Site-Specific Nutrient Management

For Nutrient Management Planning To Improve Crop Production, Environmental Quality, and Economic Return

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Introduction

Consistent use of nutrient management planning has been identified by USDA/NRCS as lacking on many farms in the USA (Conservation Effects Assessment Project (CEAP), Assessment of the Effects of Conservation Practices on Cultivated Cropland in the Upper Mississippi River Basin). It has also been shown that all resource concerns are rarely achieved with a single conservation practice. Implementation of site specific nutrient management planning to minimize nutrient loss, conservation practices to control runoff, and practices to trap materials leaving the field should be utilized as a combination of efforts. In combination, these practices have the ability to reduce agricultural non-point source pollution and to enhance economically sustainable crop production. However, increased nutrient management practice implementation requires increased producer awareness and well informed crop advisers.

A team of cooperating organizations and agencies that consists of The Fertilizer Institute (TFI), United States Department of Agriculture Natural Resources Conservation Service (USDA/NRCS), International Plant Nutrition Institute (IPNI), and Iowa State University (ISU) worked together to bring expertise and coordinated outreach in an effort to help producers increase implementation of site-specific nutrient management. The primary goal of this effort was to increase awareness of site-specific nutrient management and concurrent benefits to crop production, environmental quality, and economic return. With such understanding, the number of production acres implementing site specific nutrient management planning is expected to increase the effective and efficient use of nutrients for crop production.

The specific objectives were to: 1) develop an education program, that when implemented, will provide service providers (NRCS employees, Certified Crop Advisers (CCAs), Third Party Service Providers (TSPs), retail fertilizer personnel) and producers with enhanced knowledge about site specific nutrient management planning; 2) develop a set of educational materials to support nutrient management education programs; and 3) develop educational materials for service providers to support producer education programs.

An essential component of the effort was to provide this overview document that outlines the components of soil fertility and nutrient best management. Topics include the 4R nutrient stewardship; soil fertility and plant nutrition overview; nutrient management, including nitrogen, phosphorus, potassium, sulfur, calcium and magnesium, micronutrients; soil pH and liming; soil sampling; and integrated economic and environmental nutrient management.

Having worked together as a cooperating group, the hope is that developed education materials and training curricula will serve as a multiplier of efforts and enhance the variety of groups and number of individuals reached to ultimately increase the number of production acres implementing site specific nutrient management planning. The end result, through increased understanding and implementation of site specific nutrient management planning, will be a benefit to water and air quality as well as production sustainability.

Chapter 1:
Overview of soil fertility, plant nutrition, and nutrient management

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Introduction

Understanding the principles of soil fertility is vital to efficient nutrient management, crop production, as well as environmental protection. There are 17 chemical elements known to be essential for plant growth, and 14 of these elements come from the soil (Table 1). Each essential plant nutrient is needed in different amounts by the plant, varies in mobility within the plant, and varies in concentration in harvested crop components. It is useful to know the relative amount of each nutrient that is needed by a crop and the relationship to amounts removed with crop harvest.

Table 1. Essential plant elements, source, roles, and relative quantities in plant.

Element	Source	Role in Plant	Concentration
Carbon (C)	Air	Constituent of carbohydrates; necessary for photosynthesis	45%
Oxygen (O)	Air/Water	Constituent of carbohydrates; necessary for respiration	45%
Hydrogen (H)	Water	Maintains osmotic balance; important in many biochemical reactions; constituent of carbohydrates	6%
Nitrogen (N)	Air/Soil	Constituent of amino acids, proteins, chlorophyll, and nucleic acids;	1-
Potassium (K)	Soil	Involved with photosynthesis, carbohydrates translocation, protein synthesis	0.5-1%
Phosphorus (P)	Soil	Constituent of proteins, coenzymes, nucleic acids, and metabolic substrates; important in energy transfer	0.1-0.5%
Calcium (Ca)	Soil	Component of cell walls; plays a role in the structure and permeability of cell membranes	0.1-0.4%

Element	Source	Role in Plant	Concentration
Magnesium (Mg)	Soil	Enzyme activator; component of chlorophyll	0.1-0.4%
Sulfur (S)	Soil	Component of certain amino acids and plant proteins	0.1-0.4%
Chlorine (Cl)	Soil	Involved with oxygen production and photosynthesis	0.01-0.1%
Iron (Fe)	Soil	Involved with chlorophyll synthesis and in enzyme electron transfer	50-250ppm
Manganese (Mn)	Soil	Controls several oxidation-reduction systems and photosynthesis	20-200ppm
Boron (B)	Soil	Important in sugar translocation and carbohydrates metabolism	6-60ppm
Zinc (Zn)	Soil	Involved with enzymes that regulate various metabolic activities	25-150ppm
Copper (Cu)	Soil	Catalyst for respiration; component of various enzymes	5-20ppm
Molybdenum (Mo)	Soil	Involved with nitrogen fixation and transforming nitrate to ammonium	0.05-0.2ppm
Nickel (Ni)	Soil	Necessary for proper functioning of urease and seed germination	0.1-1ppm

To be classified as essential, the element needs to meet the following criteria:

1. The plant cannot complete its life cycle (seed to new seed) without it.
2. The element's function cannot be replaced by another element.
3. The element is directly involved in the plant's growth and reproduction.

Non-mineral nutrients

Three elements, carbon (C), hydrogen (H), and oxygen (O), are non-mineral nutrients because they are derived from air and water, rather than from soil. Although they represent approximately 95% of plant biomass, they are generally given little attention in plant nutrition because they are always in sufficient supply. However, other factors such as soil management and the environment can influence the availability and crop growth response.

Mineral nutrients

The 14 mineral nutrients are classified as either macronutrients or micronutrients based on their plant requirements and relative fertilization need. There are six macronutrients: nitrogen (N), phosphorus (P),

potassium (K), calcium (Ca), magnesium (Mg), and sulfur (S). The macronutrients, N, P, and K, are often classified as 'primary' macronutrients, because deficiencies of N, P, and K are more common than the 'secondary' macronutrients, Ca, Mg, and S. The micronutrients include boron (B), chlorine (Cl), copper (Cu), iron (Fe), manganese (Mn), molybdenum (Mo), nickel (Ni), and zinc (Zn). Most of the macronutrients represent 0.1 - 5%, or 100-5000 parts per million (ppm), of dry plant tissue, whereas the micronutrients generally comprise less than 0.025%, or 250 ppm, of dry plant tissue (Table 1).

Plant uptake of nutrients

Each nutrient cannot be taken up by plants in its elemental form, but instead is taken up in an 'ionic' or charged form, with the exception of B as boric acid which is uncharged (Table 2). Most fertilizers are made up of combinations of these available nutrient forms, so when the fertilizer dissolves, the nutrients can be immediately available for uptake. Knowing what form of a nutrient the plant absorbs helps us to better focus on what controls the cycling and movement of that nutrient in soil. In addition, understanding nutrient functions and mobility within the plant are useful in diagnosing nutrient deficiencies.

Table 2. Nutrient forms taken up by plants.

Element	Form
Nitrogen (N)	NO_3^- (nitrate), NH_4^+ (ammonium)
Potassium (K)	K^+
Phosphorus (P)	$H_2PO_4^-$, HPO_4^{-2} (phosphate)
Calcium (Ca)	Ca^{+2}
Magnesium (Mg)	Mg^{+2}
Sulfur (S)	SO_4^{-2} (sulfate)
Chlorine (Cl)	Cl^- (chloride)
Iron (Fe)	Fe^{+2} (ferrous), Fe^{+3} (ferric)
Manganese (Mn)	Mn^{+2}
Boron (B)	H_3BO_3 (boric acid), $H_2BO_3^-$ (borate)
Zinc (Zn)	Zn^{+2}
Copper (Cu)	Cu^{+2}
Molybdenum (Mo)	MoO_4^{-2} (molybdate)
Nickel (Ni)	Ni^{+2}

Nutrient uptake by roots is dependent on the activity of the root, ability to absorb nutrients, and the nutrient concentration at the surface of the root. Roots come directly in contact with some nutrients (called 'root interception') as they grow; however, this only accounts for a very low percentage of the total amount of nutrients taken up by plants. Therefore, other mechanisms must cause the movement of nutrients to the plant.

Water moves toward and into the root as the plant uses water, or transpires. This process, called 'mass flow', accounts for a substantial amount of nutrient movement toward the plant root, especially for the mobile nutrients such as NO_3^-. Specifically, mass flow has been found to account for about 80% of N movement into the root system of a plant, yet only 5% of the more immobile P. It has been found that 'diffusion' accounts for the remainder of the nutrient movement.

Diffusion is the process where chemicals move from an area of high concentration to an area of low concentration. By fertilizing near the plant root, the plant is less dependent on exchange processes and diffusion to uptake nutrients, especially P. The nutrients that are most dependent on diffusion to move them toward a plant root are relatively immobile, have relatively low solution concentrations, and yet are needed in large amounts by the plant, such as P and K. The secondary macronutrients (Ca, Mg, S) often do not depend on diffusion because their solution concentrations are fairly high in soil relative to plant requirements.

<u>Nutrient mobility within the plant</u>

All nutrients move relatively easily from the root to the growing portion of the plant. Interestingly, some nutrients can also move from older tissue to newer tissue if there is a deficiency of that nutrient. Knowing which nutrients are 'mobile' (i.e., more able to move) is very useful in diagnosing plant nutrient deficiencies because if only the lower leaves are affected, then a mobile nutrient is most likely the cause. Conversely, if only the upper leaves show the deficiency, then the plant is likely deficient in an 'immobile' (i.e., less able to move) nutrient, because that nutrient cannot move from older to newer tissue (leaves). Table 3 lists the six mobile and eight immobile mineral nutrients. Sulfur is one element that lies between mobile and immobile elements depending on the degree of deficiency.

Table 3. Mobile and immobile nutrients in plants.

Mobile nutrients	Immobile nutrients
Nitrogen (N)	Sulfur (S)
Phosphorus (P)	Calcium (Ca)
Potassium (K)	Iron (Fe)

Mobile nutrients	Immobile nutrients
Chloride (Cl)	Zinc (Zn)
Magnesium (Mg)	Manganese (Mn)
Molybdenum (Mo)	Boron (B)
	Copper (Cu)
	Nickel (Ni)

Timing of nutrient uptake

Nutrient uptake does not necessarily match plant growth or the most critical need. For example, when corn growth represents 50% of its total mature biomass, it has accumulated approximately 100% of its mature K, 60% of its N, and 55% of its P (Figure 1). Phosphorus, for example, is critical for early cell division and multiplication when the amount absorbed is very small. Therefore, supplying sufficient K early in a crop's growing season is likely more important than during the middle of the growing season. However, late in the growing season, nutrients accumulate in the grain rather than in the leaves or stalk. Therefore, mid-season nutrient application may increase both quality and grain yield if other plant requirements are met, such as water. For example, N topdressed at tillering has been found to increase both yield and protein of winter wheat, especially at low soil N levels. Therefore, it is important to understand nutrient needs and timing of nutrient uptake for each crop that you're working with.
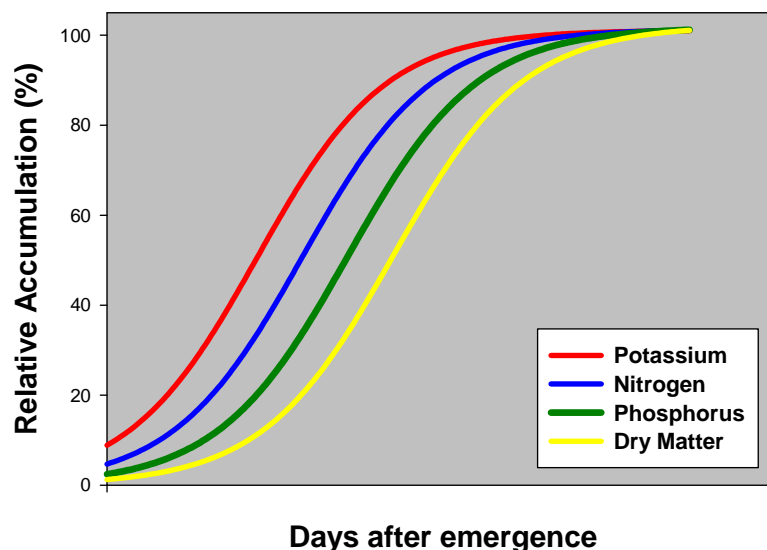
Figure 1. Schematic accumulation patterns of K, N, P, and dry mater in corn.

