices. The most obvious source of man-made variation in soil nutrients is the uneven application of nutrients as fertilizers or manures. Uneven application may be intentional, such as when fertilizer is banded or manure is injected. It may also be caused unintentionally by improper adjustment or operation of application equipment.

Tillage is a very important factor in man-made nutrient variation in the soil. The following sections describe how different tillage systems affect soil nutrient and pH content.

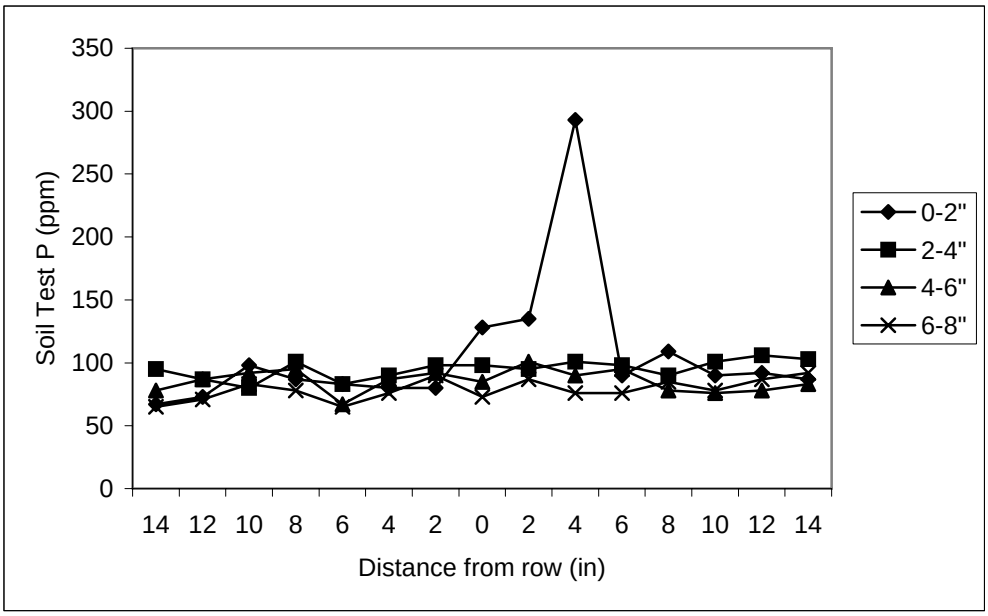
Nutrient variability under conventional tillage

The repeated mixing of the surface layer of soil by conventional tillage reduces the effects of man-made variation due to nutrient application.

Conventional tillage can also increase the variability of soil test levels over time if tillage is not performed consistently. For example, the depth of plowing can alter soil nutrient concentrations. Occasionally, deep plowing may mix low fertility subsoil material with the plow layer and thus, lower the soil test levels for nutrients in this soil layer.

Cultural practices performed after tillage (e.g., banding a starter fertilizer), however, can result in variation for the rest of the growing season. The spike in Figure 7.1 is an example of the effect of the starter fertilizer band from the previous year. This variability will persist until the fall or early spring and must be taken into account when soil testing is preformed for the next year's fertilizer recommendations. Consequently, for example, most labs recommend sampling in the middle of the row to avoid the effects of banded fertilizer from the previous year.

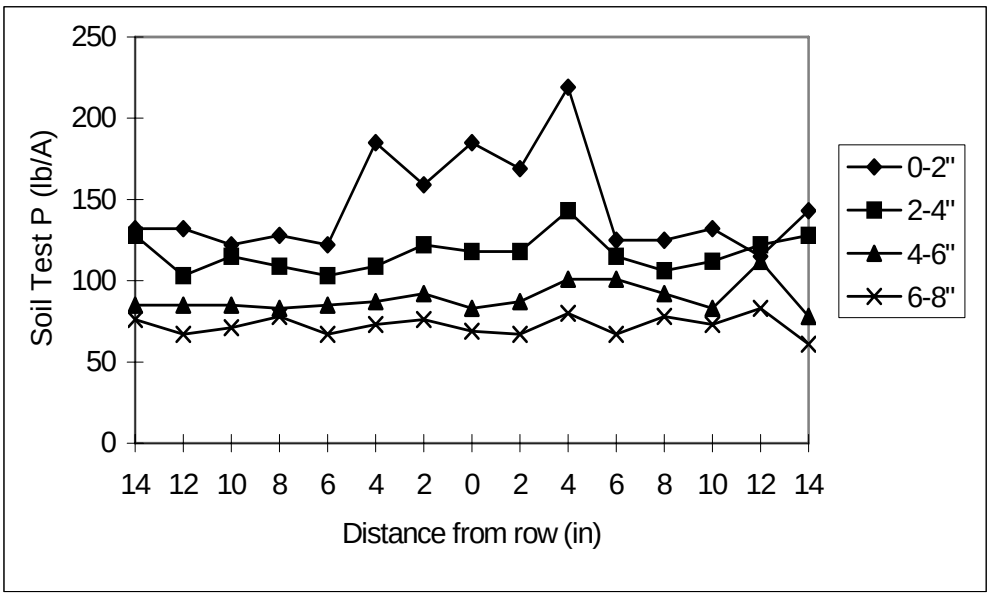
Figure 7.1. Variation in P across the row and with depth in a long term conventional till corn field.



Nutrient variability under no-tillage and reduced tillage

In no-tillage and reduced tillage systems, there is increased emphasis on residue management, which results in even more soil nutrient variation. There is no mechanical mixing of the soil in no-tillage systems, so natural or man-made variation in soil nutrient levels tends to become amplified over time. Application of immobile nutrients such as P in fertilizer or manure will result in higher soil test nutrient levels near the surface and declining soil test levels with distance down through the plow layer (Figure 7.2). Nutrients and organic matter released from crop residues also accumulate at the soil surface.

Figure 7.2. Variation in P across the row and with depth in a corn field in long-term conservation tillage.



Variability in pH under no-tillage

Variation in soil pH with depth often results from no-tillage systems. Nitrification of surface-applied fertilizer and manure N causes lower soil pH at the surface of no-till fields (Figure 7.3).

The effects of surface-applied limestone will be greatest at the surface of the soil because limestone is immobile in the soil. Thus, limestone application will usually result in a higher pH near to the soil surface. Figure 7.4 shows that when the lime is applied to the soil surface of a continuous no-till field, there is little pH effect below the surface 2 inches even after 7 years.

Figure 7.3. Variation in pH across the row and with depth in a long term no-till corn field.

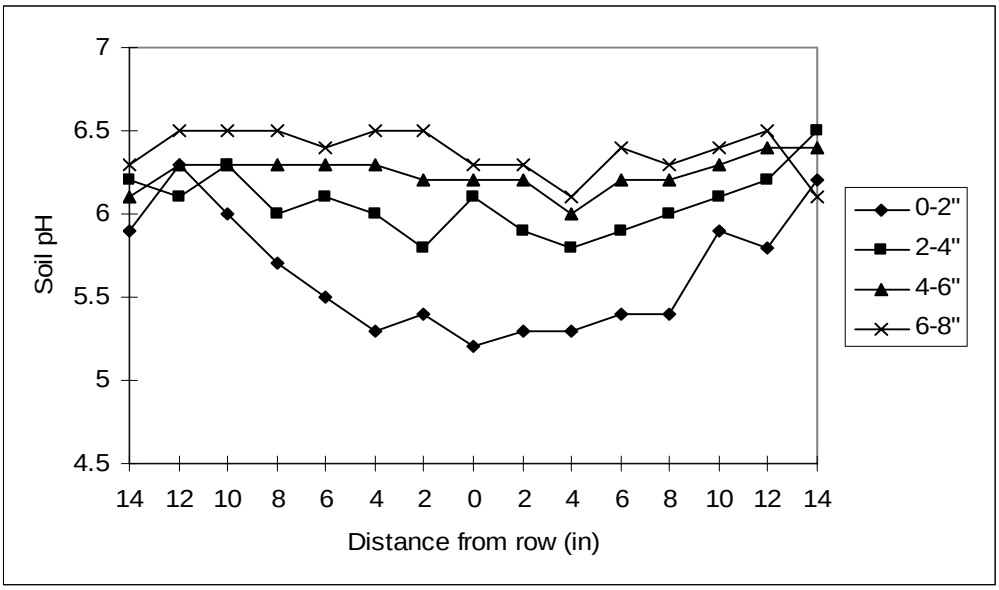
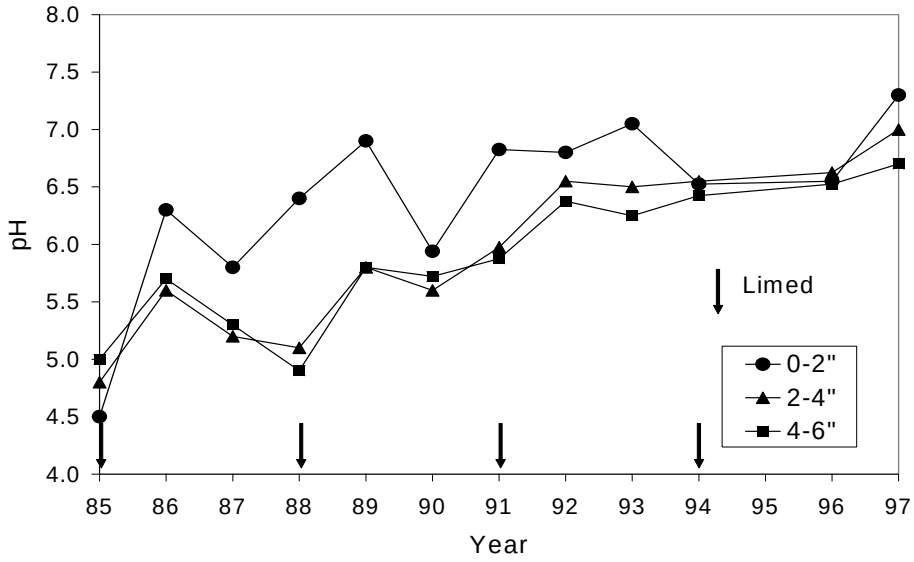


Figure 7.4. Soil pH vs. time for a no-till soil limed at 6000 lb/A every third year.



