

## ISSUE PAPER

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# RELEVANCE OF SOIL TESTING TO AGRICULTURE AND THE ENVIRONMENT

## Summary

Soil tests are widely used to predict the probability of crop responses to application of fertilizers, particularly phosphorus (P), potassium (K), and in some instances manganese (Mn), copper (Cu), zinc (Zn), and iron (Fe) and application of lime. Soil-test levels at which no response is obtained are defined as critical soil-test levels that have been determined by greenhouse and field experiments. The commonly used soil-test extractants for P in the United States are the Bray-1 (Midwest), Mehlich 1 and 3 extractants (southeastern United States), and the Olsen extractant (calcareous soils). The Mehlich 3 extractant is being used by many laboratories because it is suitable for measuring soil-test P over a wide range of soil properties and also is a multi-element extractant.

Because nitrogen (N) can be a very mobile element, most laboratories do not routinely run a N soil test. Nitrogen recommendations are made on the basis of yield goals for a given crop. Where

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nitrate-leaching potential is at a minimum, the amount of residual nitrate in the soil profile before planting has been related to the need for fertilizer N. In certain humid regions, nitrate levels of the soil have been measured before N side dressing of corn, and the values interpreted as to the amount of fertilizer N to apply.

There is interest at present as to whether soil tests can be used to determine if application of fertilizers and/or waste materials will result in pollution of surface and ground waters. Using soil testing to identify the potential for an environmental impact may have value, but only if a comprehensive approach is taken. Response parameters for other uses of soil testing have not been so well defined, and linkages often remain intuitive or based on the best professional judgment of a team of scientists. Although agronomic responses have been used as surrogates for other secondary effects, including water-quality degradation, this approach is conservative and does not consider adequately the existence of in-

field soil processes, multiple loss-pathways, and nutrient retaining processes beyond the field's edge and in streams. Progress in soil testing is facilitating assessment of soils likely to act as sources of nutrients for surface and ground water. Extractable soil concentrations of nutrients (or of nonessential elements, organics, etc.) are only a few of the many factors, including transport phenomena, management practice effects, and adjacent water sensitivity to an increase in nutrient concentration that must be considered in determination of an appropriate loading rate for nutrient sources potentially affecting water quality.

### INTRODUCTION

In the late 1940s, soil testing became an important practice for determining the need for lime and fertilizer in the United States. This change was brought about by several factors. Mechanization led to increased farm size; and the large-scale use of synthetic N fertilizers led to increased crop yields. As crop nutrient removal increased with these higher yields, soil reserves of certain plant nutrients, particularly P and K, began to be depleted, resulting in nutrient deficiencies and lower yields. In response to these problems, there was a concerted effort to develop soil-testing methods that could identify P and K deficiencies in different regions of the United States. These initial efforts later were expanded to include soil tests for other plant nutrients, such as calcium (Ca), magnesium (Mg), boron (B), sulfur (S), Cu, Fe, Mn, molybdenum (Mo), and Zn. Soil testing now is widely accepted as a valuable tool that can be used to identify the economically optimum rates of nutrients required by most crops.

New uses for soil testing are being proposed, with much of this new interest directed toward environmental applications of soil-testing methods. One important issue involves the use of soil tests to determine application rates of waste materials so the environment will not be harmed. Although research has demonstrated numerous benefits of using by-products as soil amendments, a number of problems also have been identified. There is concern that waste applications based on rates needed to meet crop N requirements (a longstanding practice in the United States and much of the world)

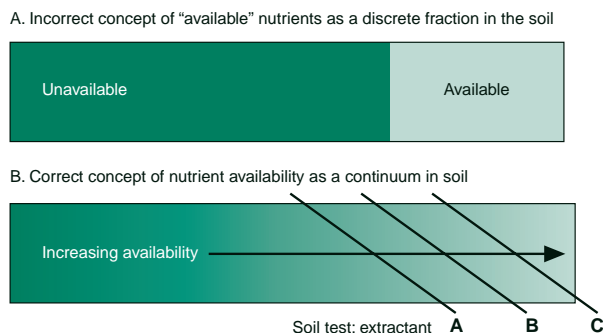
may result in the buildup of certain nutrients, particularly P, Cu, Zn, and potentially arsenic (As), cadmium (Cd), nickel (Ni), lead (Pb), mercury (Hg), and selenium (Se). The potential buildup of these elements in soils has raised questions about the long-term effects on the environment. New nutrient management regulations are being developed to address land application of waste materials. In these proposed regulations, soil tests are being considered as tools with which to determine environmentally sound limitations of application rates of certain elements. This raises questions as to the suitability of commonly determined soil tests for environmental interpretations. Because the heavy metals, As, Pb, Hg, and Cd, are not determined by most soil-testing laboratories, they are not covered in this paper.