Nutrient response function

In Figure 2, yield is severely affected when a plant nutrient is deficient, and when the nutrient deficiency is corrected, yield increases rapidly (Zone A) until the critical range of plant nutrient concentration is reached and yield is maximized. Nutrient sufficiency occurs over a wide concentration range, where yield is unaffected (Zone C). Increases in nutrient concentrations (by fertilizer application) above the critical range indicate that the plant is absorbing nutrients above that needed for maximum yield, commonly called *luxury consumption*. Elements absorbed in excessive quantities can reduce plant yield directly through toxicity or indirectly by reducing concentrations of other nutrients below their critical ranges (Zone D). The minimum amount of fertilizer required to maximize crop yield is called the *optimum physical rate* or *agronomic optimum rate* (AOR) and it is located within Zone C. Even though the exact relationship between crop yield and nutrient rate will vary, the general shape of this relationship is relatively consistent for many crops and nutrients.
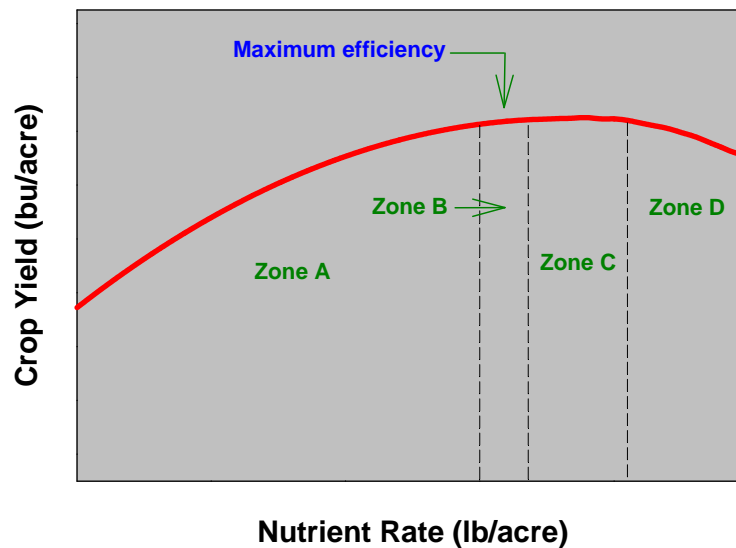

Figure 2. Relationship between crop yield and essential nutrient application rate.

Adequate nutrient supply, from the soil or applied nutrient, is vital to soil fertility and crop production. A limited supply of one of the essential nutrients can limit crop yield, although other factors such as another nutrient, light, heat, or water can also limit yield. The concept that a certain sufficiency level of a nutrient will limit plant growth or yield to a certain level independently of levels of other nutrients or growth factors is known as the 'law of the minimum'. Nitrogen and water are known as closely following this principle. On the other hand, insufficient supply of other nutrients (such as P and K, for example) tend to

limit growth or yield to a certain proportion of the potential maximum depending on sufficiency levels of other growth factors. Therefore, how different nutrients behave according to these principles generally influence the degree and type of interactions between nutrients and with other growth factors. Although N is usually the first limiting nutrient for non-legume crops, without adequate supply of other nutrients, N use efficiency (NUE) suffers. For example, increased N uptake and utilization with adequate K means improved NUE and higher yields. Figure 3 shows how corn yield and NUE were increased by fertilizer K application to a deficient soil, resulting in improved economic and environmental benefits.
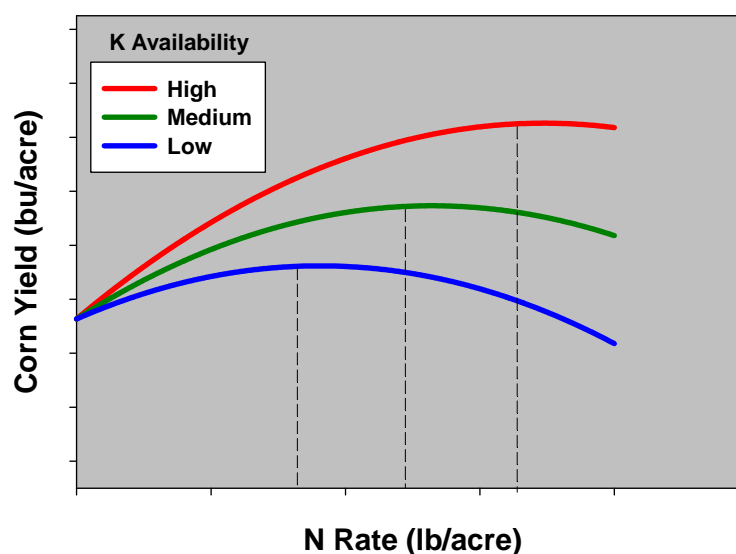

Figure 3. Potassium improves yield response to N fertilizer and N use efficiency.

Nutrient diagnostic methods: correlation, calibration, and interpretation

Nutrient diagnostic methods are tools for determining plant nutrient needs. They can include soil testing, plant analysis, crop sensor readings, etc. The development of a diagnostic method for a given nutrient has historically involved three steps: 1) selecting a soil/plant extractant or methodology to measure any crop characteristic related to plant nutrition, 2) correlation of the value of any of these methods with the amount of nutrient taken up by plants, and 3) calibrating the value in terms of its effect on some desirable crop characteristic, usually yield of marketable product. Fertilizer recommendations are then based on interpretation of calibration data and fertilizer response curve (Figure 2).

No matter how good a chemical method of analysis, a soil/plant test value is meaningless unless it can be related to the nutrient status of the soil and sufficiency for a specific crop in order to apply a corrective soil amendment or fertilizer treatment. A single numerical value reported by a soil test (say 11 ppm for P) has no meaning unless information is gathered to evaluate (1) what tat value means concerning growth

and/or yield level in relation to the amount needed to maximize growth or yield, (2) whether crop growth or yield will be greater when the nutrient is added to the soil and how much greater , and (3) the amount of nutrient needed for the crop to attain better growth or yield in different soils and for different crops at different test levels.

A combination of correlation and calibration research is necessary to gather information needed to answer these questions. Correlation is a relationship between the amount of nutrient extracted from soil by a laboratory test and nutrient uptake by plants and/or crop yield in the greenhouse or field. If such a relationship cannot be established, the analytical procedure has little or no usefulness. Sometimes the relationship can be established for only one nutrient and one crop, and on a particular group of soils. This is a limitation that the producer must know and recognize, and the soil test should only be used for those specific conditions. For example, useful correlations have been established between the Bray-1 P test and percent of maximum yield for different crops in many states. These correlations help determine when soil test P is adequate for maximum yields—when no response from additional fertilizer is expected. Different crops such as wheat, corn, and soybean vary in their response to the amount of P in the soil (Figure 4). Yields of both corn and soybean change rapidly with small differences in soil test P. Winter wheat requires higher levels of soil P to attain maximum yields. Because of crop differences, soil test correlation research must be conducted with a large number of crops.
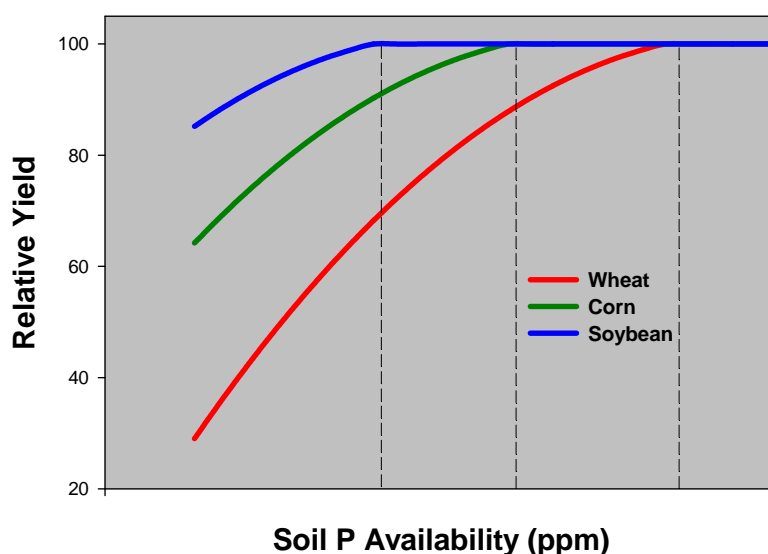

Figure 4. Different crop responses from different soil Bray-1 P levels.

Calibration establishes the relationship between a given soil/plant test value and the yield response from an addition of the fertilizer nutrient to the soil. Figure 5 represents a general example of this relationship. From crop yield responses, one can determine the amount of fertilizer needed over a range of test levels for many soils where a given crop is grown.

Soil Nutrient Availability
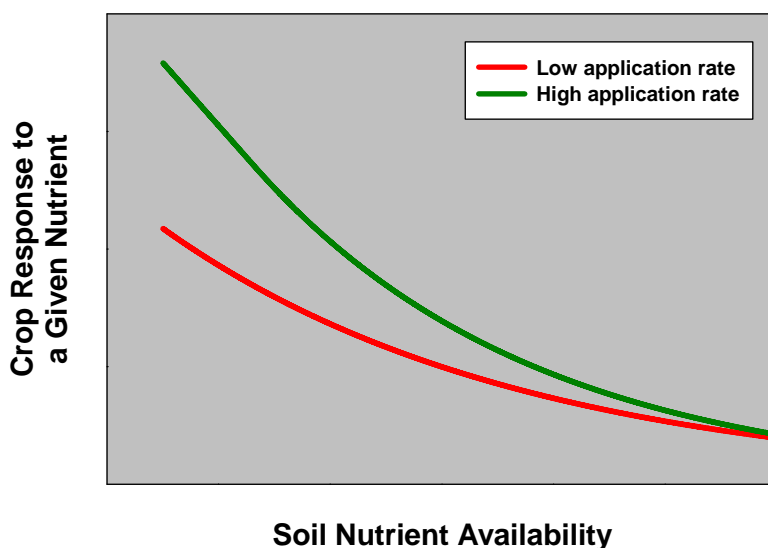
Figure 5. Crop yield response to a low and high rate of a given nutrient as related to the original soil nutrient level.