Collecting a representative soil sample

With all of this variation in field soils, it is easy to see why collecting a representative soil sample is a major potential source of error in soil testing. In a 10-acre field there are approximately 20 million pounds of soil in the plow layer. Out of this, a sample of 1/4 pound is collected that will ideally represent all of the soil in the field. A handful of soil grabbed from the surface along the road at the edge of the field is not likely to be representative of the rest of the field. Thus, a rigorous procedure for obtaining a representative soil sample must be followed.

The two main questions that must be considered when developing the sampling plan for a field are:

- How deep should the samples be taken?
- What pattern should be followed when selecting sampling locations?

Sampling depths

Depth is an important factor that must be considered in developing a sampling plan for a field. Traditionally, it has been recommended to sample the plow layer (6-8 inches) for P, K, Ca, Mg, micronutrients, pH, and lime testing.

Under **conventional tillage**, nutrients and pH in the plow layer of soil are most affected by nutrient additions and have the greatest impact on crop nutrition. For these reasons, this is still the sampling depth recommended by most labs for conventional tillage systems. In addition, shallower sampling usually will not affect fertilization recommendations because the plow layer is uniform throughout under conventional tillage.

In **reduced and no-tillage** systems, the correct sampling depth is less clearly defined, yet the depth sampled has a much greater impact on the soil test result than in conventional tillage systems because nutrients concentrate near the surface. Root systems and nutrient uptake zones are also concentrated near the surface in conservation tillage systems, so shallower sampling than 6-8 inches may be more appropriate. Some soil testing labs now recommend that minimum and no-till fields be sampled to “plow depth,” and that an additional shallower sample of 1 to 2 inches be taken, primarily for measurement of soil pH. It is usually recommended that soil be sampled to a depth of 2 to 4 inches for routine soil tests under permanent sod crops.

The recommended sampling depth for **nitrogen** is deeper than for other soil tests because of the greater mobility of nitrogen. The most common soil test for nitrogen in the humid region of the United States is the pre-sidedress soil nitrate test (PSNT) for corn. The recommended sampling depth for this test is 12 inches.

The above are general guidelines for sampling depth, but because soil test interpretations and recommendations are based on a specific sampling

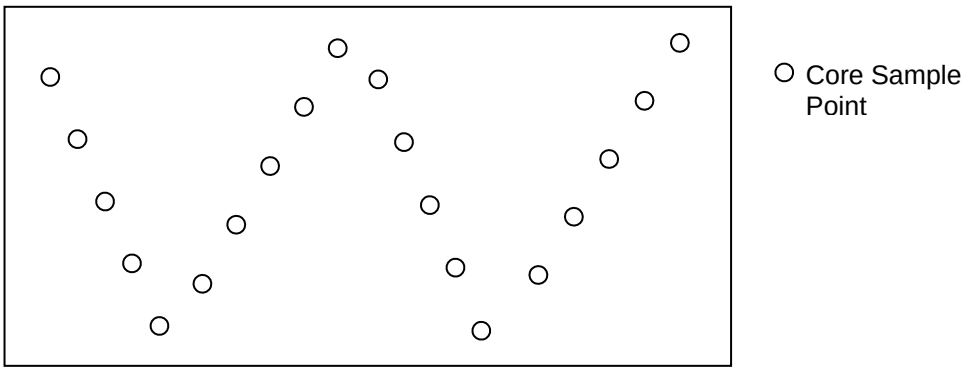
procedure, it is critical that the exact instructions from the soil testing lab be followed.

Sampling patterns: random

There are two general patterns for sampling a field: *random sampling* and *grid sampling* (or systematic sampling).

The best approach for a uniform field is to collect a *random* composite sample by randomly selecting locations in the field from which to take soil cores, which are then thoroughly mixed and subsampled for lab analysis. The result is an average soil test level for the field. Usually, 15 to 20 cores are taken at random locations to make up the composite sample. In practice, the locations for taking cores are not usually chosen completely at random, but are selected by walking a zigzag pattern that covers the whole field and approximates a random sample and collecting a core at regular intervals (Figure 7.5).

Figure 7.5. Example of a random sampling pattern in a field.



Sampling patterns: grid sampling

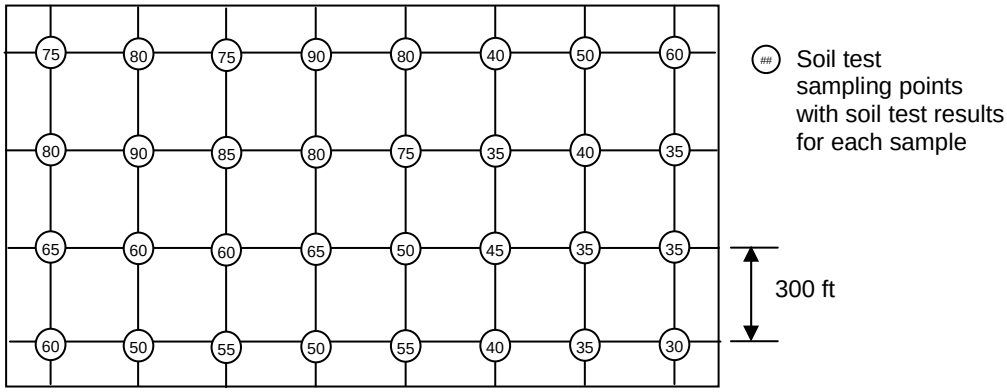
A soil test value from a composite sample may not be very useful for a non-uniform field. In this situation, the field is comprised of several distinctly different soil test levels because of natural or man-made variation caused by different soil types, topographic locations, previous management, old field layouts, and so forth. Thus, the soil test value resulting from a randomly collected composite sample may not actually exist anywhere in the field.

Ideally, the variability in a non-uniform field should be determined and mapped to permit the various areas of the field to be managed differently. The usefulness of characterizing the variability in a field will depend on the ability to change management based on this variability. A *grid sampling* (or *systematic sampling*) approach is often used to map the variability of a field.

To accomplish this, a grid is superimposed on the field. A common grid size is 2 acres or approximately 300 feet on a side. At each intersection of grid

lines, 5 to 10 soil cores are taken within a 10 foot circle and composited to make up the sample for that point (Figure 7.6). This systematic sampling approach is best suited for large, regularly-shaped fields.

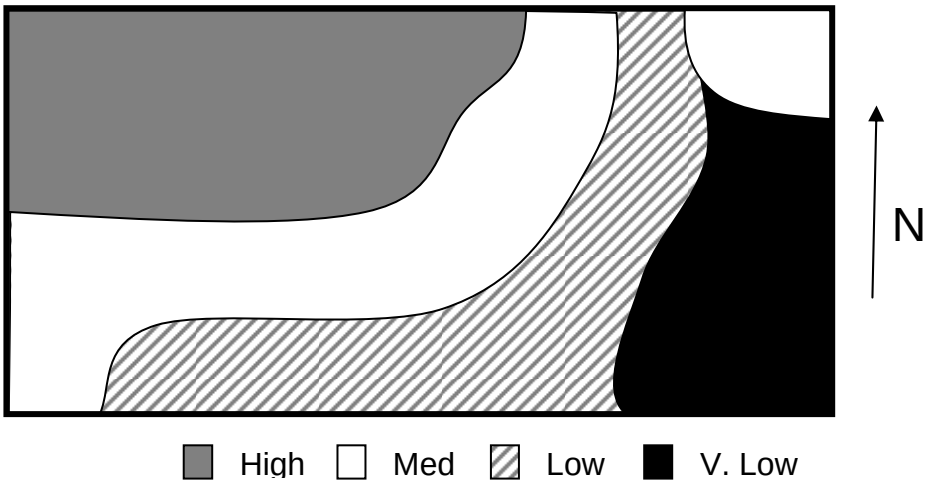
Figure 7.6. Example of a systematic or grid sampling pattern in a field.



Soil fertility maps

Analysis of the composite samples from each of these grid points is used to make a *soil fertility map* showing the variation across the field. A simple example of such a map is shown in Figure 7.7. Notice the generally high levels along the northwest side of the field. The southeast end of the field has very low soil test levels with some medium and low areas in between. Ideally, nutrient application rates will be adjusted accordingly when fertilizer or manure is applied to this field.