This paper addresses the following key issues: (1) What do soil-test results mean, and how can they be used to determine economically optimum nutrient application rates for crop production? (2) Are soil-test methodologies used by different laboratories comparable to each other? (3) Do soil sampling and handling methods for agronomic purposes differ from those used for environmental purposes? (4) Can conventional soil tests alone be used to determine the appropriate application rate for agricultural, municipal, and industrial by-products; if not, what other factors must be considered as we develop profitable and environmentally sound recommendations for the beneficial use of these materials?

### THE MEANING OF SOIL-TEST RESULTS

#### Agronomic Interpretations

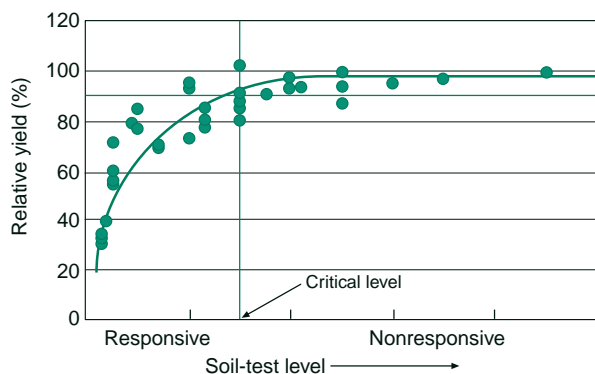
Soil tests are most commonly used to predict the likelihood of crop-yield responses to inputs of fertilizers and lime. There now is interest in extending the use of soil testing to assess the potential impact of soils and soil amendments on other sectors of the environment. Interpreting the quantitative results of a soil test requires that we understand many factors, including the soil-test extractant used; the methods of soil sampling, handling, and storage; and the intended use of the soil. A common misconception is that soil-test solutions extract the exact amount of plant available nutri-



**Figure 1. Concepts and relationships between available nutrients and soil test extractions.**

ents (Figure 1A). Rather, soil-test procedures sample this continuum by extracting different amounts depending on the extractant. For example, soil-test A in Figure 1B would extract a greater amount than soil-test C would on the same soil. The extractant used will depend on soil properties (pH, organic matter content, cation exchange capacity, etc.), and the overall purpose of soil testing (agronomic vs. environmental; measurement of total vs. soluble vs. plant available; element concentration; and others).

When characterizing soil fertility, the amount of nutrients extracted by a soil test must be shown to be well correlated with plant nutrient uptake by plants for the test to be useful. Greenhouse and field research is conducted to determine which particular soil-test extractant is best suited for a given combination of soil, crop, and growing conditions. Accurate interpretation of a soil test and recommendations based on test results require that



**Figure 2. Relative yield vs. soil-test level showing the crop response curve and graphical separation of the data into populations of soils where crops would be responsive and nonresponsive to the addition of the nutrient tested.**

the relationship between the amount of a nutrient extracted by a given soil-test and the expected crop response to the added nutrient for each crop must be known. The process of determining the degree of crop growth limitation, or the probability of growth response to an applied nutrient at a given soil-test level, is known as *soil-test calibration* and must be determined experimentally in the field. A common procedure for calibrating a soil test is to grow a range of crops in soils representative of those on which the test will be used. These experiments quantify the relationships between crop yield and the amount of nutrient extracted by the soil test (Figure 2).

Although the specific relationships between soil-test levels of nutrients and crop yields (or relative yields) can differ, the general nature of the relationships is fairly consistent (Figure 2). At low levels of soil-test extractable nutrients, crop yield is limited by nutrient deficiency. As soil-test level increases, yield increases until the nutrient is no longer limiting and yield response to inputs of the nutrient ceases. At this point, there is no longer a relationship between the soil-test extractable amount of nutrient and yield. At very high soil-test levels, yield may actually decline. The point at which the curve initially levels off is called the soil-test *critical level* (Figure 2). This is the soil-test level that produces the best separation between (1) soils where a positive yield response to an added nutrient for a given crop can be expected with a high degree of probability and (2) those where nutrient inputs cannot realistically be expected to improve crop yields. The soil-test response curve often is used to divide soil-test levels into several categories such as low, optimal, and high.