After field correlation-calibration experiments have been conducted, soil test levels of a given nutrient can be placed into categories related to the magnitude and probability of yield response. These categories give quick insight to fertilizer decisions. Their general meaning is given in Table 4 in terms of the probability of a yield increase due to fertilizer application. This explanation illustrates much of the basic science behind using correlation-calibration to develop fertilizer recommendations, especially for nutrients considered immobile in the soil (such as P and K).

Table 4. Probability of a crop yield increase due to nutrient fertilizer application.

Nutrient Index Level	Meaning of Index Level for Crops
Very low	Applying the nutrient will be beneficial over 80% of the time.
Low	Applying the nutrient will be beneficial 65% of the time.
Optimum	Applying the nutrient has about 5% chance of being beneficial in growth or yield.
High	Applying the nutrient will be beneficial less than <1% of the time.

Nutrient Management

Nutrient management involves managing all crop fertility inputs and other production practices to achieve efficient crop growth and water quality protection. Nutrient management plans for site-specific situations should minimize undesired environmental effects while optimizing whole-farm profits and production. The term "nutrient management" is most often associated with animal manure management, but applies to all crop fertility inputs whether manure, organic by-products, amendments, or commercial fertilizers.

What is Nutrient Management Planning?

Nutrient management planning principles are basic, and like sound fundamentals necessary for any good business management. They involve:

• Knowing what you have

• Knowing what you need

• Managing properly

• Documenting practices and outcomes

Nutrient management plans must be site-specific, tailored to the soils, landscapes, and management objectives of the farm. In effect, nutrient management planning is much like developing a cash-flow analysis, but using nutrients instead of dollars, although dollars and environmental impacts also should be considered.

Steps in Nutrient Management Planning

1. Obtain accurate soil information for each field or management unit. This could be use of existing NRCS soil maps or require a new farm soil map. Soil samples should be obtained and analyzed according to recognized soil fertility sampling and analytical procedures.

2. Estimate crop yield potential based on soil productivity and intended management. It is impossible to foretell growing seasons, but average yields over last four to six years should provide a reasonable estimate. It is important to be realistic.

3. Calculate plant nutrient applications required. Nutrient recommendations and harvest removal information for common crops are available from the NRCS, local Extension offices, and University soil fertility publications and web sites. It is important to distinguish between nutrient recommendations for specific situations, crop uptake or use by the growing crop, and crop removal which is the physical removal of nutrients from the field with harvesting.

4. Determine the plant-available nutrients in any livestock manure or other by-product amendments that are available for application.

5. Estimate any applicable residual nutrient contributions from fertilizer or manures applied in previous seasons.

6. Determine need for purchase of off-farm nutrients, such as fertilizer or manure.

7. If necessary, use an applicable environmental risk assessment tool, for example the Phosphorus Index (PI), to determine the potential for offsite movement of nutrients on a field-by-field basis. The PI, for example, incorporates several site specific soil conditions and conservation practices; soil test phosphorus level, soil permeability, field slope, manure and fertilizer applications, distance to surface water, and other factors are used to determine the probability of phosphorus movement in the landscape.

8. Apply animal manures and commercial fertilizers to supply nutrients when needed using practices that ensure high use efficiency, such as right source, rate, timing, and placement.

9. Keep records of nutrient sources, application dates, rates, and methods.

Nutrient Management Planning Summary

• Know the soils and fields of your farm

• Be realistic about crop production goals

• Determine nutrient levels and application needs

• Determine all farm-level nutrient resources available

• Assess environmental risks from nutrient applications

• Apply nutrients using sound nutrient management and cropping practices

• Keep field records

Summary

Managing crop nutrients goes beyond soil fertility basics and decisions for single nutrients or application needs for single fields. Nutrient management should encompass the entire production enterprise, which can be comprised of crops and livestock, and should include recognition of all nutrient inputs and outputs from the farming enterprise. Flows of nutrients to, within, and from the enterprise should be identified to provide best management in regard to economic and environmental concerns. Such flows can include fertilizer purchases, manure production, manure purchases, crop harvest and sales, and crop harvest and feeding on farm. While nutrient balance is not a necessity, avoiding nutrient deficiency or excesses helps provide greatest economic return. Coupled with soil management practices, enterprise nutrient management also helps provide longevity of soil productivity and environmental stewardship; both of which are important for future generations use of land and water. With the continual changing of production practices and increasing needs from crop production (such as biomass for feed, bedding, and energy), continual monitoring and adaption is needed to maintain nutrient management stewardship.

Chapter 2:
Nitrogen Management

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Developed in cooperation with Lara Moody, TFI; John Davis, NRCS; and Steve Phillips, IPNI.

Introduction

Nitrogen (N) is essential for plant growth and is part of every living cell. It plays many roles in plants and is a component of chlorophyll, which is necessary for photosynthesis. Symptoms of N deficiency in plants generally include chlorosis or yellowing. Nitrogen is typically taken up in larger amounts than other nutrients and is the most common, and most important, limiting nutrient for non-legume agricultural crops. Not only does N nutrition affect yield, but it also affects the quality (protein or sugar content) of crops such as grain and sugar beets, for example. In addition, N also has interaction implications with efficient use of other nutrients. To understand how N management (cropping systems, N fertilizer forms, application rates, and timing of N fertilization) affects crop yield and quality, it is important to first understand the various processes that N undergoes in the soil-plant system.

Basic nitrogen processes in the soil-plant system

Nitrogen, present or added to the soil, is subject to several changes (transformations) and gain/loss mechanisms that dictate the availability of N to plants and influence potential N-related environmental issues. These processes are listed and briefly described in Table 1. As is demonstrated by the extensive list, N cycling in the soil-plant system is complex, which increases the difficulty for N management.

Table 1. Processes that N undergoes in the soil-plant system, factors that influence these process, and consequences for N management.

| Process	Definition	Enhanced by	Consequence for N management
Mineralization	Conversion of organic N forms to inorganic N (ammonium, NH_4^+) through microorganisms.	Warm, moist, well-aerated soils.	Increase N (NH_4^+) readily available for crop uptake or loss by leaching.
Nitrification	Conversion of NH_4^+ to nitrate (NO_3^-) through bacteria.	Warm, moist, well-aerated soils.	Increase N (NO_3^-) readily available for crop uptake.
Immobilization	Conversion of inorganic N forms (NH_4^+ and NO_3^-) to organic N through bacteria.	High carbon-low N residues. Warm, moist, well-aerated soils.	Reduction in the amount of plant-available N.
Leaching	Loss of NO_3^- as it moves with soil water below the root zone.	Coarse-textured soils, excess rainfall or irrigation.	Reduction in the amount of plant-available N and water contamination.
Denitrification	Process by which bacteria convert NO_3^- to N gases (N_2 and N_2O) that are lost to the atmosphere.	Waterlogged and warm soils with high soil organic matter (OM).	Reduction in the amount of plant-available N and air contamination.
Volatilization	Process by which N is lost as ammonia (NH_3) gas to the atmosphere. This mechanism is enhanced greatly by the enzyme urease, which is present in the soil and plant residues.	Application of manure and fertilizer products containing urea. Warm, low cation exchange capacity (CEC) soils, high pH soils, high surface residue.	Reduction in the amount of plant-available N and air contamination.
Crop uptake and removal	Amount of N that is lost from the soil system through crop harvest.	Good conditions for plant growth.	Reduction in the amount of plant-available N.
Erosion	Nitrogen loss from agricultural lands through soil erosion and runoff.	Highly erodible soils with excess tillage.	Reduction in the amount of OM and potential plant-available N and reduced water quality/contamination.
Symbiotic N fixation	Conversion of N gas (N_2) in the air to plant available N through microorganisms in association with legume plants.	Good conditions for plant growth and low levels of inorganic soil N.	Increase available N supply to legumes and decrease fertilization need of subsequent crops.

A good knowledge of these processes and their interactions helps with understanding the underlying principles for optimal N management practices, from both the production and environmental perspectives. Many years of research and experience by crop producers and advisers have resulted in valuable tools to aid in determining when, how, where, and how much N to apply to crops. For example, tools include fertilization rate guidelines, analysis of soils and plant tissues, chlorophyll meter (CM) and crop canopy sensing for plant N stress, site-specific technologies, and economic evaluation of N management practices and fertilization recommendations.

Rate determination and economic response

Nitrogen fertilization rate is the most important N management decision regarding potential to achieve optimum crop yield, influence nitrate loss to water systems, and return maximum economic profitability. Nitrogen fertilizer price volatility has increased in recent years, and continues to be one of the most expensive variable production costs. For cereal crops, N fertilization is required to achieve acceptable production levels. Several terms or acronyms are important to be understood in relation to yield response to N and economic returns. The term "Agronomic Optimum N Rate" or AONR defines the N rate that will produce maximum grain yield, regardless of cost. The term "Economic Optimum N Rate" or EONR defines the N rate that will result in the maximum economic return to N, the point where the last increment of N just pays for the applied N. The recently developed recommendation approach "Maximum Return to N" or MRTN is similar to EONR and defines the maximum response rate and an N rate range within a set economic return level from the maximum return (within $1/acre). The MRTN is derived directly from a population or database of N response research trials. The EONR, and MRTN rates are less than the AONR, will decrease as N prices increase relative to crop price, increase as grain prices increase relative to N price, and remain the same if the ratio between N and grain prices remains the same even though prices change. These economic rate determination approaches require yield response data from numerous field trials documenting yield responses to N fertilizer rates across different soil types, growing seasons, crop rotations, genotypes, tillage systems, etc.

Figure 1 depicts a low corn grain yield when no N is applied, and a large increase in yield with N application. The challenge is to identify application rates that allow for maximum economic net return without over- or under-fertilization for different conditions. In Figure 1, the blue points indicate the EONR. Due to the need to pay for the fertilizer input, recommended rates are less than the rate to produce maximum yield (indicated by the vertical lines). They are close to the rates that result in the maximum yield, however, and in the example the yield for the EONR is 98% of agronomic maximum yield. One can also see the influence of the prior crop on crop response to N and yield. For example, the EONR is

170 lb N/acre for corn following corn (CC) and 123 lb N/acre for corn following soybean (SC), with an approximate 15% higher yield for the rotated corn.
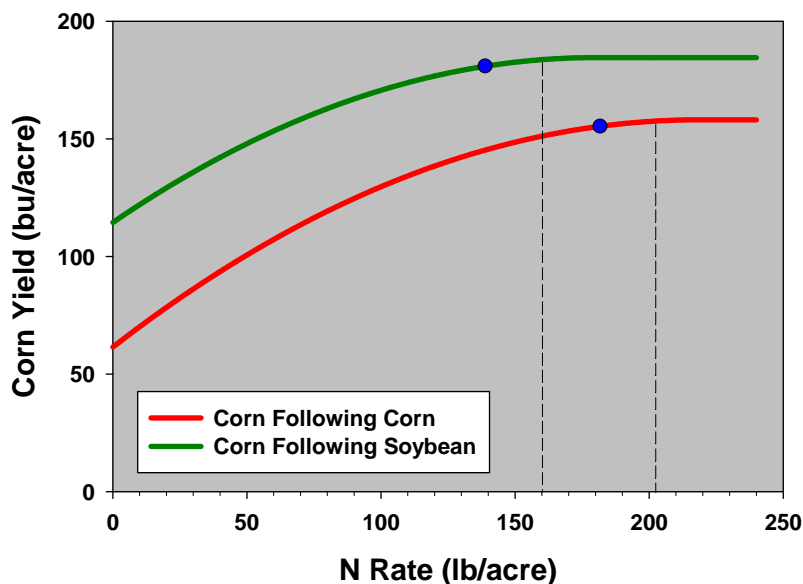
Figure 1. Nitrogen rate response of corn following corn and corn following soybean in Iowa. The vertical lines indicate the agronomic optimum N rate (AONR) and the blue points the economic optimum N rate (EONR). J.E. Sawyer, Iowa State University.