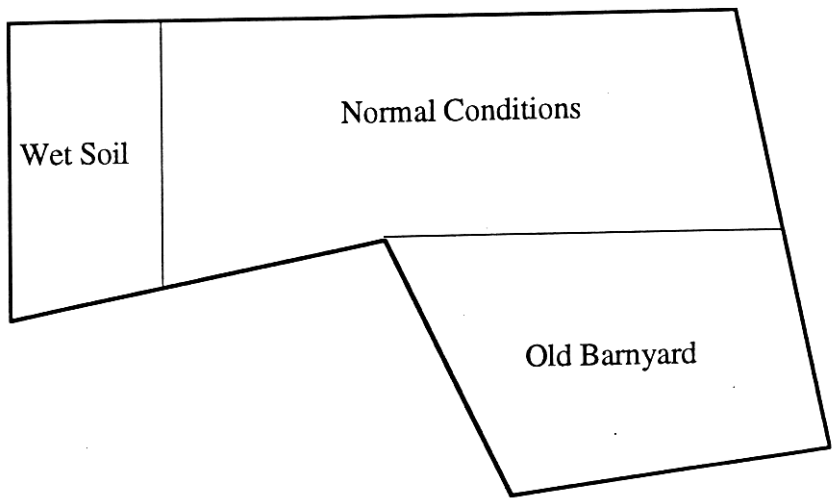
Figure 7.7. Example of a soil fertility map. This is a map of soil test levels based on the analyses of the samples taken from the grid layout.



Sampling on the basis of known or suspected variability

Small and irregularly shaped fields make grid sampling and variable management very difficult. One common compromise is to systematically sample on the basis of known or suspected variability in the field. Examples of known or suspected variability might include: historical manure or fertilizer spreading patterns, soil drainage, soil type, slope, etc. This type of sampling is illustrated in Figure 7.8. In this field, three areas that could be sampled and managed separately include an old barnyard area that has historically had heavy manure applications and is expected to contain high organic matter and nutrient concentrations; a small area of wet soil that is not productive and has not received much manure; and a well-drained unmanured area.

Figure 7.8. Example of systematically dividing a field for soil sampling on the basis of known or suspected variability. An individual composite sample would be taken and analyzed from each different area in the field.



One should not attempt to take a random composite sample that represents the whole field depicted in Figure 7.8. The result of the soil tests on that composite sample will be useless in most cases. If the field can not be divided, sampled, and managed separately, it is probably best to sample the largest and/or most productive section of the field and ignore the odd areas.

Soil laboratory analysis

Understanding soil test extractants

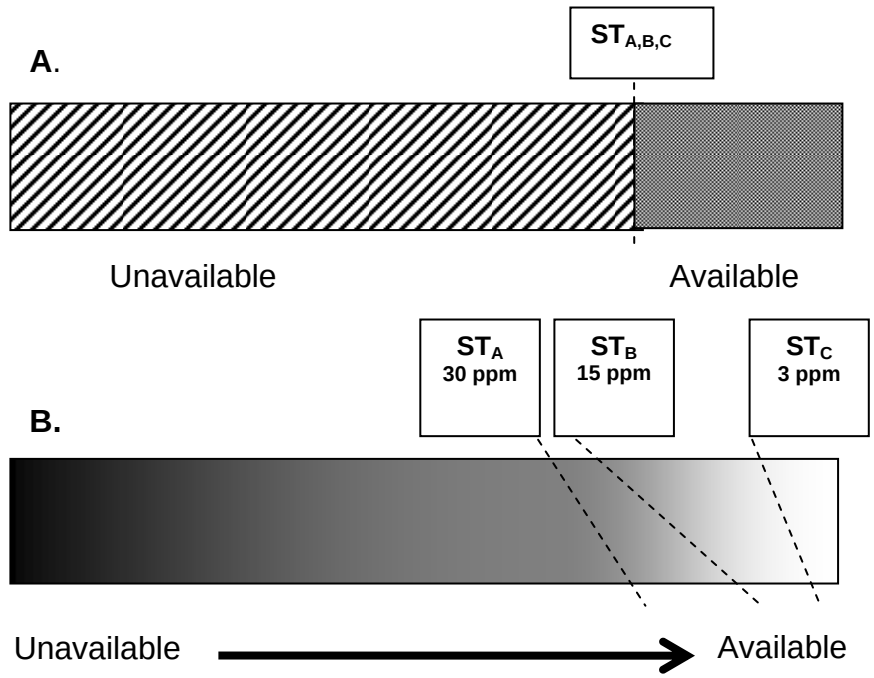
Laboratory analysis of a properly sampled soil provides the basis for assessing soil nutrient status. With few exceptions, such as the measurement of NO_3^--N, most soil test extractants do not directly measure the total amount of available nutrients in the soil because there is usually not a clear cut distinction between available and unavailable nutrients.

Part A of Figure 7.9 illustrates the commonly held misconception about available nutrients in the soil. The availability of nutrients ranges from completely insoluble (unavailable) to completely soluble (readily available). Availability is a relative term covering this entire range. Soil tests generally extract a fraction of the nutrient from the soil that is correlated to the plant-available portion of that nutrient.

Different extraction methods can extract different amounts of nutrients and provide different soil test results. Research is conducted to determine which soil test extractant works best for predicting the ability of a soil to supply available nutrients for crop uptake under conditions where the test will be used.

An example of how three extractants might extract different fractions from the same soil, resulting in three differing soil test levels, is illustrated in part B of Figure 7.9. All three of these extracted fractions may be correlated with plant availability, or one of these tests may perform better under certain conditions. It is important to use a test that has been verified to work under conditions similar to the ones in your area.

Figure 7.9. Illustration of how different soil test extractants might extract different fractions of the nutrient in the soil. A is the common **incorrect** view of nutrient availability and soil test extraction. B is nutrient availability as a continuum, showing how different soil tests ($ST_{A,B,C}$) extract different fractions of this continuum. (In this example, the numbers would be representative of ppm P by ST_A= Mehlich 3, ST_B=Bray P1, ST_C= Modified Morgan.)



Using soil test procedures recommended for your region

Generally, the soil test user need not be concerned with the details of the soil test methods. The most important consideration for the user is that the testing lab is using **standard procedures that are recommended for the region** where the samples were collected. If not, the results and/or interpretations may be misleading. Be careful if you consider sending samples to a lab in another part of the country. The lab may have an excellent reputation, but the procedures that they use may be totally inappropriate for Mid-Atlantic soil conditions.

It is also important to know which analytical methods are used when comparing results from different labs. You should only compare results from laboratories that use the same methods. If test results from two different labs are being compared and both are valid for the area where the sample was taken, the interpretation of the results should be the same even though the numerical analytical results from the two tests might differ.

In the Mid-Atlantic region, the most common analytical method used is the *Mehlich 3* soil test. Other methods that have been used (and that are still used

occasionally) in the region are the Mehlich 1, Bray P1, and 1N Ammonium Acetate. Each of these methods will extract a different amount of the nutrient but, if properly calibrated, they can all provide valid results for our region. Some states have developed conversions between the different methods. -Use conversion factors with caution. It is always better to use the recommended test rather than using an alternative test and converting the results.

The **units employed to express soil test results** sometimes cause confusion. The most common system is based on an actual or assumed weight for the soil. Results in this system are usually presented as parts per million (ppm) or pounds per acre (lb/A). As a further complication, some labs present results as pure elements (i.e., P, K), while others use the fertilizer oxide form (i.e., P_2O_5, K_2O). Results for cations like Ca^{2+}, Mg^{2+}, and K^+ are sometimes presented as milliequivalents per 100g (meq/100g). All these units can be converted mathematically to each other. Some common conversion factors are given in Table 7.1.

Table 7.1. Common conversions for soil test units

ppm x 2* = lb/A	lb/A ÷ 2* = ppm
P x 2.3 = P_2O_5	P_2O_5 ÷ 2.3 = P
K x 1.2 = K_2O	K_2O ÷ 1.2 = K
NO_3^--N x 4.4 =NO_3^-	NO_3^- ÷ 4.4 =NO_3-N
meq K/100g x 780 = lb K/A	meq K/100g x 390 = ppm K
meq Mg/100g x 240 = lb Mg/A	meq Mg/100g x 120 =ppm Mg
meq Ca/100g x 400 = lb Ca/A	meq Ca/100g x 200 = ppm Ca

* This factor only applies to furrow slice depth, approximately 7 inches, which is assumed to weigh 2,000,000 lb/A.

Soil test interpretation

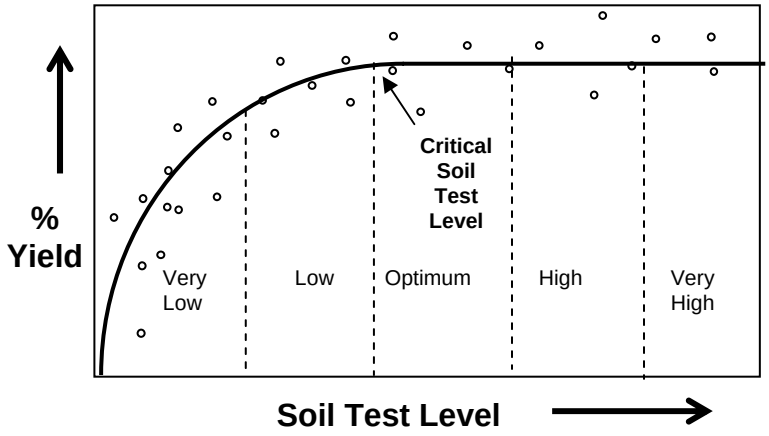
The soil test-yield response relationship

The analytical results from a soil test are relatively meaningless by themselves. Soil nutrient levels must be interpreted in terms of the soil's ability to supply the nutrients to crops. To make this interpretation, the soil test level must be calibrated against crop response to the nutrient. This is accomplished by conducting fertilizer response experiments at different soil test levels covering the range of interest for use of the soil test. These experiments must be conducted for all crops and under all the conditions where the test might be used.