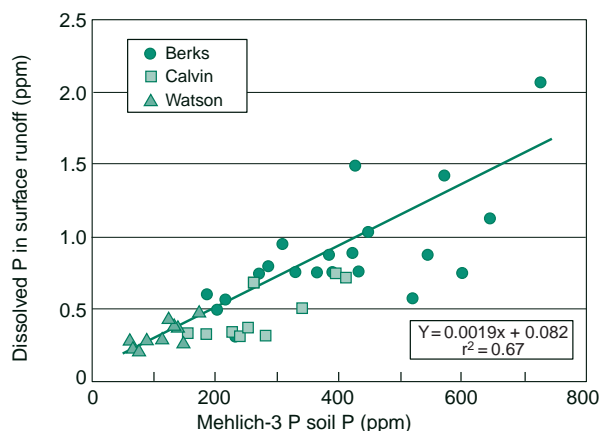
Several issues must be addressed to clarify the implications of interpreting soil-test results. As described, a clear relationship usually exists between soil-test nutrient level and crop production, but many other factors also influence crop growth. These factors may affect the crop independently or may interact with soil nutrient levels. A thorough understanding of crop response to nutrients and other factors such as sampling method, e.g., depth or spatial pattern; nutrient forms, e.g., fertilizer or manure; method of nutrient application, e.g., band

or broadcast; and application timing is needed to facilitate interpretation of soil-test results.

It also is important to recognize that in some instances soil-test nutrient levels cannot be calibrated easily with crop response. This problem typically occurs with nutrients that are quite mobile in soils or whose soil concentrations are influenced markedly by environmental factors, such as soil temperature and moisture, that change during the growing season. Examples include nitrate-N, sulfur, and B, for which more complex soil-testing methods, such as the use of subsoil testing or soil testing during the growing season, are needed. In arid irrigated regions, deep soil-tests conducted before planting may be used to estimate available N, because leaching is not a major loss pathway. In warm humid regions, soil N tests have proved unreliable, for N reacts very weakly with the soil, and concentrations are subject to rapid change with every rainfall. In colder climates, where soils remain frozen throughout much of the winter and much of the total soil N is present in organic forms, soil tests taken shortly after planting have proved useful in estimating the amount of N available to crops. Thus, interpretation of soil-test results must be based on knowledge of local conditions. Tests proven to work in one area cannot always be used successfully in another.

### Environmental Interpretations

The same process used for agronomic interpretation must be followed to clarify the meaning of a soil test for environmental purposes. First, it must be asked whether routine soil-test extractants designed to assess plant availability of a nutrient measure the nutrient forms most important to eutrophication, i.e., nutrient enrichment, or other negative environmental impacts. Current research indicates that in many instances there is a useful relationship between routine soil-test extractants and, for example, soluble P in runoff. If the soil test is appropriate, what should the basis be for interpreting results for environmental purposes? Simply extending the interpretive process to state that the buildup of nutrient concentrations in a soil to values above those needed for crop production will result in environmentally significant nutrient losses in runoff ignores many important aspects of



**Figure 3.** The relationship between surface soil (0 to 5 cm) Mehlich-3 extractable soil P and the concentration of dissolved P in surface runoff from several soils in Northumberland Co., Pennsylvania (Weld et al. 2000).

nonpoint source pollution. If soil tests are to be interpreted to predict the probability of nutrient pollution, calibrations relating the soil test to some specific measure of environmental response, such as the concentration or load of P in runoff waters, will be necessary (Figure 3).

For several reasons, calibration and interpretation of a soil test to reflect environmental impact potential is more complex than for crop yield response. Establishment of nutrient loads that can result in unacceptable water-quality degradation will depend on many factors, including the proximity of a nutrient-sensitive water body, the use of that water, and the socioeconomic factors of rural land use. A critical soil-test level for nutrient pollution is unlikely to be found. An integrated approach incorporating many other site-specific factors will be needed in interpretations of soil tests for environmental pollution potential.