Applying "more than enough N" is no longer a safe and cheap "insurance"; certainly not as it once was due to the increased cost of N fertilizers. Also, applying "more than enough N" is not environmentally friendly and, therefore, must be avoided. High N fertilizer costs, uncertainty about crop process, and environmental impacts should encourage growers to critically determine N application rates. Figure 2 shows how nitrate-N loss increases as N rate increases beyond the optimum N. This concept applies for all crops fertilized with N and most production scenarios, which highlights the importance of accurately determining the optimum N rate to maximize profitability and minimize environmental impacts within specific crops and production systems. In spite of much research, this is much easier to say than actually achieved in production fields due to the numerous and unpredictable factors that affect the optimum N rate and the crop response to applied N.
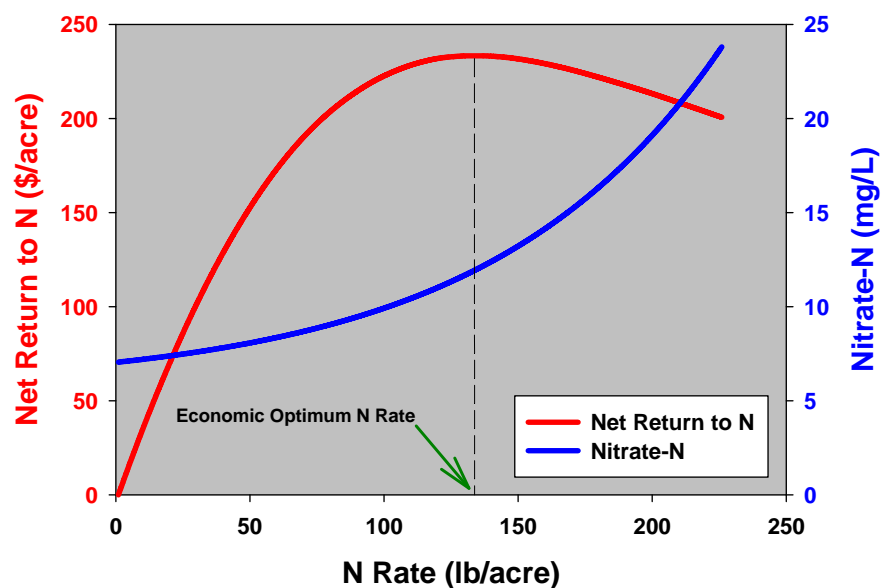
Figure 2. Importance of using optimum N rates for greatest profit and minimizing nitrate-N loss (via subsurface tile drainage).

The common N rate recommendation system used in cereal crops for many years in the Midwest USA and other regions was a yield-goal based factor. This approach uses expected crop yield as the criterion for determining N rates; the higher the expected crop yield the greater is the N requirement, and presumably the recommended N rate. For example, N recommendations for wheat in Ohio have been based on this rate equation: 40 + [1.75 x (yield potential - 50)] (mineral soils, with 1 to 5% organic matter and adequate drainage). The equation indicates that a realistic yield goal should be the first place in which to consider rate adjustment. For example, if the yield goal has been targeted at 100 bu/acre but yield has actually been 80 bu/acre, then the crop has received 35 lb/acre each year that were not needed for grain yield production and therefore prone to be lost.

This yield-goal recommendation approach is still the recommendation system in some regions and some crops (for example, irrigated corn in Nebraska). In the Midwest USA, however, research for corn and other grain crops has identified a poor correlation between individual site-year crop yield and EONR, and that the EONR for a specific soil do not necessarily change with yield level. Figure 3 shows an example of this issue for corn in Iowa, but similar results can be found for other regions and crops. At issue is the concern of too high or low calculated N recommendations when based on yield goals. Therefore, some university N recommendation systems have moved away from yield-based systems to N response data-driven recommendations that are sensitive to N and grain prices. In the Midwest USA this approach is

called MRTN, Maximum Return To N. Economic-based approaches are not new; however, this particular approach links documented yield responses to N rate from recent research trials directly with the relative economics of grain price and N cost.
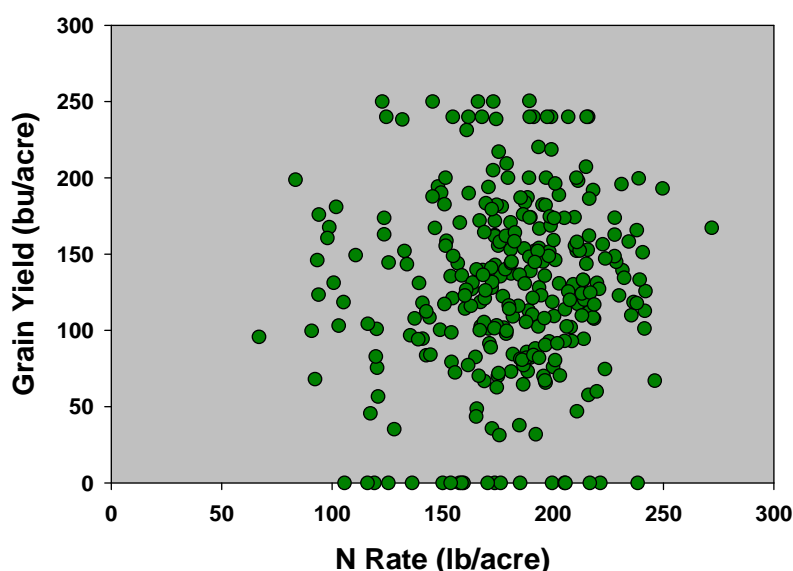
Figure 3. Relationship between net return to N and applied N rate for corn after soybean in Iowa. J.E. Sawyer, Iowa State University.

An important aspect of the data-driven approach is the need for current N response trials. This is an issue with all recommendation systems, that is, keeping current with changing cropping practices and environmental conditions. It is also important to utilize rate recommendations derived from research in representative geographic areas and cropping systems as needed fertilization rates vary based on soils, climatic conditions, and crops grown.

Soil testing and rate adjustment

Soil testing for relatively "immobile" nutrients, like phosphorus and potassium, is commonplace in most production systems. With the importance of N fertilization, and the difficulty in rate prediction, one would assume that soil testing would be as widely used for N management as is for other nutrients. However, soil sampling and testing for N is less used, and often works best only in certain geographic regions and crops. The reason for limited use is due to the many and rapid processes that influence N in soil, such as change in inorganic N forms and levels, especially in humid regions, variation in net N mineralization rate and prediction of that rate, and nitrate losses after measurement. The limited use of

soil N testing is also related to the time required for sampling/analysis and the desire for rapid results, for example when adjusting sidedress N applications. There are two general soil N test sampling approaches used, with both based on soil nitrate. One is post-harvest/preplant sampling and the other is in-season sampling.

Preplant soil sampling

Post-harvest or preplant soil sampling is based on determination of the profile (rooting zone) soil nitrate-N amount. This is either determined directly by sampling the rooting depth or by sampling a shallower depth and then predicting the amount for a deeper profile. Usually only nitrate-N is measured, and not ammonium-N as ammonium is converted quickly to nitrate and the measurement is attempting to find residual inorganic N from mineralization or unused fertilizer which would be predominately nitrate. In humid regions (like the Midwest, Eastern, and Southern USA), leaching and denitrification typically cause soil profile nitrate levels to change rapidly and therefore be unreliable as an adjustment to application rates for subsequent crops. Profile nitrate sampling/testing is more reliable and useful in dry climates (for example the northern Great Plains area) and areas where soils remain frozen for much of the time between fall harvest and spring planting (for example the upper Midwest).

Preplant profile sampling systems account for the amount of nitrate-N. The amount of nitrate-N is subtracted from the general recommended rate to arrive at the amount of fertilizer N to apply. This is illustrated in Figure 4. In some systems a baseline amount of nitrate is assumed, so the amount measured is adjusted downward for that baseline before determining the fertilizer rate to apply.
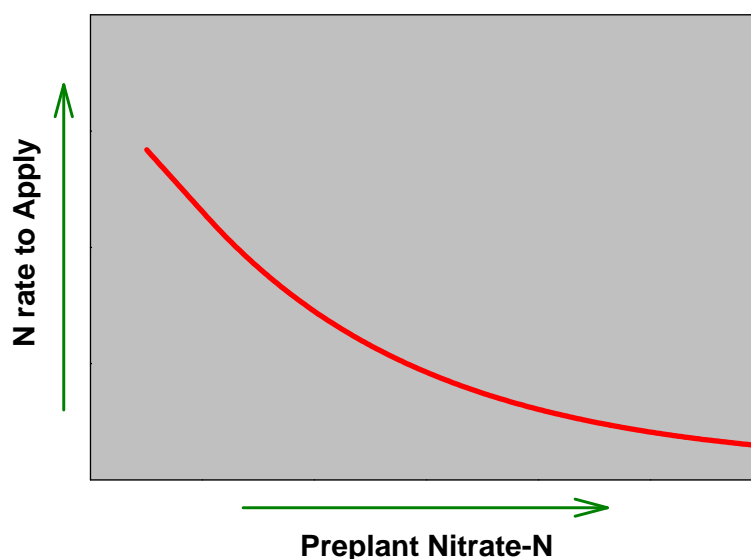
Figure 4. General relationship between N fertilization rate and preplant soil nitrate-N content.

The depth of soil sample and the depth increments separated for nitrate analysis are determined by local research and cropping system needs. Fall profile sampling may be to the rooting depth, up to four or five feet, or more shallow for spring preplant profile sampling (often 2- to 3-ft sample). In Montana, for example, fertilizer guidelines for spring wheat consider the total of amount of nitrate-N (2-ft soil depth) in the spring and a general estimate of fertilizer N needed. Then specific fertilizer rates for a field are calculated by subtracting the measured nitrate-N from the recommendation. For example, if the spring wheat yield potential is 50 bu/acre (the recommended total N is 165 lb N/acre for that yield), and if the preplant 2-ft depth soil nitrate-N measured is 40 lb N/acre, then the fertilizer rate to apply is 165 – 40 = 125 lb N/acre.