An example of the relationship between yield and soil test levels is illustrated in Figure 7.10. In Figure 7.10, the value presented as % yield is the yield in the unfertilized soil divided by the yield in a soil where the nutrient is non-limiting. For example, 70% yield means that the crop yield with the unfertilized soil is 70% of the yield at optimum concentration of the nutrient. This *soil test-yield response relationship* shows that at low soil test levels yields are low relative to the optimum. As soil test levels increase, yield increases until that nutrient is no longer limiting and then the response curve levels off. This point where the relationship levels off is called the *critical level* and indicates the soil test level above which you would not expect a yield increase from adding more of the nutrient.

Soil test critical levels will vary among soils, crops, climatic regions, and extractants. For example, the critical level for soil test phosphorus for the Mehlich 3 soil test is around 30 ppm for Mid-Atlantic soils. If the test is below 30 ppm we would expect a profitable increase if we add P. However, if the soil test is above 30 ppm, no yield response is expected. For soils in the Midwest, this critical level is closer to 20 ppm. Ideally, we would like to maintain the soil test level at the critical level for optimum economic production.

Figure 7.10. Example relationship between yield and soil test level. Each point in the graph would be the relative yield for an individual field experiment.



Soil testing interpretation categories

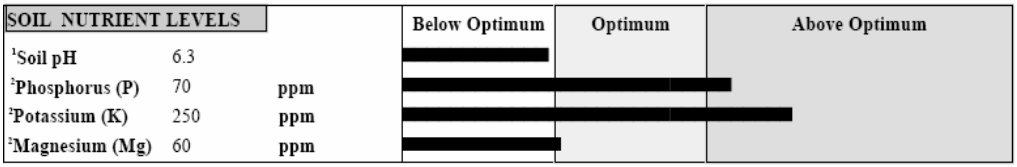
It is important to use a laboratory where the soil test results have been calibrated for your region so that an accurate interpretation of values can be determined. Most soil test laboratories use the response curve from the calibrations to develop *interpretation categories*. The dotted lines and names in Figure 7.10 illustrate how the data might be used to develop soil test interpretation categories.

Defining the terms used for interpretation categories

The qualitative terms used for the interpretation categories are related to quantities of nutrients extracted but may have different absolute meanings depending on the laboratory using them. It is important to understand exactly what these terms mean for any laboratory that you use. For example, Pennsylvania once termed the category that is designated as “Optimum” in Figure 7.10 as “Medium” while Maryland termed that same category as “High”. Today that category is called “Optimum” in both states, which has eliminated the previous confusion between state testing lab results.

Soil test labs may report these interpretations in different ways. Some labs use words such as “Low,” “Optimum,” or “High” while some use abbreviations such as “L,” ”O,” or “H.” Often the results are presented in graphical form. An example of an interpretation in the form of a chart from the Penn State Soil Testing Program report is shown in Figure 7.11.

Figure 7.11. Example of a bar chart for displaying the soil test interpretation on a soil test report (from Penn State Soil Testing Program).



Finally, some labs report their results in the form of an index number. A common index system would assign an index of 100 to the optimum level. With this system, index numbers below 100 would indicate the fraction of nutrient sufficiency, and numbers above 100 would indicate an excess of nutrient over the optimum for the crop.

Regardless of the system used to indicate the interpretation on a soil test report, the lab should provide you with clear definitions of the terms used so that you know exactly what the results mean. For example, the Penn State Soil Testing Program provides the definitions in Table 7.2 on all soil test reports.

Table 7.2. Example of definitions for soil test interpretation categories from the Penn State Soil Testing Program.

Category	Definition and Interpretation
Below Optimum	• Indicates that the nutrient is probably deficient and that the deficiency will likely limit crop growth. • High probability of a profitable return from correcting a low level. • Recommendations for a soil testing “below optimum” are designed to gradually build up the nutrient level to optimum and to maintain it at that level.
Optimum	• Indicates that the nutrient is probably adequate and will likely not limit crop growth in a typical growing season. • There is a low probability of a profitable return from increasing the soil test level above optimum. • Recommendations for a soil testing “optimum” are designed to offset crop removal in order to maintain the nutrient in the optimum range. • If you are soil testing on an annual basis, no maintenance fertilizer is needed when the soil tests in the optimum range.

Category	Definition and Interpretation
Above Optimum	• Indicates that the nutrient is more than adequate and will not limit crop growth. • Very low probability of a profitable return from applying additional nutrients to a soil testing "above optimum." • No fertilizer is recommended on these soils. Too much of a plant nutrient may cause a nutrient imbalance in the soil and, as a result, in the plant, which may adversely affect plant growth and environmental quality.

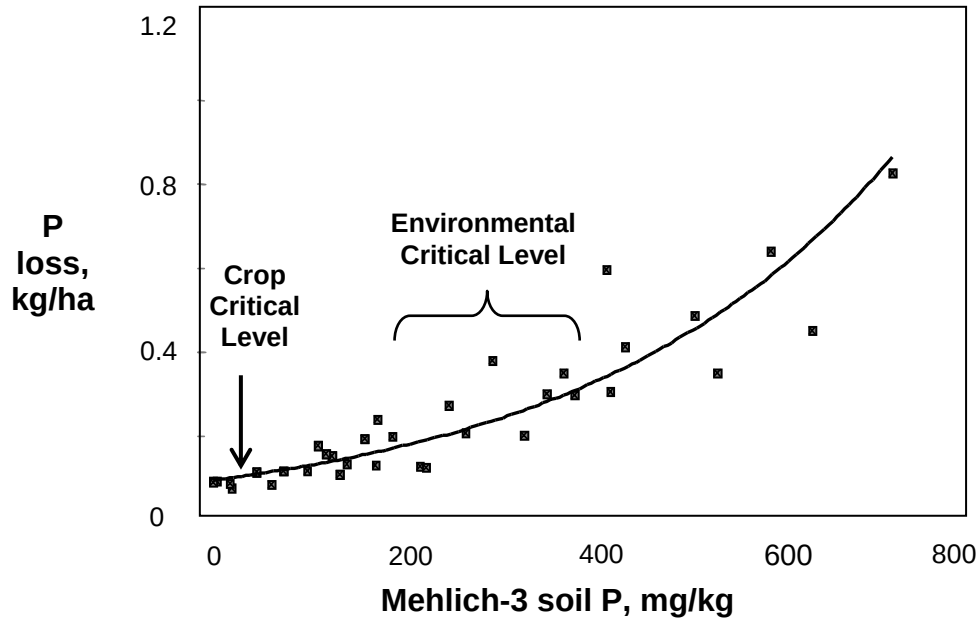
Predicting potential environmental impact from nutrients

Soil test results are most commonly interpreted on the basis of the probability of an economic response to adding additional nutrients. Because of the concern about the potential impact of nutrients on the environment, soil tests are increasingly being considered in terms of predicting potential environmental impact from nutrients. However, it is not possible to directly use conventional soil test interpretations for crop response to make an environmental interpretation. If a soil test is above or below optimum for crop response to a particular nutrient, this tells us nothing about whether that level of the nutrient represents an environmental threat. Calibrations that relate soil test level to nutrient loss are required in order to determine this information.

An example of such a relationship between soil test and phosphorus loss is shown in Figure 7.12. One challenge is that there is often not a clear critical level in this type of calibration data. A value judgment is usually needed, and the soil test level should be interpreted in the context of the characteristics of the soil and the site.

One instance of this approach is the *Phosphorus Index*. The Phosphorus Index provides a site vulnerability index for potential P loss based both on the soil test level and on other site characteristics such as soil erosion, irrigation erosion, runoff class, P fertilizer application rate, method of P fertilizer application, organic P (manure, sludge, compost, etc.) application rate, and organic P application method.

Figure 7.12. Example of soil test calibration for P based on environmental impact (adapted from Sharpley et al, 2001).



Soil test recommendations

Developing fertilizer recommendations

The final step in the soil testing process is making a recommendation. Soil test calibration studies similar to the one shown in Figure 7.10 can provide the data on whether or not additional nutrients are needed. However, additional information is required in order to determine the appropriate amount to apply.

To determine how much of a nutrient is needed at a given soil test level, experiments with multiple rates of the nutrient are conducted on soils with a range of test levels. For example, in Figure 7.13, rate experiments were conducted on soils with a soil test level of 5 and 15 ppm where 0, 40, 80, and 120 lb/A of the nutrient were applied at each site. At the end of the growing season, yield was plotted versus the fertilizer added for each experiment. From these results we can see that at a 5 ppm soil test, approximately 50 pounds of fertilizer were required for maximum yield. Conversely, at a soil test of 15 ppm, only 20 pounds of fertilizer were required. This type of experiment is then repeated on many sites with different soil test levels below the critical level to develop the relationship between soil test level and nutrient requirement (Figure 7.14).

Figure 7.13. Illustration of how fertilizer recommendations are developed.