Not all areas on a landscape contribute equally to nutrient loss. For loss to occur, both a source of the nutrient and a mechanism for transporting it to surface or ground water are needed. A key concept in effective management of nutrient pollution is to focus on the critical areas in which these two factors overlap. The Phosphorus Index (P-Index) is an example of a tool being developed to use soil tests and other site-specific factors (hydrology, nutrient management, water body proximity and sensitivity to nutrient inputs) to delineate critical source areas of nutrient loss and to manage

them accordingly. The P- Index includes not only soil-test levels as a source of P but also fertilizer and manure application rates and methods as measures of other potential sources of P loss. The P-Index includes erosion, runoff, leaching, and proximity to sensitive water as transport factors. The ongoing national effort to develop a reliable P-Index system seems a more rational approach to addressing environmental concerns regarding nutrients in a way that is more economically and environmentally effective than proposals to limit nutrient applications based on soil-test levels alone. Notwithstanding this, soil testing will remain the foundation of any successful attempt to understand and control nutrient losses from soils.

### SOIL-TEST EXTRACTANTS AND METHODOLOGIES

Agronomic soil-test extractants were designed to (1) rapidly and accurately assess the available nutrient status and/or elemental toxicity in soils and (2) to provide a quantitative basis for recommendations of the rates of plant nutrients that should be added in fertilizers, manures, or other materials to achieve economically optimum crop yields. A primary requirement of any soil test for a nutrient is that the amount of nutrient extracted by the test must be correlated with some measure of crop response. Additional criteria of a successful soil test are that (1) it be fairly easy to perform to ensure rapid turn-around time; (2) it be cost-effective to promote wide usage; and (3) its results be reproducible.

In almost all areas of the United States, soils are tested routinely for pH and the primary plant nutrients P and K. In some regions of the United States, soils are also tested routinely for N, Ca, Mg, and some or all of the essential micronutrients, Zn, Cu, Fe, Mn, and B. While all of these nutrients are important from a soil fertility standpoint, P and N are of greatest importance in terms of environmental impact. Consequently, the following discussion will focus on these two nutrients.

#### Phosphorus Soil Tests

Soil tests for P have been developed based on an understanding of the chemical forms in which

P exists in the soil. In most soils, P is primarily associated with aluminum (Al), Fe, and Ca. Phosphorus adsorption to Fe and Al oxides generally predominates in acid (pH < 7.0) to neutral soils whereas precipitation and/or adsorption reactions of P with Ca occur in primarily *calcareous* soils, or those with greater than 2% calcium carbonate present. The relative importance of Al, Fe, and Ca for P retention in soils depends on geography and climate, with the influence of Fe and Al increasing and that of Ca decreasing as rainfall, temperature, and weathering increase (Fixen and Grove 1990). Degree and strength to which P is bound in soils are determined by the specific types of Fe, Al, and Ca compounds present and by other soil properties such as pH, organic matter, clay mineralogy, and the amount of P currently present in the soil.

Phosphorus soil-test procedures usually employ, either singly or in combination, dilute strong acids, dilute weak acids, complexing ions, and/or buffered alkaline solutions. Most P soil-tests have been developed to reflect the soil characteristics related to P sorption that predominate in different regions. Thus, the Bray P-1 test (Bray and Kurtz 1945) was developed for use in the acid-to-neutral soils in the North Central region, whereas the Olsen test (Olsen et al. 1954) was developed primarily for use on calcareous soils. In the South and Mid-Atlantic, the Mehlich 1 test was developed for the low-cation-exchange-capacity, highly weathered acidic soils common to this region (Mehlich 1953). The relationship between the amount of P extracted by these tests within a given region and crop response has been correlated and calibrated extensively, and reliable soil-tests for P now exist for the major physiographic regions of the United States. The Mehlich 3 test (Mehlich 1984) has shown promise as a soil test for P that is suitable for a much wider range of soil properties than the current, regionally-oriented soil P tests. Because of its flexibility in P testing, as well as the fact that it is a multi-element extract (i.e., used for P, K, Ca, Mg, B, Cu, Fe, Mn, S, and Zn), the Mehlich 3 test is used extensively throughout the United States. A summary of recommended P soil-tests developed for soils of the northeastern (Wolf and Beegle 1995), southern (Johnson 1984; Tucker 1992), north central (Frank, Beegle, and Denning 1998),

**Table 1. Recommended soil tests for P within U.S. geographic regions**

Soil Test Method	Soils for which test is appropriate	Region			
		Northeast	South	North Central	West
Mehlich 3 <sup>a</sup>	Acid and calcareous	+	+	+	
Mehlich 1 <sup>a</sup>	Acid to neutral	+	+		
Bray and Kurtz 1	Acid to neutral	+		+	+
Olsen's	Calcareous			+	+
Morgan or Modified Morgan's <sup>a</sup>	Acid to neutral	+			+

<sup>a</sup>Multi-element extract that can also be used to test for potassium, calcium, magnesium, and trace elements.

and western (Gavlak, Horneck, and Miller 1994) regions of the United States is presented in Table 1.