In-season soil sampling

The objective of in-season sampling is not to quantify the total inorganic N present in the soil rooting profile, but to develop an index of N availability that integrates residual inorganic-N and springtime mineralized N up to the sampling time. Soil samples are collected prior to the maximum crop N uptake period, and allowing for time to make needed N applications. For example, the nitrate-N concentration determined in soil samples collected in corn at V6 (when plants are 6 to 12 inches tall) or in winter cereals at tillering has been related through research with crop yields and EONR. This type of test goes by different names depending on the region and intent. A test for corn, for example, in some regions is

known as the pre-sidedress nitrate test (PSNT) while in other states is referred to as the late-spring nitrate test (LSNT). For both, the soil is sampled to a one-foot depth and analyzed for nitrate-N concentration when corn is 6 to 12 inches tall. The test is calibrated for a specific sample time, crop, and region. That is, the nitrate concentration (index) is evaluated against relative yield and fertilization rate requirement for specific situations (general example in Figure 5).
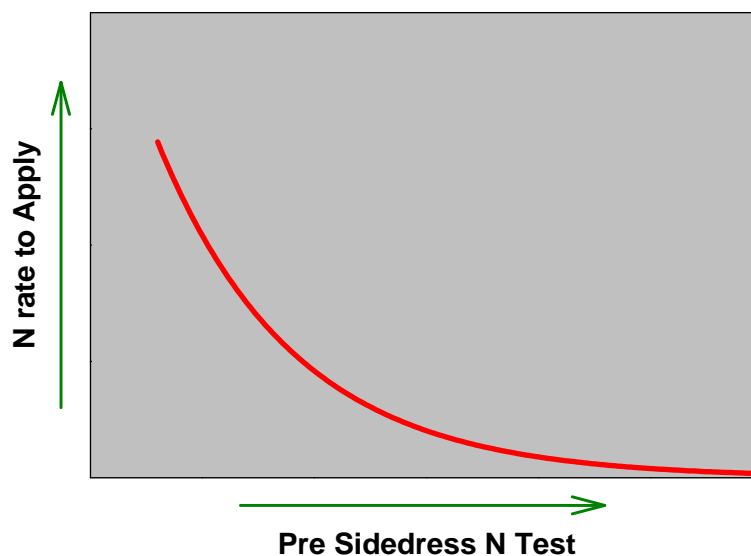
Figure 5. Generic relationship between economic optimum N rate and in-season soil N, i.e. PSNT in corn or soil N at late tillering in small grain cereals.

Use of locally developed critical values is important as the soil, environment, and crop influence the relationship between soil nitrate concentration and crop response to N application. Also, states may have specific adjustments for test interpretation based on situations such as previous legume crop, manure application, and springtime rainfall amount. For the PSNT or LSNT in corn, for example, is approximately 20 to 25 ppm nitrate-N. There may be some states or regions that include ammonium-N in addition to nitrate-N in specific situations, such as soils amended with organic wastes (manure, sewage sludge, etc.), where ammonium plus nitrate analysis may improve prediction of in-season N responses compared to nitrate alone.

The N-fertilizer need is calculated by subtracting the measured concentration of soil-test nitrate-N from the previously determined critical concentration and then multiplying the result by a factor, or using a table where the N rate recommendation is reduced as the test concentration increases. In Iowa, for example, the difference between the test result and the critical value for the LSNT is multiplied by 8

because studies have shown that it generally takes 8 lb N/acre to increase the soil-test nitrate-N by 1 ppm. For example, if a soil tests 15 ppm and the critical concentration is 25 ppm, then the fertilizer recommendation would be 80 lb N/acre [(25 ppm – 15 ppm) x 8 = 80 lb N/acre.

## Chlorophyll/Canopy Sensing and Plant Sampling

Plant N sufficiency/stress sensing offers a relative new approach to determine crop N status and manage in-season fertilizer applications. The concept is to have the plant assess the supply of plant-available soil N, and show potential deficiency through reduced plant growth and coloration. Instead of a soil test, the plant is the used as the integrator of soil N supply with plant need. Adequate crop growth is needed in order for the plant to have significant N uptake and have potential to show N deficiencies; and then time is needed to make N rate decisions, apply N, and have the crop respond to that N. Cereal crops take up N rapidly beginning at specific growth stages (V6-V8 in corn and late tillering in small grains for example). Since the objective is to detect and correct N deficiency in time for adequate yield recovery, N stress sensing may begin at those growth stages. If there is no expression of N deficiency, then the sensing either misses later season development of deficiency or none exists in the field.

Plant sampling with N analysis is infrequently used to derive rate recommendations in many crops. This has been due to difficulty in determining specific critical values and correlation to rate need, practicality for sampling, cost, and other issues similar to those with plant sensing. Plant sampling of specific plant parts has been useful in certain crops, especially for monitoring and to determine N adequacy/deficiency, for example, petiole nitrate analysis in potato and cotton, and total N in winter wheat at tillering. With corn, in-season plant tissue sampling/analysis has been difficult to find strong relationships with N fertilization need, and therefore research efforts have been directed to plant and canopy sensing to determine N need and rate determination. In corn the concentration of nitrate-N in the lower stalk near plant maturity has been useful to determine situations of excess N availability. It has not, however, been calibrated to specific rate adjustment, and of course is specific to adjusting N in future years, not the current year.

Chlorophyll meter (CM) and canopy sensor readings are unit-less values and by themself do not adequately determine N sufficiency/stress. When readings are compared (normalized) with readings from an adequately N fertilized reference area (non-N stressed), then the crop N status relative to the greenest and/or greatest vegetation crop area in the field is evaluated. It is critical that each field has reference strips or areas to reduce the confounding effects of other variables on growth and coloration such as hybrid/varieties, other nutrient deficiencies, soils, or environmental conditions. Reference strips or areas

can be created by applying extra N (approximately 50 percent more than typically required for the rotation) at preplant or early sidedress growth stages. Other reference concepts include using a "virtual reference", where the best (greenest and greatest growth) crop in the field is used as the reference and no pre-set references are created with extra applied N. Normalization is made by taking the average reading of the crop in the area of interest and dividing this number by the average reading of the closest reference area. Enough reference areas are needed to characterize differing field areas.

Figure 6 shows a conceptual relationship (calibration) between normalized CM or canopy sensor values and the differential (N rate difference) from the EONR. Information like this, or other calibrated algorithms, should be used to decide how much N (if any) is necessary to apply based on CM or canopy sensor determinations. This type of information is being developed by universities and the industry to help producers make in-season N decisions based on these sensing tools. Various sensing devices are available, including the Minolta SPAD 502® CM (Konica Minolta) and several canopy sensors like the GreenSeeker® (NTech/Trimble), Crop Circle®/OptRx® (Holland Scientific/AgLeader), and CropSpec® (TOPCON).
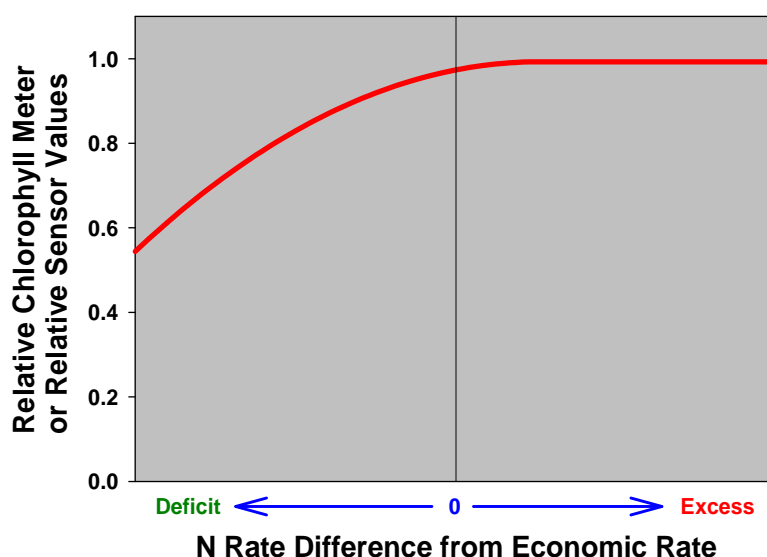
*Figure 6. Relative chlorophyll meter or relative canopy sensor value
as related to the differential from the economic optimum N rate in corn in Iowa.
Rates to the left of zero are deficient N, and to the right excess N.*

Chlorophyll Meter

The Minolta SPAD 502 CM is a handheld device that measures the greenness of crop leaves as reflected by the chlorophyll content and N status. The relationship between leaf greenness and N sufficiency is well documented for various crops. Plants will reach a maximum greenness with adequate N and when N stressed, the plants will be less green. The CM is highly portable and provides an instantaneous non-destructive reading of the crop N status. It is important to sample the plant part (same leaf at the same spot on the leaf) and growth stage that has been used for the CM sensing calibration. For corn, this is halfway down the leaf from the tip to the base and halfway from the leaf edge to the midrib, and the uppermost leaf that is fully collared (leaf collar fully visible around the stalk) at mid-vegetative growth stages. For cereal crops, sampling may be at or after late tillering. Readings should be collected from many plants to account for sampling errors and natural color variation across leaves and between plants.

The example for Iowa research of the CM method for corn in Figure 6 shows that relative CM values decline below optimal N, and as the relative values become smaller, the N deficiency and needed N application rate increases. However, relative CM values are similar with slight deficient N, adequate N, and excess N. This makes it difficult to determine in-season N need when N deficiency is slight. Research has shown that in-season N applications may be suggested by relative CM values when the N deficiency appears slight, but yield response indicates the in-season N is not always needed. At a given relative CM value, the N rate is derived from the calibration curve. For example, at a relative value of 0.93, the suggested N rate would be 60 lb N/acre. Either an equation can be used for determining application rates, or a table can be created that gives N rates for ranges in relative CM values.

In the same way, in-season N recommendations for wheat (Kentucky) are based on CM readings at Feekes 5 growth stage (late tillering): N rate (lb N/acre) = 6 + (7 x (CM reference area – CM field)). For example, if the CM value of the reference area at late tillering is 52 and the CM value of the rest of the field is 45 the recommendation would be 6 + (7 x 7) = 55 lb. N/acre. When using a CM to determine N stress and N application need, it is important to follow locally suggested sensing timing, crop stage, plant part, and calibrated application rates.

Active Canopy Sensors

Active canopy sensors, which are positioned above the crop canopy, have been developed as a tool to determine plant N stress deficiency and provide an on-the-go decision for implementing variable rate N application. This is a relatively new method of remote sensing. It is similar to that of natural light reflectance with passive (reflected sunlight) sensing technologies. However, active canopy sensors utilize

their own light source and measure light reflectance in real-time at the canopy level. Initial research with the GreenSeeker active canopy sensor in Oklahoma documented that active sensors are a viable method to improve N use efficiency in winter wheat, and when compared to uniform N rate application based on traditional yield goal, N use efficiency was improved 15%. In corn, research with active sensors has investigated issues such as growth stage for sensing, need for normalization of sensor readings to non-limiting N field areas, and calibration of sensor indices to N fertilization requirements. Also, use of active sensors to direct variable rate N must include an understanding of situations where other factors are limiting growth, such as poor stand, excess water, or other nutrient deficiency.

Many canopy indices can be calculated from the visible (VIS) and near-infrared (NIR) light reflectance variables typically collected with active sensors. Examples being implemented are normalized difference vegetative index (NDVI) and chlorophyll index (Chl). Indices emphasize different plant characteristics important for determining N stress, such as plant canopy biomass or plant coloration. The various indices have different strengths and weaknesses. Most important is to know the sensor and especially the index being utilized, and the specific calibration of the index for the crop being sensed. As with the CM, there needs to be a calibration between the relative index, N stress level, and recommended N rate to apply. Nitrogen application rates based on canopy sensors should be calculated using locally developed algorithms and recommendation systems.