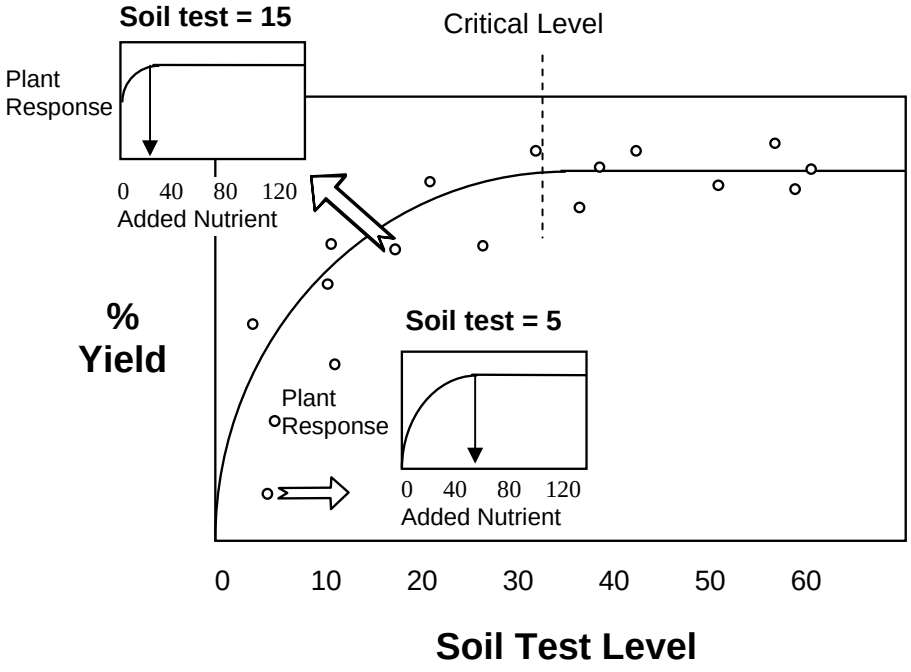
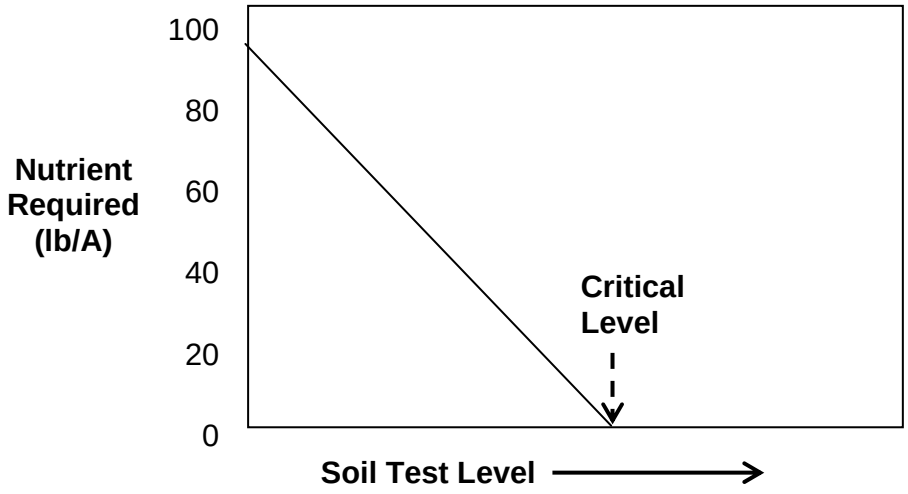


Figure 7.14. Illustration of the relationship between soil test level and nutrient recommendations.



Fertilizing the soil vs. fertilizing the crop

A factor that sometimes results in different recommendations is the philosophy of fertilization recommendations. Fertilizer recommendations are usually based on one of two general approaches: **fertilizing the soil** or **fertilizing the crop**.

Fertilizer recommendations based on **fertilizing the soil** are intended to:

(1) Build the soil test values to a level determined by field calibrations to be sufficient for optimum crop production ("*buildup*").
(2) Maintain that optimum value over time by replacing nutrients removed by the crop.

The "fertilize the soil" approach is most appropriate for longer-term management where a return from the investment in building soil test nutrient values into the optimum range will be achieved. Soil testing every 3 years is recommended with this approach.

Recommendations based on this approach differ in advocating how quickly nutrient levels in the soil should be built up. Some soil testing programs recommend that the soil be built up within the first year of application. This approach can lead to some very large, economically questionable recommendations. Most labs follow a slower approach to buildup, either by dividing the estimated buildup requirement over a certain number of years, or by simply including a small, fixed, "buildup" component to the recommendations for soils with low levels of a particular nutrient.

The maintenance component of the "fertilize the soil" approach is based on the crop nutrient removal, which is estimated from the expected yield of the crop. Long-term average yields and standard crop removal levels for those yields will usually keep soil test levels within the optimum range. If the yield and crop removal estimates are in error, regular soil testing will allow for periodic corrections before soil nutrient levels become too high or too low.

Fertilizer recommendations using the **fertilize the crop** (or *sufficiency level*) approach are based on applying just enough nutrients to achieve optimum response of the crop at a given soil test level. It can be easily argued that this approach has a sounder agronomic and economic basis than the "fertilize the soil" approach. The "fertilize the crop" approach is especially appropriate when short-term economics and short-term land tenure are critical management factors. Numerous public soil testing labs use this method, but it has not been as widely adopted as the "fertilize the soil" approach. Rigorous application of this method requires annual soil testing to determine the nutrient requirement for the current crop, and very few farmers will soil test annually.

Soil test recommendations are increasingly becoming a hybrid of these two strategies. The soil test goal for buildup in the "fertilize the soil" approach is often very close to the critical level for sufficiency in the "fertilize the crop" approach. It is often difficult to clearly distinguish whether the critical level is a sufficiency level for crop fertilization or an optimum level for soil fertilization because of the inherent variability in soil test calibration data and

the high level of uncertainty in determining either the actual sufficiency level for a crop or the optimum value for a soil. This then becomes a question of philosophical perspective and, in some cases, simply semantics. Many labs that use the "fertilize the crop" approach to make recommendations also recognize the periodic nature of soil testing by farmers and include a maintenance component in their recommendations to account for the impact of crop removal on the soil test level between soil testings. In the long run, with periodic soil testing, either approach should result in similar annual recommendations.

Assessing soil acidity

Soil pH and lime requirement

Two soil tests are normally run to provide information to manage soil acidity:

- soil pH
- lime requirement (or buffer pH)

Results from these tests may be the most important parts of a soil assessment, since soil acidity affects many critical processes in the soil-plant system, such as root growth, nutrient solubility, microbial activity, pesticide activity, and others. It is also important that the soil pH be in the optimum range to assure maximum response from other inputs and management.

The soil pH provides a measure of the current acidity level in the soil. The optimum pH for most crops and soils in the Mid-Atlantic region is 6 to 7. The exact optimum varies with the crop and soil conditions. If a soil's pH is below optimum, it is not possible to determine how much limestone is required from the pH measurement alone. A lime requirement test is run to determine how much limestone will be needed to raise the pH into the optimum range.

Limestone recommendations are made as amount of neutralizing agent to apply, and are usually given as pounds of *calcium carbonate equivalent* (CCE) per acre. The major quality factors that determine the effectiveness of a limestone are CCE, fineness, and Mg content. Limestone recommendations either assume that a certain quality of limestone will be used or provide instructions for adjusting the recommended amount of limestone to account for the quality of the limestone to be used.

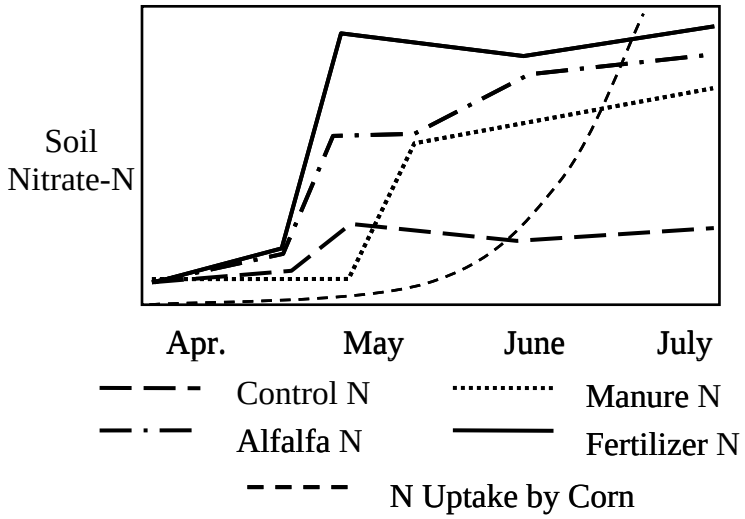
Assessing soil N levels

Introduction

Soil testing has been used effectively for years to determine the availability of P and K in agricultural soils and to determine fertilizer recommendations for these nutrients. Due to the complex behavior of nitrogen in the soil, however, development of a reliable soil test for availability of N in humid regions of the country has been more difficult.

In humid regions, a soil test taken before the growing season would not accurately reflect the availability of N later when it is most important to the crop. This is shown in Figure 7.15, which illustrates the considerable increase in soil NO_3^--N levels from early in the season to the time when the major demand for N by a corn crop occurs. In this example, if the early season soil NO_3^--N levels were used to predict availability, all of the fields would have the same soil test level and thus, the same recommendation. However, later in the season when the crop takes up most of the nitrogen, nitrogen availability is very different among the fields. Thus, an at-planting NO_3^--N test would have been misleading and, because of this, attempts to develop a reliable soil test for N as part of a traditional pre-season soil testing program have not been successful. Since corn has the greatest need for N several weeks after emergence, a successful soil test for N should reflect N availability at that time.