Although the results of the different soil-test methods are often highly correlated, the actual quantities extracted can differ and may not be comparable. For instance, the Mehlich 3 soil test usually extracts 1.5 to 2 times the amount of P as the Mehlich 1 soil test, but both are accurate predictors of the likelihood of crop response to applications of P. It should be emphasized that soil-test results cannot be interpreted alone but must be considered within the context of field calibrations that relate the soil-test value to crop response as influenced by soil type.

### Nitrogen Soil Tests

The behavior of N in soils is unique and requires a soil-testing approach different from that used to test for P and other soil nutrients. Over 97% of N in soils is present in an organic form that is converted to inorganic, plant-available forms of N through microbial activity. Challenges to developing an adequate soil test to predict N availability to plants are as follows: (1) the rate of N release from organic to inorganic forms is difficult to predict because it depends on temperature, moisture, aeration, organic matter type, pH, and other factors; and (2) the inorganic forms of N released from organic matter are subject to loss by leaching, fixation, and denitrification (Dahnke and Johnson 1990). Because of these factors, as well as the fact that naturally occurring levels of organic matter in the soil generally are insufficient to meet the N needs of most crops, N fertilizer recommendations frequently are made on the basis of yield goals of a given crop and N credits and not on the basis of soil testing.

Despite these shortcomings, there are some specific instances where testing soils for nitrate-N, the primary inorganic N form used by plants, is recommended. One of these instances is with soils in low-rainfall areas, such as the Great Plains, where nitrate leaching potential is minimal. Here, the quantity of residual nitrate-N measured in the soil profile before planting can be credited directly against the N needs of the crop (Gelderman and Beegle 1998).

The late spring soil test for nitrate-N has been used to determine the need for N application to corn in Iowa (Blackmer et al. 1991; Binford, Blackmer, and Cerrato 1991). Samples are collected from the surface foot of soil when the corn plants are 6 to 12 inches tall and extracted with 1 M KCl. Nitrate-N concentration of manured soils of 25 parts per million (ppm) in the surface foot of soil is considered optimal for corn and response to fertilizer N is not expected. For each ppm nitrate-N below the optimal level (25 ppm), 8 pounds of N/acre is suggested (Blackmer, Voss, and Mallarino 1997).

In humid regions, such as the northeastern United States, nitrate-N testing early in the growing season can provide an index of the soil N-supplying capability before N sidedressing of corn (Magdoff, Ross, and Amadon 1984; Magdoff et al. 1990). The critical nitrate-N concentrations suggested for the northeastern United States were in the range of 20 to 30 mg/kg of soil. These N tests use the same measurement, nitrate-N; but the interpretation and use of values may differ.

In the southeastern United States from North Carolina to east Texas, rainfall during late November to early March results in high percolation rates and leaching of any residual soil nitrate out of the root zone (Nelson and Uhland 1955). For this reason, nitrate soil tests to determine N-sidedressing

requirements for corn and cotton have not proven to be of much value in the southeastern United States.

### Quality of Soil Tests

The quality of soil-test results is evaluated on the basis of two components: bias and precision. *Bias* refers to the deviation of the analytical result from the true value and measures accuracy of the result. *Precision* refers to the reproducibility of a given test value. A soil-testing laboratory could have good precision for a specific test procedure, i.e., the lab could be able to reproduce the same number for a given test on a specific soil; but exhibit bias in its results, i.e., they could be significantly different from the true value. A primary means of evaluating soil-test quality procedures as well as laboratory performance is through comparison of laboratories performing the same test procedure on the same soil, as is currently done through the North American Proficiency Testing (NAPT) program for soil and plant analysis laboratories (Wolf and Miller 1998). Results from this program indicate that, for the P-test procedures listed in Table 1, average variability is on the order of 10 to 15%, and that 65% of participating U.S. laboratories produced results within this level of variability. These data suggest that, on average, a level of accuracy within 10 to 15% of the true value can be expected by a large percentage of U.S. laboratories performing the tests listed in Table 1. Within any given laboratory, variability is lower. Data from the NAPT program indicate that precision levels for the P tests discussed are on the order of 5 to 10% within each laboratory. Consequently, a user of any respected soil-testing laboratory could expect results on a specific sample to be reproducible to within approximately 5 to 10% of the mean laboratory value. Variability in test methodology is only one of the factors affecting variability of soil-test results for field samples. Another primary factor is soil sampling.