An important consideration for active canopy sensing is the crop stage to sense. For corn, this is still a subject of research. It appears that the early to mid-vegetative growth stage may allow for adequate expression of N stress, if it is to occur, and if N deficiency is found then time for corn to respond to applied N. Of issue, as with the CM, is the rate of N applied preplant, at planting, or early sidedress. The greater that N rate, the less chance for significant N stress to develop by the time of sensing, especially for early growth stages. The lower that rate (or no application), then the greater the chance for N stress development that can be measured, but also the greater chance for too much N stress and loss of crop yield potential. As with the CM, the difference between slight N deficiency and adequate to excess N is difficult to differentiate with active canopy sensors.

Two general approaches could be implemented with active sensors. One is to plan on conducting canopy sensing each year, with a reduced N rate applied preplant, at planting, or early sidedress and then sensing conducted at mid-vegetative growth to determine additional application need. A second approach is to conduct sensing only if conditions result in N loss from the primary N application, or other factors change expected crop requirements. Both approaches could address variable N fertilization and seasonal circumstances. The second approach allows producers to use normal preplant or early sidedress N

management. However, there could be instances where less than normally recommended N rates would produce optimal yield, and those situations would be missed with that approach. Also, as with CM sensing, canopy sensing may miss season-long N deficiency if the preplant rate is adequate to meet plant needs through the time of sensing.

Variable Rate Technologies

Recognition of within-field variability in soil properties, crop yield, crop nutrient need, and nutrient supply by site-specific nutrient management is gaining popularity as technology advances. Applying different amounts of N fertilizer in different parts of the field according to soil conditions and crop need seems intuitively obvious. Crop producers are interested in variable rate N management due to the popularity of site-specific phosphorus, potassium, and lime application. Producers know soils differ within fields, and often those differences can result in significant yield variation. During the growing season, crops may express differences in leaf color if N or other nutrients are low in supply and deficiencies result. Crop and soil computer simulation models also suggest there can be substantial differences in soil N supply or crop N demand within a field.

Whole fields are divided into management units where the fertilizer application may differ using some form of field diagnostic, such as intensive soil sampling, soil and crop remote sensing, aerial images, yield mapping. Consistently poor crop performance in one part of the field may indicate (although not always) greater potential for N loss if N is applied uniformly across the field. Variation in soil organic matter and soil texture can be important influences on N management. Soil maps, bare soil images, grid soil sampling and/or mapping of electrical conductivity may indicate this type of variation. For example, a field divided into knolls, mid-slope and depressions areas may have a small N demand in the depressions, moderate on the mid-slope, and high on the knolls. However, producers know that while the fertility level may be low on the knoll, so can be water supply and yield potential. Field history can also be zoned to account for old barnyard sites, past manure management and sections of the field which may have been broken from natural grassland later than other areas. Together, this information can be used to develop zone specific nutrient application strategies. However, the magnitude of the variation or lack of predictability or repeatability in N rate need may not justify varying N rates. Aerial imagery is useful once the crop canopy is sufficiently developed and soil reflectance no longer dominates the image. These tools are particularly suited for surveying large areas, such as when wet weather creates potential for N loss. Aerial photos or calculated sufficiency indices potentially can be calibrated to predict likely yield gain from applying additional N.

A recent, and potentially the most promising approach for making variable rate N applications, is the use of the previously mentioned active canopy sensors. The sensor is mounted on a field applicator capable of varying the N rate on-the-go. In instances where field variability of N is large, this type of application prevents the over-application characteristic of fixed field rates in those areas where the soil N supply is sufficient. Potential drawbacks of chlorophyll or canopy sensors were discussed before and apply to their use for variable-rate application. For example, the leaf area needs to be sufficiently developed to reflect enough light to reliably indicate N fertilization need. This increases risk as wet weather may delay or prevent sidedress application. To approach in-season N management in tall crops, i.e. corn or sorghum, high clearance equipment is likely needed to apply sensor-based N. In-season variable rate N application may be useful and very practical for fertigation because of rapid advances in the technology to sense N deficiency and vary N application rates through center-pivot systems. The specific knowledge and recommendations for variable-rate N application at this time vary greatly across states due to the different set of issues across regions and different pace of research.

Application Timing, Product and Placement

Timing

The demand for N by a growing crop is not constant through the growing season, with the highest uptake associated with the period of most rapid growth. Timing N fertilizer applications so that they provide a plant-available supply of nutrients when the crop needs them is the desired goal. Plants subject to deficiency during a high demand period may not recover to achieve full yield potential even with high N rates applied too late. Because N fertilizers are subject to transformation in the soil, application timing can play a critical role in optimizing crop response and high use efficiency.

Producers in certain geographic areas, such as the upper Midwest (colder winter season) and Great Plains (drier winter season) prefer to apply N fertilizer for corn as anhydrous ammonia in the fall when there is more time for application, the N price may be lower, and the soil is more likely to be in good condition for application. The disadvantage of fall application is increased risk of loss before crop N uptake the next summer. Nitrification of ammonium N will be slow if the soil temperature is low after application, with a suggested practice to not apply ammonia in the fall until soils cool to $50°$F and continue to get colder. Fall-applied N may be nitrified before the crop is planted due to application when soil temperatures are relatively high, unexpected warming of the soil after application, periodic warming during the winter, and early warming of the soil in spring. This nitrate will be subject to leaching and denitrification with spring rains and waterlogged soils that occur before and after the crop is established. Anhydrous ammonia is slower to convert to nitrate than ammonium from other fertilizers and is the only N source that should be

considered for fall application in most areas. Use of a nitrification inhibitor (such as N-Serve®, Dow AgroSciences) with fall-applied ammonia can improve the effectiveness by slowing nitrification. Many studies show, however, that spring applied N is more effective than inhibitor-treated fall ammonia when conditions favoring N loss develop.

Despite the advantages of anhydrous ammonia and potential slowing of nitrification with an inhibitor, geographic areas with warm winters and high rainfall do not utilize fall applied ammonia due to the high risk of nitrate loss. Fall application is only suggested for regions where winters have frozen soils, rainfall is low, and soils have good but not excessive internal drainage – that is, are not coarse textured with excess leaching or poorly drained and subject to excessive wetness. Nitrogen use efficiency with fall application typically averages 10-15 percent lower than spring application, and reduced yield will cancel other benefits of fall application.

Benefits from delayed, sidedress, and split N applications are greatest where there is a high risk of N loss between planting and crop N use. These typically are with sandy soils that have high leaching, poorly drained soils that increase chance of saturated soils and denitrification, and regions with early high spring rainfall. In these cases, N use efficiency and crop yield can be increased and nitrate leaching reduced by applying a major part of the N in-season, at or near the time when crop N demand is high. Sidedress application also allows for use of in-season soil tests and plant N stress sensing to adjust N rates. Many producers are reluctant to apply N in-season as they may be busy with other operations, concerned about yield loss due to early N stress, or concerned that wet weather will prevent application. Delay in sidedress applications can reduce yield, but this can be avoided or minimized by applying a portion of the needed N before or at planting as a split application.

Applying N through irrigation systems (fertigation) is an important form of in-season N management in irrigated regions. Fertigation can be very efficient, especially in sandy soils with high leaching potential, but must be practiced with appropriate safeguards such as backflow contamination and avoiding over watering which can result in leaching. In most cases, N application through irrigation systems is completed by the end of vegetative growth.

Product

Several organic and inorganic N sources can supply N required for optimum crop growth. Efficient management of all N products requires an understanding of N cycling, soil transformations, and crop demand. Product management that minimizes losses and maximize the quantity of applied N recovered by the crop will increase production efficiency and reduce potential impacts on the environment.

Manure

Manure sources have characteristics that make nutrient management different and sometimes more complicated than fertilizer. These characteristics include a mix of organic and inorganic N forms, variation in N concentration and forms, handling as a liquid or solid, and relatively low nutrient concentration requiring large application volumes. Since manure N composition can vary significantly, sampling and laboratory analysis are always needed. As with fertilizers, significant amounts of plant usable manure nutrients can be lost and became unavailable to crops after application. For example, inorganic N in manure or derived from manure through mineralization can be lost through processes such as volatilization, leaching, or denitrification. Also, inorganic N can be converted for short or long periods of time into forms not usable by plants through processes such as immobilization to organic materials. Conversely, with high carbon containing manure sources, significant time may be needed to provide plant available inorganic N.

Anhydrous ammonia (NH_3) (82 percent N)

Anhydrous ammonia is widely used for direct application because of its relative low cost and high N concentration. Many safety features must be considered when transporting and applying anhydrous ammonia, and strict safety procedures must be followed during handling. It can be applied preplant or sidedressed in row crops. Soil moisture content should not be too dry or too wet when anhydrous ammonia is applied in order to avoid volatile losses due to poor soil sealing or coverage of the injection track. Shallow placement may result in early season crop seedling or root damage from free ammonia. Proper depth and injection in good soil conditions helps avoid such problems. Also, injection between future corn rows, using GPS and auto guidance, can avoid future corn rows. In corn, application can be made between every other row. For small grains, knife spacing needs to be close enough to avoid streaking of poor plant growth between injection tracks. Addition of a nitrification inhibitor with late fall application may be beneficial to slow nitrification in the fall and early spring.

Urea (CO(NH$_2$)$_2$) (46 percent N)

Dry urea is widely used as a broadcast N product for many crops. It converts quickly to ammonium (a process called hydrolysis), especially in warm-moist soils. That conversion is increased rapidly due to the urease enzyme, found in soil and plant residue. In no-till situations, ammonia volatilization from surface application is a concern, especially if there is high crop residue, soils are warm and moist, soil has high pH, and there is not a significant (> 0.25 inch) rainfall for many days after application. Incorporation soon after application (within 2 days), or injection, places urea into the soil and avoids loss of ammonia. If surface application with no incorporation is planned, then urea can be treated with a urease inhibitor (Agrotain®, Agrotain International) to slow urea conversion to ammonium and give more time for rain to move urea into the soil. The best management, however, is to incorporate broadcast urea. Because of urea hydrolysis and production of ammonia, urea should not be placed in furrow with seed placement.

Coated urea and slow release products

Coating urea with various impermeable substances (such as elemental sulfur, polyurethane, semi-permeable polymers, etc.) allows the urea to be protected from conversion to ammonium and subsequently to nitrate when applied to soils. This technology allows production of urea based fertilizers that have controlled release characteristics. That means the timing of urea conversion (release) to plant available inorganic ammonium and nitrate can be controlled to match the unique uptake pattern of specific crops. For crops like wheat, this would be an early spring release. For corn, it would be release in late spring before rapid vegetative growth. The reason for having such products is to have urea in a form that is not be affected by wet weather, and thus avoids times where excess rainfall and wet soils would cause nitrate loss. Many such products have been developed. Most are targeted and most useful in specialty crops and turf. More recently, products have been developed for agronomic crops, such as corn. An example is ESN® (Agrium, Inc.). That product, for example, controls release based on soil temperature. Product cost is higher due to the need for adding the coating. While a controlled release product has advantages to help control N loss, there is also the option for using traditional products and changing the timing to more closely match crop uptake. A similar strategy is used with products that have varying chemical structures that slow the conversion to plant available inorganic N. There are many of these products, with greatest use in specialty crops and turf. Timing of N release has been an issue with agronomic crops due to rapid crop N uptake patterns and too slow of release to plant available N. If the N remains in the original fertilizer form as when applied, then it will not be in a plant available form and not be taken up by the intended crop.