Figure 7.15. Relative levels of nitrate-N vs. corn N uptake soil in corn fields with different management systems (R.H. Fox, Penn State University, unpublished data).



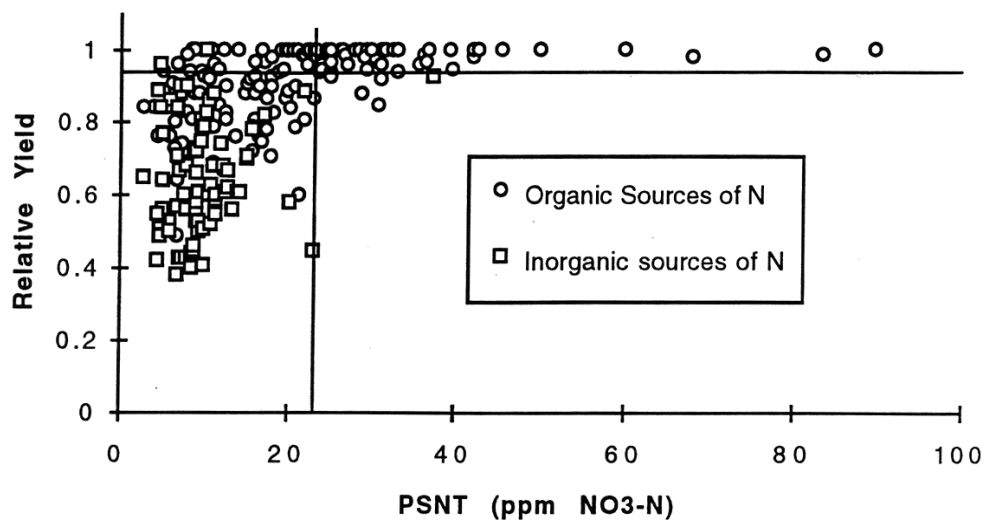
The Pre-sidedress Soil Nitrate test

An approach to N soil testing called the *Pre-sidedress Soil Nitrate Test* (PSNT), which involves soil sampling during the growing season, has been successfully implemented in the Mid-Atlantic region. The PSNT involves taking 12 inch deep soil samples just before sidedressing (after the spring wet period but before the period of major N demand by corn) and determining the amount of NO_3^--N in this soil sample. At this point in the season, the NO_3^--N level in the soil is the result of the integration of many factors that influence the soil N transformation from organic forms to NH_4^+ to NO_3^- and has been found to be related to the soil's nitrogen supplying capability over the growing season. The results of the test provide an index of N availability for corn production and are used to make sidedress N recommendations.

Calibration research with the PSNT has resulted in a remarkable consistency in critical levels used to interpret this test. Most critical levels from Vermont to Iowa have fallen between 20 and 25 ppm NO_3^--N. Data from field research experiments conducted in Pennsylvania, Maryland, and Delaware with the PSNT (Figure 7.16) indicated that the NO_3^--N level from this test was very good for identifying soils where there would be no yield increase from fertilizing with N (a relative yield near 1 in Figure 7.16).

The vertical line in Figure 7.16 at 21 ppm soil NO_3^--N is the **critical level** for the PSNT that separates the sites where additional N is needed for maximum yield from those where there is no yield increase when N is added. Almost all the sites with soil NO_3^--N levels above this critical level did not respond to added N.

Figure 7.16. Pre-sidedress Soil Nitrate Test calibration data from Pennsylvania, Maryland, and Delaware combined (Fox et al., 1992).



In most states, the PSNT is primarily recommended for use on fields where there are significant organic N contributions such as a history of manure, biosolids applications, or forage legumes in rotation (these are represented by open circles in Figure 7.16). In the past, these fields have been the most difficult sites for which to determine a sound N recommendation. The PSNT is of limited value on most fields without organic N contributions (represented by squares in figure 7.16), because these sites generally have low N levels where the standard recommendations are usually adequate.

The **best use of the PSNT** is to confirm the adequacy of N to meet the needs of a corn crop on sites where it is expected that applied and residual manure nitrogen should be adequate. If the estimate of N available from the manure is found to be inadequate, there is still time to make a sidedress application of N fertilizer. Thus, this test can reduce some of the uncertainty associated with utilizing manure N to meet the needs of a corn crop and also reduce the use of unnecessary fertilization.

Be sure to follow the specific PSNT procedure for your state. References for procedures for several Mid-Atlantic states are listed below.

- **Maryland**:
Making Decisions for N Fertilization of Corn Using the Pre-Sidedress Soil Nitrate Test (PSNT) (Coale et al., 1996):
http://www.agnr.umd.edu/users/agron/nutrient/Pubs/SFM-2.pdf

- **Pennsylvania**: Pre-Sidedress Soil Nitrate Test for Corn (Beegle et al, 1999):
http://cropsoil.psu.edu/Extension/Facts/agfact17.pdf

- **Virginia**:
Nitrogen Soil Testing for Corn in Virginia (Evanylo et al., 1998):
http://www.ext.vt.edu/pubs/rowcrop/418-016/418-016.html

Test-based recommen-dations for N

Below the critical level, the PSNT can give some guidance for adjusting N recommendations. However, there is considerable scatter in the data below the critical level (Figure 7.16). It is generally agreed that no sidedress N should be recommended when the soil test value is above the critical level. When the test level is below the critical level, there are several general approaches to making recommendations:

- In the first approach, if the test value is below the critical level, the full rate of N is recommended.

- A second approach is to fall back on traditional methods of adjusting N recommendations based on field history, manure applications, previous

legumes, etc. to make an adjusted recommendation when the test value is below the critical level.

- The third approach is to use the test value as a guide for adjusting recommendations when the test is below the critical level.

- A final approach is a combination approach which uses the test value in combination with some of the traditional factors to come up with a recommendation.

Again, it is important to follow the recommendation procedure developed for your state.

Chlorophyll meter N test

An alternative to the PSNT soil test used in some states is the chlorophyll meter test. Instead of taking a soil sample, a chlorophyll meter (Minolta Spad Meter) is used to estimate the N status of the corn plants. The basic principle of this test is the same as the PSNT in that this is an in-season assessment of N status that can be used to estimate corn response to N and help improve sidedress N recommendations. Research in Pennsylvania has shown that the accuracy of the chlorophyll meter test is similar to the PSNT for predicting response to N.

This test has not been adopted in all states in the Mid-Atlantic region. Check with your local cooperative extension service to see if this test has been adopted in your state and for the specific procedures to be followed.

Figure 7.20. Chlorophyll meter nitrogen test.

The chlorophyll meter readings are taken by placing the sensor of the chlorophyll meter on the fifth leaf of the plant about 3/4 of the way towards the outside of the leaf and midway between the edge and the midrib, when the corn is at the 6 leaf stage of growth. The meter will take the reading, display the results, and keep a running average of the results. Usually, readings are

taken on 20-30 plants randomly selected across a field. After the readings are taken, the results can be averaged, and this average used to make a recommendation. The advantage of this procedure is that the results are instantaneous and there are no samples to process or analyze. The meter is relatively expensive (~$1,500) but, when compared to the labor and analysis costs for the PSNT, it can be very cost effective.

The chlorophyll meter measures the "greenness" of the corn leaf, which is correlated to the N status of the plant. One problem with this method is that other factors can affect the "greenness" of the plant, such as hybrid differences and weather. Several approaches have been developed to compensate for this problem.

The most common approach is to establish a small high N reference area early in the season in fields to be tested with the chlorophyll meter. When it is time to run the test (6 leaf stage), readings are taken in both the high N reference area and the rest of the field. Interpretations are made by comparing the results of these two readings. This method normalizes many of the non-N-related influences.

An alternative procedure for the high N reference area approach involves taking multiple readings in a field with time. In this procedure, readings are taken at the 6 leaf stage. Based on this reading, recommendations can be made for fields that test very high or very low. Fields that do not test very high or very low are then tested again in 4-7 days. This second reading is used to make recommendations for this second group of fields. This method seems to be more practical for consultants to use than the high N reference area method.

Late Season Stalk Nitrate Test

A final N testing procedure used in the Mid-Atlantic region is the *Late Season Stalk Nitrate Test*. The Late Season Corn Stalk Nitrate Test has been shown to be a reliable end of season indicator of crop N status. It provides a good assessment of whether the crop had the right amount of N, too much N, or not enough N. This information, combined with records of N management, can be very useful for making future management decisions. Testing a few representative fields will probably be adequate to provide a good assessment of your N program.

The stalk nitrate test is performed anytime between ¼ milkline, which is just before silage harvest, to about 3 weeks after black layer formation. To collect a sample, cut 8-inch long sections of corn stalk (subsequently cut into two inch long segments) starting 6 inches above the ground. If possible, dry the samples immediately or send them to the lab as soon as possible after collection. If more than a day will pass between sampling and sending, refrigerate (don't freeze) the samples until you can send them to the lab. Keep

the samples in paper (not plastic) bags. The results of the nitrate analysis on these samples will indicate if the crop had adequate, deficient, or excess N. This information can be used to adjust future N management.