### SOIL SAMPLING

The object of soil sampling is to collect, in a cost-effective manner, a sample or set of samples

that accurately represent the properties of interest for the area of interest, e.g., a crop field. Sampling is a critical component of the soil-testing process because it usually represents the largest single source of error. A multitude of factors varying both spatially and temporally influence nutrient concentrations in soils. Sampling protocols must account for the great diversity in magnitude, structure, and spatial scale potentially present in agricultural fields and other ecosystems.

### Sources of Soil Nutrient Variability

Soil nutrient variability within a field may be due to soil formation factors or to management effects. Factors such as landscape position and soil parent material can cause great changes in soil texture, organic matter, drainage, and numerous other properties affecting nutrient levels directly or indirectly through their effect on crop yield potential and thus the cumulative nutrient removal by crops. These factors tend to be the dominant source of variability in regions with limited historical use of manures or fertilizers, e.g., the Great Plains of the United States. Variability caused by long-term history of management effects and land use practices overlays that associated with soil-formation factors. The cumulative effects of nonuniform manure or fertilizer application are sources of potentially extreme variability, especially for P. Old building sites, livestock confinement areas, feed storage areas, and field boundaries are additional examples of historical factors causing great variability in many of today's consolidated fields. Microscale variability may be due to residual fertilizer bands or localization of any of the factors already discussed. The object of sampling is to composite a sufficient number of properly collected cores (usually ten to twenty, depending on the size and variability of the area being sampled) to account for micro-scale variability.

Soil-test levels may change markedly with depth in the soil profile. This fact results from a combination of soil-forming and management factors and from the differential mobility of nutrients in soils. In contrast to movement by other nutrients, especially nitrate, retention of both P and K is high in most soils. Although P and K applied

with fertilizer and manure tend to build up in surface layers, tillage system and nutrient application method greatly affect the degree of vertical stratification. The marked stratification of both P and K in no-till soils is well known, but some degree of stratification occurs in all tillage systems.

Because nutrient concentrations in soils, and thus soil-test levels, are vertically stratified, the proper depth for soil sampling is an important consideration. Obviously, a soil test will yield different results depending on sampling depth. In general, soil samples usually should be collected at the same depth used in the calibration research that serves as the quantitative basis for the soil-test interpretation and nutrient recommendations. Typically, this is a depth of 6 to 8 inches for most nutrients (P, K, Ca, Mg, Cu, Fe, Mn, Zn). If the purpose of the soil test is not agronomic, such as using soil P testing to predict the amount of P that could be lost in erosion or runoff, a shallower sample may be suggested, e.g. 0 to 2 inches. If the goal is to determine if a nutrient (or nonessential element) is leaching downward in the soil profile, deeper soil samples, e.g., 0 to 60 inches in 4- or 8-inch increments, may be recommended. Extensive research is focusing on these issues today.

### Soil Sampling Approaches

There is no universally appropriate soil sampling approach. The structure and magnitude of within-field variability is site-specific, and the affordability of various approaches depends on crop value. The traditional sampling approach used in most regions of the country is to collect a single representative composite sample from a field. This sample usually consists of at least 20 cores, which are collected to avoid any areas of the field expected to differ from most of the remaining field. This approach is especially effective where within-field structured variability is limited. When conducted following local guidelines, soil tests should gather data within 15% of the field average 80% of the time (Franzen and Cihacek 1998).

The development of accurate and reliable global positioning technology, yield monitors, affordable geographic information systems, and variable-rate application equipment has led to wider use of

site-specific soil sampling approaches. These sampling approaches typically are used to generate a soil fertility map to serve as input to variable-rate application equipment for applying varying rates of one or more materials. One such approach is *zone sampling*, whereby field subregions with more homogeneous properties than the field as a whole and for which a unique set of input rates have been determined. Landscape position, soil color, soil mapping unit, and crop growth differences are examples of factors often used to help define management zones.

Another site-specific approach is *grid sampling*, where soil-test patterns in a field are determined by means of dense, systematic sample collection. A grid size of 2.5 acres is most common today although sizes range from 1 to 4 acres. Much of the research has indicated that grid-point size should be no larger than 1 acre, but farmers often use larger grid points for economic reasons. Microvariability is so extreme in some fields that accurate within-field soil fertility mapping is impossible. Much uncertainty still exists regarding how to best perform site-specific soil sampling and generate accurate soil fertility maps.