Urea-ammonium nitrate solution (UAN) (28-32 percent N)

Urea-ammonium nitrate solution is widely used as a broadcast and injected product for many crops. It is approximately one-half urea and one-half ammonium nitrate. Therefore, the product contains 50 percent of the N as urea, 25 percent as ammonium, and 25 percent as nitrate. UAN is popular because of the versatility as a liquid, as well as widespread availability and applicability. The nitrate portion is immediately subject to leaching and denitrification upon application. The urea portion is subject to ammonia formation, and therefore the same loss and plant injury mechanisms as dry urea. UAN can also be banded on the soil surface by dribbling, which reduces the interaction with crop residue and potential for volatile ammonia loss. As with dry urea, a urease inhibitor can be added to UAN for planned surface applications that will not be incorporated. Potential effectiveness of a urease inhibitor is similar to that with dry urea, but overall the potential gain is less with UAN as only half of the N is in the urea form.

Ammonium nitrate (NH_4-NO_3^-) (34 percent N)

In recent years, use of dry ammonium nitrate as a fertilizer has decreased due to regulations and safety issues. Both the ammonium and nitrate portions (50 percent each) are immediately available for plant uptake. The nitrate portion is immediately subject to leaching and denitrification upon application. There is no volatile loss potential from surface application on most soils, with some on calcareous (high pH) soils. This characteristic has made ammonium nitrate popular as a broadcast material in grass crops, small grains, and no-till production systems.

<u>Placement</u>

An important part of optimizing crop response to fertilization is ensuring that N is placed in a location where crop root interception or dissolved nutrient movement to roots is in time for optimum growth. Maximizing crop N uptake also reduces the potential for nutrient loss, and placement can be a powerful management tool to help minimize N losses. Under ideal conditions, the goal is to have applied N so that it is in a plant-available form and in close proximity to roots when plants require the N. Since nitrate is rapidly produced from all applied fertilizers, and it moves easily in soil with water, N placement is not as critical as for nutrients that have limited movement. Nitrogen fertilizers can be applied by several methods depending on the N source, equipment availability, and time of application. In some cases, the fertilizer product characteristic dictates the placement method, such as anhydrous ammonia.

Injected or banded

Injecting N fertilizers and manure may be required due to the product, to avoid volatile losses and odors, to match crop row spacing, to avoid crop injury that may occur with broadcast application, or may simply be of convenience. Anhydrous ammonia must be injected into the soil as if it were surface applied the majority would simply go into the air. Urea and UAN solutions can be surface applied, but injection avoids potential volatile losses. Applying in a concentrated band within the root zone can ensure N placement where roots can access the N, which can be especially important in dry conditions. Surface banding liquids, like UAN, can increase product contact with soil and reduce volatile loss. In small grains, surface banding UAN instead of broadcasting can help avoid plant foliage injury. Banding N beside and below the seed placement at planting is a viable approach to have a high N starter available for early growth – something shown to be effective in no-till corn production and especially when sidedressing the major N application. Due to seed safety issues, placing N with seeds limits the application rate. This application may be helpful for very early growth, but cannot be used as a replacement to meet early season crop demands. In addition, urea should not be placed with seeds due to ammonia injury potential.

Broadcast

Broadcast applications uniformly distribute N across the soil and are often applied preplant or prior to emergence. In conjunction with incorporation, applied N is mixed uniformly within the upper rooting zone. This can be particularly important for solid seeded or close row spaced crops when banding is not viable. As mentioned before, surface broadcast applications of urea-based fertilizers and high ammonium containing manure sources should be incorporated to minimize volatile losses. Broadcast fertilizer application after crop emergence should be carefully evaluated due to potential for crop injury. Application when plants are small or use of low application rates will help minimize potential injury. Product use also has a large effect on potential foliar injury, with dry materials like urea having much less injury potential than UAN solutions.

Fertigation

Irrigation systems, especially pivot systems, can be fitted with equipment to apply N solutions with the irrigation water. This method has the advantage of avoiding a separate field operation to apply N and allows for multiple applications throughout the season to "spoon feed" the crop. This is especially useful on coarse textured soils with high leaching loss potential. Nitrogen fertigation has the disadvantage that timely rains may reduce or eliminate the need for irrigation, thus limiting N application opportunities.

Case Study

There are many different nitrogen (N) management strategies for crop production that are used by producers across the U.S. It is impossible to give one example representative for all geographic areas, crops, current management systems, and options for improved N use. These would vary by producer philosophy, crop, rotation, climate, available fertilizer or manure, and application equipment. The following example describes a N management system being used for a specific farm in the U.S. Corn Belt, and possible practices the producer could consider to improve crop N use efficiency, economic return from N application, and reduce nitrate loss to surface waters.

<u>Example Scenario</u>

- A 1,500 acre farm in North Central Iowa.

- Soils are prairie-derived, glacial till parent material silt loam and silty clay loam, with variability between fields in soils from well drained (not excessively drained) to poorly drained with subsurface tiles for improved drainage.

- The farm has fields with continuous corn and corn rotated with soybean.

- Each year some fields have solid chicken layer manure applied as a nutrient input.

- The producer always applies chicken manure early in the fall for the next corn crop, and fertilizer N in the late fall (after soils cool below $50°F$) as anhydrous ammonia. No N is applied in the spring or after planting.

- The N fertilizer application does not account for any N supply from the applied chicken manure, with the manure solely viewed as a P and K nutrient source.

- The anhydrous ammonia rates are based on a yield goal system (corn yield times 1.2 minus a soybean credit), with historical yields of 190 bu/acre in continuous corn and 210 bu/acre in corn following soybean in good production years. However, yields are considerably lower in years with excessive rainfall. The N rates are not adjusted by field, are based on the years with best yields, and average 220 lb N/acre for corn following corn and 200 lb N/acre for corn following soybean. The rates are not adjusted for corn price or N cost, and no in-season N diagnostic tools are used to adjust rates.

In wet years, and especially in the fields with poorly drained soils, the producer has noticed yellow corn late in the growing season, indicating N loss via leaching and/or denitrification. This has occurred despite improved drainage with tile.

This example scenario is not uncommon in many areas of the U.S. Corn belt, and emphasizes the potential benefits from development of an improved N management plan.

Following are management options to consider. These are listed in order of greatest potential to improve N use and provide tools to adjust N rate in season for varying climatic conditions.

Practice One

The rate of N application has a large impact on corn yield and nitrate loss to water systems. Therefore, the rate decision process should change from the old and no longer recommended yield goal times a yield factor system to the current system used across the Corn Belt that is based on current N response trials, N and corn prices (Maximum Return To N, MRTN), and results from the Corn N Rate Calculator for the specific state and production system. The N rate recommended will change depending on the current N and corn prices. For example in Iowa, at a price for anhydrous ammonia of $800/ton ($0.49/lb N) and a corn price at $6.00/bu, the recommended rate for corn following soybean is 140 lb N/acre (MRTN rate), with a profitable range of 129 to 151 lb N/acre. For corn following corn, the MRTN rate is 199 lb N/acre with a profitable range of 185 to 209 lb N/acre. The rate change from the current practice for corn rotated with soybean would be 60 lb N/acre lower and for continuous corn would be 20 lb N/acre lower. Both rates would improve economic return (less N cost and unlikely impact on yield) and have less impact on N loss via tile flow or leaching to groundwater. The largest impact on reducing nitrate loss to water systems would come from the rate change in the corn-soybean rotation. That system has the highest corn yield and N removal, but research has also shown it to have much lower N fertilization need than derived from yield based recommendations.

Practice Two

For the fields receiving fall poultry manure applications, a priority would be to account for the crop available N in the manure application. In addition, the N component of the poultry manure should be accounted for in the total crop available N application. According to Iowa research and recommendations, 50 to 60% of the total poultry manure N applied is crop available in the year of application and 10% is available in the second year. Subtract appropriate manure N supply amounts from the corn N recommendations. Accounting for available N from the poultry manure should be done in conjunction with the switch to the MRTN rates, and then apply the remaining N need as fertilizer. Try to schedule applications for late fall or spring to help reduce conversion of N to nitrate. In addition, if possible incorporate the manure to reduce volatile ammonia-N loss on fields where fall tillage will not increase chance of soil erosion.

Practice Three

With the reduced MRTN-based N rate recommendations for both cropping systems, N application management should be improved to help reduce nitrate losses in spring and early summer and therefore avoid potential yield issues. Instead of a fall application of anhydrous ammonia to all fields, fall application should be targeted only to fields with well drained soils and also should consider use of a nitrification inhibitor along with a late fall application. For fields with more poorly drained soils, N application should be switched to spring or post-emergence sidedress application. The producer can continue to use anhydrous ammonia for either timing. If spring application is preferred, then anhydrous ammonia would be a preferred source. Another option could be use of a coated urea product to slow release of N. If sidedressing is preferred, either anhydrous ammonia or N solutions could be used. When sidedressing, use of a split application (some preplant or at planting and the largest amount at sidedress) would ensure adequate N for the corn until sidedressing – which would be especially important for late sidedress applications (V5 or later) in corn following corn. These N options spread out the N application workload, and still allow use of a least cost N source such as anhydrous ammonia, but may not always result in significant further reduction of nitrate loss in addition to practices outlined in option 1 and 2.

Practice Four

In fields that have poultry manure applied, and where sidedress fertilizer N application will be practiced, in-season diagnostic tools can be used to adjust corn N fertilizer inputs. One tool is the soil nitrate test (called LSNT in Iowa, PSNT in other areas). This test can help to better account for available N from the poultry manure, including in the second corn year following manure application, and adjust for seasonal effects on soil and manure N supply. For this test, soil is sampled in late spring to a one foot depth when corn is 6 to 12 inches tall. The sidedress fertilizer rate is then adjusted based on the results of the test. Use of this nitrate test does not mean that no preplant N should be applied, especially in continuous corn.

An alternate in-season diagnostic tool is the emerging use of active canopy sensors at the mid-vegetative corn growth stage to determine potential N shortages by sensing the plant N status and vegetative growth. In years with excess wetness, this practice may allow for application of additional N if shortages occur during the early season. This practice could be especially helpful when there is no soil nitrate testing and where it is difficult to collect representative soil samples (due to N banding) for a soil nitrate test. Canopy sensing can be used in addition to previously suggested N-rate reduction practices, in fields with manure application, or where N was applied well in advance of plant need such as late fall ammonia. Use of this canopy sensing technology requires well fertilized reference areas across fields (known non-N deficient reference) to compare against, so additional planning is required for implementing these references. In

addition, the sensing is conducted after corn has reached a height that will likely not allow use of traditional sidedress application equipment, and instead will require high clearance applicators that can dribble or coulter inject N solutions, or broadcast dry fertilizer such as urea. Use of this tool does not mean that no preplant N should be applied, especially in continuous corn. Trial use of this technology could be targeted to fields with known history of N loss and crop N shortages when climatic and field conditions are conducive to N loss.

Chapter 3:
Phosphorus Management

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Introduction

Phosphorus (P) is an essential nutrient for crop production since it is required for many plant functions, including energy transfer and protein synthesis. Phosphorus is included in adenosine phosphates (ADP and ATP) that play a crucial role as "energy currency" within plants. It is also a component of deoxyribonucleic acid (DNA) and ribonucleic acid (RNA), which contain the genetic code of the plant. Adequate P supply is associated with increased cell multiplication, stem and root growth, stem strength, nitrogen (N) fixation capacity of legumes, and grain yield. The most common visual symptoms of P deficiency in plants include overall stunting and, in with extreme deficiency, dark green/purple coloration of leaves.