Assessing soil P levels for environmental management

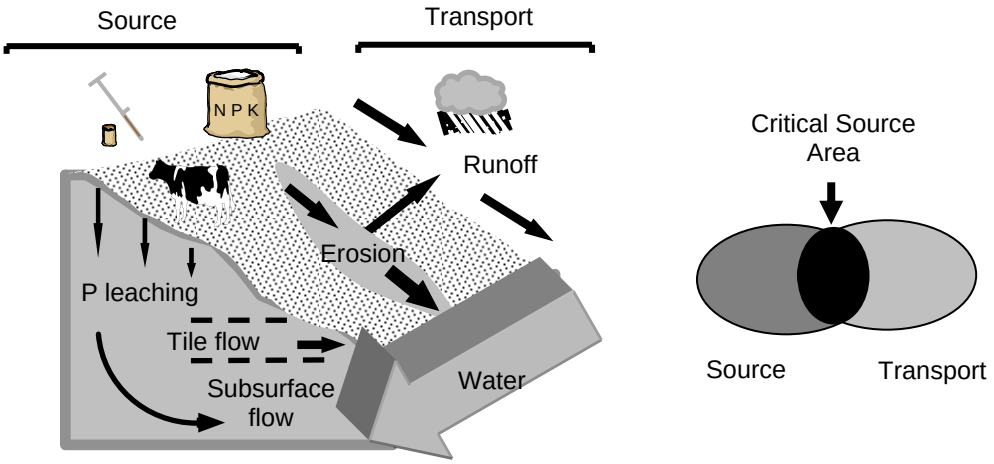
The critical source area approach

As noted earlier in the chapter, soil testing for environmental protection is becoming more important. While it has been shown that soil test levels for P are related to P loss, many other factors also play important roles in determining P loss from a given field.

The most common approach to managing P in order to minimize environmental impact is the *critical source area approach* (Figure 7.17). This approach is based on integrating site specific information on sources of P (soil, fertilizer, manure, etc.) and on transport mechanisms (erosion, runoff, leaching, distance to water, etc.) to delineate areas on a landscape that have a high risk for P loss. These critical source areas are areas where a high source of P and a high potential for transport overlap. Once these areas are identified, management can be focused where it will have the greatest impact on protecting water quality.

This targeting provides maximum management flexibility for the whole farm because only a small proportion of most farms will be designated as critical source areas. For example, research in an agricultural watershed in Pennsylvania showed that 90% of the P that was getting into the water came from just 10% of the watershed. This 10% of the watershed was the critical source area. The other 90% of the watershed did not require special P management.

Figure 7.17. Critical source areas are locations where a high source of P coincides with high potential for transport of the P.



The Phosphorus Index

The Phosphorus Index (or P Index) is a tool that can be used on a farm to estimate the relative risk of P loss based on site characteristics and management. A P Index value is established by evaluating source and transport factors to determine the risk of P loss to the environment. The Pennsylvania P Index shown in Figure 7.18 is an example. The P Index evaluations used by other states in the region are very similar (Coale, 2005; Mullins et al., 2005; Sims and Leyten, 2002).

If a site has a “Low” P Index value, no specific management modifications beyond standard best management practices are required to address P. If the P Index is “High,” however, the amount of P that can be applied is limited, usually to the amount of P that will be removed by crops. If the P Index is “Very High,” no P can be applied.

One of the strengths of the P Index is that it provides options for managing P to protect the environment. If the P Index is “High,” one option is to restrict P application, but an analysis of the P Index to determine what factors gave the high result may suggest other management practices that could protect the environment without restricting P applications. For example, if erosion is high, then adopting improved erosion control practices may reduce the risk of P loss and thus, allow P applications.

Figure 7.18. The Pennsylvania Phosphorus Index (Beegle et al., 2003).

PART A: Screening Tool

User's Note: If a field has a soil test level greater than 200 ppm Mehlich-3 P or is within 150 feet of a water body, then continue with Part B.

Field ID	
Soil Test Mehlich-3 P	Greater than 200 ppm P
Contributing Distance	Less than 150 ft.

PART B: Source Factors

Soil Test	Soil Test P (ppm Mehlich-3 P)				
Soil Test Rating = 0.20 x Soil Test P (ppm Mehlich-3 P)					
Fertilizer Rate	Fertilizer P (lb P_2O_5/acre)				
Fertilizer Application Method	0.2 Placed or injected 2" or more deep	0.4 Incorporated in less than 1 week	0.6 Incorporated after 1 week or not incorporated April to October	0.8 Incorporated after 1 week or not incorporated November to March	1.0 Surface applied during frozen or snow-covered conditions
Fertilizer Rating = Fertilizer Rate x Fertilizer Application Method					
Manure Rate	Manure P (lb P_2O_5/acre)				
Manure Application Method	0.2 Placed or injected 2" or more deep	0.4 Incorporated in less than 1 week	0.6 Incorporated after 1 week or not incorporated April to October	0.8 Incorporated after 1 week or not incorporated November to March	1.0 Surface applied during frozen or snow-covered conditions
Manure P Availability	Refer to Table 1: Organic Phosphorus Source Availability Coefficients				
Manure Rating = Manure Rate x Manure Application Method x Manure P Availability					
Source Factor = Soil Test Rating + Fertilizer Rating + Manure Rating					

PART B: Transport Factors

Erosion	Soil Loss (ton/acre/year)				
Runoff Potential	0 Very Low	2 Low	4 Medium	6 High	8 Very High
Subsurface Drainage	0 None		1 Random		2** Patterned
Contributing Distance	0 > 500 ft.	2 500 to 350 ft.	4 350 to 250 ft.	6 150 to 250 ft.	8 < 150 ft.
Transport Sum = Erosion + Runoff Potential + Subsurface Drainage + Contributing Distance					
Modified Connectivity	0.7 Riparian Buffer *Applies to distances < 150 ft.*		1.0 Grassed Waterway OR None		1.1 Direct Connection *Applies to distances > 150 ft.*
Transport Factor = Transport Sum x Modified Connectivity / 22					

Phosphorus Index Value = 2 x Source Factor x Transport Factor

**Or a rapidly permeable soil near a stream

Using the P Index in nutrient management planning

The P Index is important in the nutrient management planning process. Most nutrient management plans are based initially on balancing the crop N requirements with manure N. As the plan is developed these N- based rates and management must be evaluated with the P Index.

If the P Index for the N based plan is “Low,” no additional P- based management is required. However, if the P Index is “High” or “Very High,” the N- based plan will have to be modified to address this risk of P loss either by restricting or eliminating P applications or by changing management to reduce the potential for P loss.

Plant analysis

Purpose of plant analysis

Plant analysis is the laboratory determination of elemental composition of a sample of plant tissue. This technique is most commonly used to diagnose nutritional problems related to soil fertility or to monitor the effectiveness of fertilizer practices on growing crops. Plant analysis is not a substitute for soil testing and is most effective when used in conjunction with a regular soil testing program.

Elements analyzed

The number of elements measured will depend on the laboratory analyzing the samples. The most common elements analyzed in plant tissue samples are:

- Nitrogen (N)
- Phosphorus (P)
- Potassium (K)
- Calcium (Ca)
- Magnesium (Mg)
- Iron (Fe)
- Manganese (Mn)
- Boron (B)
- Copper (Cu)
- Zinc (Zn)
- Aluminum (Al)

Other elements that may be measured either routinely or upon request include:

- Sulfur (S)

- Sodium (Na)
- Molybdenum (Mo)
- Cobalt (Co)
- Silicon (Si)
- Cadmium (Cd)
- Nickel (Ni)
- Lead (Pb)
- Chromium (Cr)
- Arsenic (As)
- Selenium (Se)

Although some of these elements are not essential for plant growth, the results may be used to identify elemental toxicities.

Sampling plant tissue for elemental analysis

Sampling in different situations

In order for plant analysis to be effective, considerable care must be given to collecting, preparing, and sending plant tissue to the laboratory for analysis. The sampling procedure will vary depending on the situation.

- For **routine monitoring of crop nutritional status,** very specific plant sampling instructions must be followed so that the results can be properly interpreted. The exact instructions for sampling will depend on the published values that will be used for interpretation.

- For **diagnosing nutritional problems**, sampling is usually guided by the plant symptoms. Two samples should be collected: one from plants showing the symptoms and one from nearby non-symptomatic plants growing under the same conditions as the symptomatic plant.

When and what to sample

Proper sampling for a particular crop requires that a specific plant part be taken, such as a particular leaf, group of leaves, or portion of the plant. Instructions will also include the number of individual parts to sample, as well as the number of plants. This procedure will ensure that a sufficient quantity of plant tissue is submitted for analysis and that the collected sample is statistically representative of the area sampled.

Plant nutrient concentrations vary with position within the plant. For mobile nutrients like N, P, and K, concentrations will usually be lower in the bottom of the plant as the plant approaches deficiency. For immobile nutrients, concentrations will be lowest in the new growth as the plant approaches

deficiency. Follow the sampling instructions from the lab or person that will be interpreting the results of the analysis as closely as possible.

When no specific sampling instructions are given for a particular crop, the general rule of thumb is to sample the uppermost recently mature leaves. Young emerging leaves, older mature leaves, or seed are not usually suitable plant tissues for analysis because they do not reflect the general nutrient status of the whole plant.