### USE OF SOIL TESTS TO DETERMINE LOADING RATES

Soil testing is an established practice used to determine the probability of an economic crop response to applications of fertilizers, animal manures, municipal biosolids, and other soil amendments, e.g., lime. Recently, interest has grown in the use of soil testing, or historical soil-test data, to determine whether environmentally unacceptable conditions are present in soils or are likely to occur should soils be amended further with these types of materials. The term *loading rate* implies that when excessive or inadequate amounts of an element are applied to soils when crops are fertilized or amended with agricultural, industrial, or municipal by-products, the result will be negative. Using soil tests to determine acceptable loading rates implies, further, that the negative effect is related directly to nutrient concentrations measured by the test. Clearly, soils can be overloaded with



a variety of nutrients, nonessential heavy metals, organic chemicals, and pathogenic organisms, among other things; and overloaded soils can affect the environment in various ways. This discussion is focused on plant nutrients.

For farmers and their advisors to make confident decisions about nutrient loading, soil tests must be proved to predict loading rates and critical levels over the range of crops, soils, and environmental conditions under which the soil test is to be used (Figure 3). A soil test therefore must be calibrated by repeating experiments at locations evidencing the range of expected soil and crop growth conditions. Results of these experiments must be combined in a manner ensuring that the soil test will avoid nutrient deficiencies and excesses throughout the defined region or major subregions of the geographic area.

#### **Soil Tests and Nutrient Loading Rates for Environmental Purposes**

There is interest today in using soil testing to help protect the environment as well as to optimize agricultural productivity and profitability. In many U.S. states, regulatory initiatives are under way that are not targeted at optimizing agronomic or economic responses to nutrient loading per se. Rather, the focus of most of these initiatives is on mitigating water-quality problems associated with N and P, such as ground water pollution by nitrate-N and eutrophication of surface waters used for fishing or recreation, and drinking water. Other environmental efforts to which soil testing might contribute include preventing animal health problems and phytotoxicity, or plant injury or death, by ensuring that soil nutrient concentrations are not excessive or unbalanced; and protecting the food chain from accumulations of nutrients or nonessential elements of concern to human health. These environmental problems usually occur at soil-test levels well in excess of those required for optimal plant growth, or as a result of clearly undesirable events, e.g., nutrient movement to waters in floods or attached to eroding soils. Regarding phytotoxicity and feed or forage quality, soil tests have the potential to predict negative responses of plants to soils overloaded with a nutrient or nonessential

element.

To achieve a predictive soil test, the negative effect must be well defined and readily measurable (tissue concentrations, yield reductions, etc.) and must be related, through a valid calibration process, to soil-test level. In many instances, the most appropriate parameters to measure and the protocols for establishing calibration tests have yet to be agreed on, for research has shown that the magnitude of these responses depends on soil pH, soil properties, crop species, weather conditions, and animal species. Most soil-test calibration research so far has focused on defining suboptimal or optimal nutrient concentrations in soils to prevent nutrient deficiencies. Data relating soil-test measurements in the “very high” or “excessive” ranges to environmental or ecological impacts are scarce.

When the goal is protection of water quality, the issue gains complexity for several reasons. First, soils can contribute to nonpoint source pollution of ground and surface waters even when soil-test levels are in the optimal range for crop production. That is, soils do not have to be overloaded to contribute environmentally significant amounts of N and P to waters by erosion, runoff, and leaching. Second, nonincorporated surface applications of nutrient sources may result in unexpectedly high nutrient losses not correlated with soil-test levels. In this instance, surface transport of soluble materials in the nutrient source occurs without significant interaction between source and soil. Using only a soil test would not permit accurate characterization of the risk of nutrient loss from soil to water; estimates of the amount of soluble or particulate nutrient directly lost from surface applied materials also would be needed.

More important, regarding water quality, the response parameters of interest often are not defined as they are for crop production or phytotoxicity. For example, the USDA’s Natural Resources Conservation Service has proposed (U.S. Department of Agriculture 1999) and a number of states have adopted or are considering adopting (Lory and Sharf 1999) the use of upper soil-test limits for P, or thresholds, to determine when the loading of P in manures should cease to prevent water-quality degradation. Most proposed soil-test P threshold

values are three to four times higher than the critical soil-test level for agronomic response, so there is some logic in restricting nutrient additions to soils at rates well in excess of crop needs. On the other hand, agronomic rates are based primarily on economic considerations for an expensive input; additions above the agronomic response zone do not imply automatically that water quality will be degraded.