For many plants, the recommended time to sample is just prior to the beginning of the reproductive stage. However, sampling earlier or even later than that may be recommended for specific plants or circumstances. Plant nutrient concentrations change throughout the life of the plant. For example, the P concentration in a healthy seedling corn plant is approximately twice the concentration found in the same plant at the reproductive stage. Thus, it is critical to follow the recommendations for time of sampling.

When sampling, do not include diseased or dead plant material in a sample. Do not sample plants or leaf tissue that has been damaged by insects, mechanically injured, or stressed extensively by cold, heat, or moisture deficiency/excess. Remove the roots from whole plant samples. Examine the roots. The presence of nematodes, insect damage, or disease damage could preclude the need to sample.

Multiple sampling for diagnosing nutritional problems

When a nutrient deficiency is suspected at a time other than a time recommended for routine sampling, collect two sets of samples: one from plants showing symptoms and one from normal plants growing in the immediate or adjacent areas. Take care to ensure that the two sets of plants are at approximately the same stage of growth and have been grown under the same conditions. Comparative analyses are questionable when the two sets of plants are not at the same stage of growth, have not received the same treatment, or are not the same variety or hybrid.

The best **time** to sample plants that are showing a suspected nutrient deficiency symptom is when, or shortly after, the visual symptoms appear. The best **plant part** to sample is the uppermost recently mature leaves. Be sure to take the same plant part in both samples. The plant showing the deficiency may be of different size, or at a different growth stage, than the non-affected plant, so it may be necessary to count leaves or nodes to ensure that the sample is collected from the same position on the both plants.

Interpreting plant analysis data

Introduction

Plant analysis is an effective management strategy for a sustainable soil fertility program because it provides a direct measure of nutrient concentrations and of nutrient balance within the plant. Principles and procedures used for plant analyses have evolved over many years as knowledge has increased about each essential element. The use of plant analyses has become an integral part of most agronomic research and is used as a tool for crop consultants and fertilizer dealers to monitor production fields.

Plant analysis data can be interpreted using several techniques, which include:

- *critical levels* or *sufficiency ranges*
- *total nutrient accumulation*
- *nutrient use efficiencies*

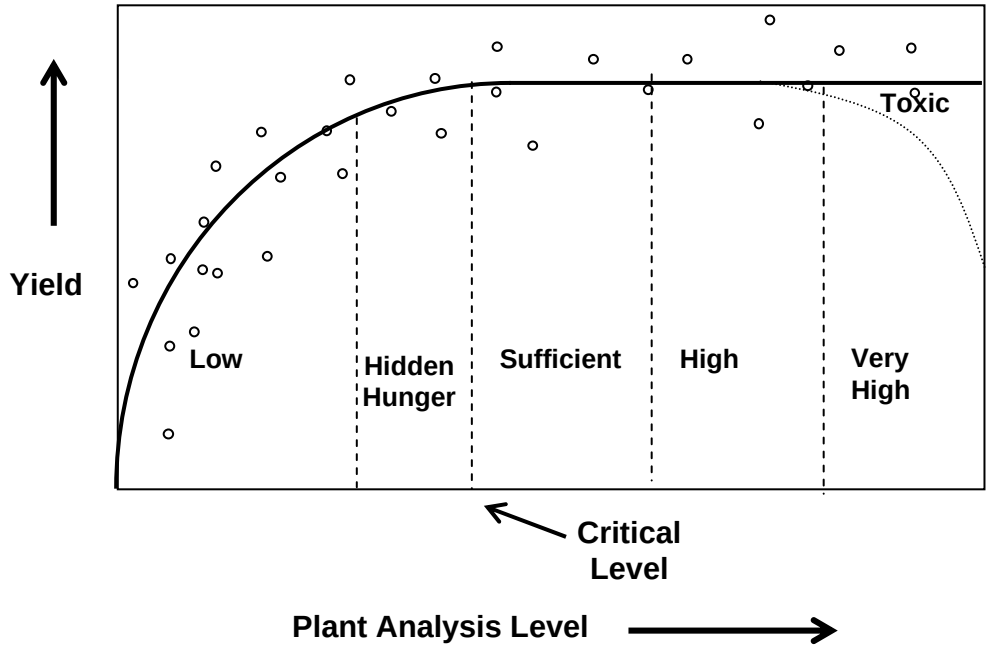
Critical levels and sufficiency ranges

The most common approach is to interpret plant analysis based on *critical levels* (also called *critical values* or *standard values*). This concept is the same as the critical level in soil testing. The critical level is determined by research plot calibration in the same way as for soil testing.

A critical level is that concentration below which deficiency occurs (Figure 7.19). A *sufficiency range*, which is similar to the optimum soil test range, is also designated. A plant analysis value in the sufficiency range indicates that the nutrient level is neither limiting nor too high. The effects of sampling time, variety, or hybrid, and environmental factors, such as soil moisture, temperature, and light quality and intensity may significantly affect the relationship between nutrient concentration and plant response. Thus, a defined sufficiency range may not apply to all situations or environments.

An additional category in tissue analysis is the "*Hidden Hunger*" category. This occurs where the plant is suffering from a deficiency of a nutrient that is causing reduced yield and/or quality but is not severe enough to cause clear deficiency symptoms. Plant analysis is very useful for finding hidden hunger in crops. In some situations, the levels of an element in a plant can be so high that they are toxic, so the interpretation may include a *"Toxic"* category.

Figure 7.19. Relationship between plant response (yield) and plant analysis level. This relationship is used to establish interpretation the categories for plant analysis.



Using plant analysis data to determine timing of nutrient addition, and nutrient use efficiency

Plant analysis is useful in optimizing the timing and rates of nutrient addition. Information gained though plant analysis can be used to anticipate times when high plant nutrient concentrations must be maintained for rapid uptake and assimilation, or times when nutrients may be more vulnerable to loss. This approach identifies periods of intra-seasonal variation in plant nutrient accumulation which can be used to schedule efficient, sustainable, fertilizer applications.

Plant analysis data is used to determine relative *nutrient use efficiency* (NUE) for crop and soil management practices. If total dry matter and plant nutrient concentrations are measured, nutrient use efficiency values can be determined by dividing these values by the amount of fertilizer applied or the amount of nutrient available in the soil. These efficiency values may be used to determine the recovery of applied fertilizer and the uptake of residual nutrients.

Using plant analysis data with soil test results

Whenever possible, plant analyses should be interpreted in conjunction with a soil test from the same area to determine the actual cause of a deficiency. For example, if the plant analysis is low in K and the soil test is low in K, the interpretation is simple. The soil is deficient in K and the addition of K is necessary to correct this deficiency. In this case, either test would have

provided the information needed to make an appropriate management decision.

However, if the plant analysis is low in K but the soil is optimum or high in K, the problem is due to the inability of the plant to take up soil K, rather than a deficiency in soil K. Thus, adding more K will not likely solve the problem. Possible causes may be restricted root growth from compaction or acidity, root diseases, or root injury from herbicides or fertilizer. Either a soil test or plant analysis alone would not provide this information.

References cited

Beegle, D., W. Gburek, P. Kleinman, A. Sharpley, and J. Weld. 2003. The Pennsylvania phosphorus index. Penn State Agricultural Research and Cooperative Extension. Available on-line at: http://panutrientmgmt.cas.psu.edu/pdf/phosphorus_index_factsheet.pdf

Beegle, D., R. Fox, G. Roth, and W. Piekielek. 1999. Pre-sidedress soil nitrate test for corn. Penn State Cooperative Extension. Agronomy Facts 17. Available on-line at: http://cropsoil.psu.edu/Extension/Facts/agfact17.pdf

Coale, F.J. 2005. The Maryland phosphorus site index: an overview. Maryland Cooperative Extension SFM-6. Available on-line at: www.agnr.umd.edu/MCE/Publications/PDFs/SFM6.pdf

Coale, F.J., J.J. Meisinger, P.M. Steinhilber, and P. Shipley. 1996. Making decisions for N fertilization of corn using the pre-sidedress soil nitrate test (PSNT). Maryland Cooperative Extension SFM-2. Available on-line at: http://www.agnr.umd.edu/users/agron/nutrient/ Resources/Pubs/SFM-2.pdf

Evanylo, G.K., and M.M. Alley. 1998. Nitrogen soil testing for corn in Virginia. Virginia Tech Cooperative Extension. Available on-line at: http://www.ext.vt.edu/pubs/rowcrop/418-016/418-016.html.

Fox R.H., J.J. Meisinger, J.T. Sims, and W.P. Piekielek. 1992. Predicting N fertilizer needs for corn in humid regions: Advances in the Mid-Atlantic states. *In* B.R. Bock (ed.) Predicting N fertilizer needs for corn in humid regions. Natl. Fert. Environ. Res. Ctr., TVA, Muscle Shoals, AL.

Mullins, G., M.L. Wolfe, J. Pease, L. Zelazny, W.L. Daniels, M. Beck, M. Brosius, A. Vincent, and D. Johns. 2005. Virginia phosphorus index, version 1.3. Virginia Polytechnic Institute and State University. Available on-line at: http://p-index.agecon.vt.edu/

Sharpley, A. N., R.W. McDowell, J.L. Weld, and P.J.A. Kleinman. 2001. Assessing site vulnerability to phosphorus loss in an agricultural watershed. J. Environ. Qual. 30:2026-2036.

Sims, J.T., and A.B. Leyten. 2002. The phosphorus index: a phosphorus management strategy for Delaware's agricultural soils. Delaware Cooperative Extension Service Fact Sheet ST-05.