A truly predictive soil test would, again, require clear definition of (1) the measurable negative effect to be avoided and (2) its relation to the soil-test level, as determined by means of a valid calibration process. Currently, no generally accepted water-quality standard for P can be related directly to the concentration of P lost in runoff from soils. Depending on factors such as salinity, flow rate, and depth (Newton and Jarrell 1999), surface waters differ in their sensitivity to nutrient inputs; and the factors controlling the transport of nutrients to a water body — e.g., slope, drainage, soil and crop management practice — are at least as important, if not more so, than the actual amount of extractable or total nutrients in a soil.

It is important, given these complexities, to consider carefully the goals and implications of using soil testing for environmental purposes. To accept a soil test as the sole means of determining environmentally unacceptable loading rates of nutrient sources, one must essentially assume that additions of nutrients to the soil will, at some point, result in water-quality degradation. But without identifiable and easily measured water-quality response parameters that can be shown to be related directly to soil-test concentrations of nutrients in the surrounding watershed, this is a difficult hypothesis to test. What happens between the field's edge and the surface water, including the possibility for long-term retention of nutrients in buffer zones and any channel processes resulting in retention or release of nutrients at a later date, also has the potential to be overlooked. A major gap in current knowledge is how nutrients are retained within complex landscapes and released to adjacent streams and water bodies. That agricultural soil management practices used today may not affect adjacent water for months or years, if not decades,

limits the ability to link soil concentrations with off-site effects.

In summary, there is little disagreement that nutrients originating in agricultural soils, or from the loading of fertilizers, manures, and other amendments, are part of the nonpoint load to ground and surface waters and thus to nonpoint source pollution of these waters. As with predictions of plant responses to nutrients, however, the uses of soil tests clearly are limited. Between soils with the same soil-test level, the solubility and the potential bioavailability of nutrients may differ because of variations in chemical, biological, and physical processes controlling nutrient form and release to runoff or leaching waters. There are multiple loss-pathways for nutrients from fields, and unpredictable reactions of these nutrients (or eroded soil) can occur beyond the application zone. Together, these factors make it problematic to correlate directly the amount of a nutrient measured by a soil test with the potential for the soil, or further loadings to the soil, to affect other sectors of the environment negatively.

#### **Improving Soil Testing for Agricultural and Environmental Purposes**

Soil scientists and their colleagues in other disciplines recognize the value of developing testing methods to identify soils with the potential to affect the environment negatively. During the past decade, research to improve the use of soil testing has accelerated and is beginning to produce results. Researchers are attempting to define measurable parameters that ultimately may improve the ability to link soil-test concentrations and loading rates to water quality. The best example of such work is the ongoing international effort to develop a science-based approach to identifying agricultural soils likely to contribute significant amounts of P to surface waters by erosion, runoff, or leaching.

A growing body of evidence from field research demonstrates a strong relationship between soil-test P concentrations and particulate and soluble P concentrations in runoff and leaching (Pote et al. 1996). Dissolved P in runoff was highly correlated with all soil-test methods evaluated. Most field research demonstrates that soil chemi-

cal and physical properties and environmental factors interact to influence the specific nature of these relationships. Soils with high clay content have a greater sorption capacity for P than coarse-textured soils because of their higher reactive surface area. Thus, if loading rate decisions regarding fertilizers or manures were made solely on the basis of soil-test P concentrations, without allowances for P sorption capacity, erroneous decisions regarding potential for P loss in runoff events would result.

New soil tests measuring the degree of saturation of this sorption capacity in acid soils improve scientists' ability to assess both the amount of soil P and the soil's capacity to adsorb P (Mozaffari and Sims 1994). This has proved useful in assessments of the potential for soluble P losses in runoff and leaching from soils. Although such progress is encouraging, recent research also has shown that short-term transport of P in pastures actively receiving nonincorporated manure may greatly exceed losses predicted by soil-test P values alone (Ver Voort et al. 1998). Better prediction of nutrient losses from soils to ground and surface waters from complex landscapes can be achieved in a more comprehensive approach identifying the critical source areas of nutrients in a watershed, by considering factors such as topography, climate, contributing distances from streams, soil drainage, and crop management practices. Regional and national efforts to integrate soil P testing into an improved, field-scale diagnostic tool (the Phosphorus Site Index) identifying these critical source areas are under way (Sharpley et al. 1994).

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