Phosphorus uptake and removal from fields with harvest are highly dependent on yield and to a lesser extent the tissue P concentration, although amounts typically are much less than for N or potassium (K). Table 1 shows, as an example, the Iowa guidelines concerning P concentration per unit of yield for several crops. Commercial P fertilizer analysis has historically been expressed as the oxide form (P_2O_5) rather than the elemental form (P), therefore P uptake and removal values usually are expressed as P_2O_5 per unit of yield. Using the ratio of their molecular weights, %P_2O_5 can be converted to %P by multiplying by 0.44 (%P = %P_2O_5 x 0.44). To more accurately estimate P_2O_5 uptake or removal for a specific situation, one can have P analyzed in the plant tissue that is removed from the field, and multiply the result by the dry matter yield removed. The estimate of P that is being removed by the crop can help in determining P fertilization recommendations to maintain desirable soil-test P levels.

Table 1. Phosphorus amounts in harvested portions for selected agricultural crops.

Crop	Unit of Yield	Pounds P_2O_5 per unit of yield
Corn	bu	0.37
Corn silage	bu grain equivalent	0.55
Soybean	bu	0.80
Oat and Straw	bu	0.40
Wheat	bu	0.60
Sunflower	100 lb	0.80
Alfalfa	ton	12.5
Tall fescue	ton	12.0

Source: Iowa State University Extension publication PM 1688.

In some regions with short histories of grain-crop production and little application of animal manures, soil-test P levels are low and crop response to P application is very likely. In most regions of the U.S., however, the natural amount of crop-available P in soils has been increased due to long-term application of P fertilizer or animal manure. When soil P levels become excessive, the danger of freshwater eutrophication increases, which is now one of the most common water quality impairments in the humid regions of the U.S. and many developed countries. Recent outbreaks of harmful algal blooms (e.g., *cyanobacteria* and *P. fiesteria*) have increased society's awareness of eutrophication and the need for solutions. The concentration of specialized farming systems has led to a P transfer from grain- to animal producing areas. This transfer has created regional surpluses of P inputs as fertilizer and feed, increases of soil P in excess of crop needs, and increased risk of P loss from land to surface waters. The overall goal of efforts to reduce P loss to water should be to balance P inputs and outputs at farm and watershed levels, while managing soil and P in ways that maintain or increase productivity. Management strategies that minimize P loss to surface water may involve optimizing P use efficiency by using soil testing and proper P application recommendations, variable-rate application, transport of manure from areas with surplus to areas with P deficit, and implementation of soil conservation practices to reduce erosion and runoff.

In order to improve P management in agricultural systems, however, it is important to first understand the main P processes that occur in the soil-plant system.

Basic Phosphorus Processes in the Soil-Plant System

Phosphorus in Soils

Phosphorus exists in the soil as dissolved orthophosphate in solution (mainly HPO_4^{-2} or $H_2PO_4^-$ depending on soil pH), sorbed P on the surface of organic or inorganic compounds, or as part of organic P compounds or P minerals. The dissolved phosphate ion is the only form that plants can take up, yet in the surface layer of most agricultural soils there is less than 1 mg/L (1 ppm) of dissolved phosphate in the soil solution (soil water), except in recently fertilized soils. On the other hand, the total soil P concentration can vary from about 200 to 2,000 ppm depending greatly on soil parent material and histories of cropping and fertilizer or manure application. Organic P normally represents about 25 to 65% of total P in surface soils, depending mainly on soil organic matter content. Organic P usually decreases abruptly with soil depth, paralleling decreases in organic matter. The processes that control the amount of plant available P in the soil are plant uptake, sorption/desorption, mineralization/immobilization, precipitation/dissolution, runoff, and leaching. Because of the usually very small concentration of P in the soil solution, an understanding of these processes is important for implementing good P management.

Phosphorus retention in soils

Inorganic P dynamics in soils are dominated by processes of sorption/desorption and precipitation/dissolution. Sorption refers to the binding of P to the surface of soil particles. Phosphorus sorption/desorption reactions are strongly influenced by soil pH, texture, and mineralogy of fine soil particles. For example, orthophosphate reacts strongly with aluminum (Al) and iron (Fe) oxides and hydroxides, especially at low pH, and also with carbonates in high-pH soils. Fine textured soils generally can sorb more P because they have higher clay concentration and greater surface area. Dissolved organic compounds from recent organic matter additions can increase P availability by blocking sites or coating Fe/Al oxides. Phosphorus desorption generally increases as solution P decreases due to plant uptake or leaching, and also under flooded or waterlogged conditions due to changes of Fe hydroxides and oxides to more soluble forms. When high P fertilizer rates are applied, P sorption sites can become partially saturated, which increases the recovery of added P but can also increase dissolved P loss through the soil profile or surface runoff.

Precipitation/dissolution reactions occur at the same time as sorption/desorption, although not necessarily in the same volume of soil. Precipitation takes place mainly when a water-soluble P source increases the concentration of phosphate in the soil solution, and it forms compounds with cations added with the P source or already present in the soil solution. Dissolution occurs mainly when added, recently formed, or

native P compounds dissolve as a result of decreases in the concentration of soluble phosphate in solution. The P precipitation/dissolution reactions are largely dominated by a variety of calcium phosphates (Ca-P) in neutral to high-pH soils and by Al and Fe phosphates (Al-P and Fe-P) at pH levels below about 6.5. Reactions of ammonium phosphates or potassium phosphates temporarily can dominate, however, when fertilizers containing these compounds are added to the soil.

When a water-soluble P fertilizer is added to moist soil, a solution with a very high phosphate ion concentration develops at the application point (granule or band), and in the immediate vicinity an acid or alkaline condition depending on the fertilizer material. This solution is very acid (pH 1 to 2) for superphosphate fertilizers (mono-calcium phosphates), moderately acid (about pH 4) for mono-ammonium phosphate (MAP) fertilizer, and alkaline (about pH 8) for di-ammonium phosphate fertilizer (DAP). This concentration of phosphate diffuses away from the application point, and intense reactions occur with soil constituents. The phosphate concentration in the soil solution decreases over time, the original soil pH at the application point is restored, and much of the added P becomes retained by the soil particles (sorbed or precipitated) but still has high plant-availability. Therefore, added P does not have a long-term effect on soil pH. Large application rates of MAP or DAP can acidify soil, however, because of the nitrification of ammonium contained in these fertilizers.

Over a few weeks or months (depending on soil chemical and mineralogical properties) some of the applied P may become strongly retained and therefore less available for crops. Soils with high levels of calcium carbonate may strongly retain a higher proportion of added soluble P due to more adsorption to carbonate surfaces and transformation of initially soluble Ca phosphates to less soluble forms. Soils with high levels of Fe-oxides (soil can be strongly or moderately acid) may strongly retain a higher proportion of added soluble P due to high adsorption to oxides surfaces and transformation of initially soluble Al or Fe phosphates to less soluble forms. Therefore, in general and under otherwise similar conditions, P is most readily available between pH 6 and 7 (Figure 1). In many soils and outside that pH range, however, the retention is reversible. As soluble P is taken up by plants, retained P replenishes the low concentration of soluble P and, therefore, acts as a reservoir for plant available P supply.
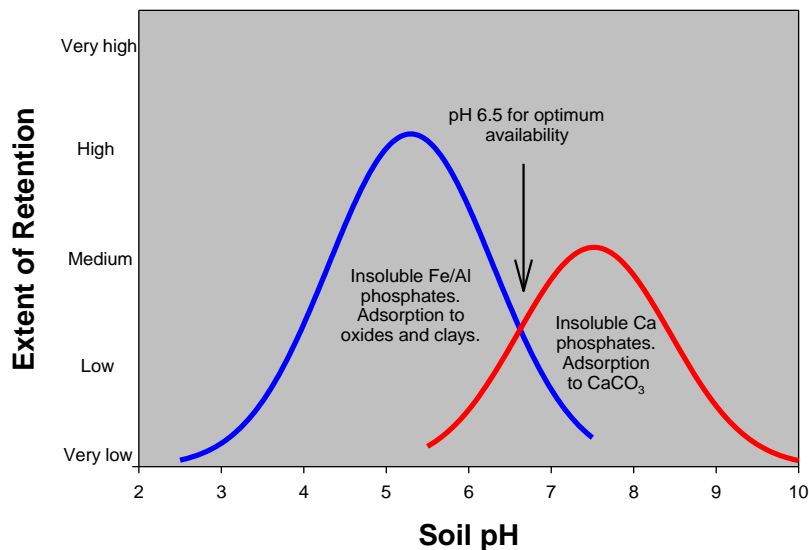
Figure 1. The effect of soil pH on P retention and availability.

Mineralization and immobilization

Phosphorus mineralization is the process by which organic P becomes converted to phosphate ions as organic materials decompose, and immobilization is the process by which soluble P becomes tied up in microorganism cells. In the U.S., annual P mineralization in soils has been found to range from 4 to 22 lb P_2O_5/acre/year, which can represent a significant portion of crop P uptake in some situations. Mineralization occurs most readily when the C:P ratio of a material is less than 200:1, and immobilization occurs when that ratio is greater than 300:1. Mineralization and immobilization of P are affected by temperature, moisture, aeration, and pH in similar ways as N mineralization and immobilization, because they involve microbial and enzymatic processes. In practice, however, and with a few exceptions, the importance of P mineralization/immobilization is much less than it is for N. This is because in most soils, the inorganic P reactions dominate and have the greatest influence on plant P availability. There are exceptions where organic P mineralization/immobilization can have a major influence on plant available P. These include large application of organic materials with very high or very low P concentration, tillage of permanent hay or pastures in soils with moderate to high P levels (net mineralization), or when soils with low organic matter from many years of improper cropping and erosion control are changed to pasture/hay or no-till management with relatively low P fertilization rates (net immobilization).

Phosphorus: A Relatively Immobile Nutrient

As a result of the P reactions and processes in soils, P moves slowly and only short distances. The amount of P that reaches the root surface with water mass flow is not sufficient to supply plant needs, and phosphate ion diffusion through the soil solution is the main mechanism of plant P uptake. This characteristic has several important consequences. From a plant uptake perspective, factors that limit the rate of P diffusion and both the rate of root growth and the size of the root system can limit P uptake. These include cold temperature and low moisture (which limit diffusion and root growth), soil physical properties that inhibit root growth, and diseases or pests that impair root function. Therefore, induced P deficiency may occur even with adequate soil-test levels. In these situations, or when there is strong soil P retention, placement that puts applied P near young plant roots (starter, banding) may increase plant growth and yield compared with broadcast application.

The typical retention of P by soil also makes soil erosion the most important P loss pathway from fields, and this can occur from water or wind erosion. For example, assuming a total soil P concentration of 500 ppm, soil erosion at 5 ton/acre would represent about 10 lb P_2O_5/acre, a substantial loss in the overall P budget. Some eroded soil from upwind or upstream may be deposited to replace a portion of that lost, although rarely is the redistribution of eroded soil uniform within fields or at field borders. Dissolved P loss with surface runoff water can represent another loss of P from agricultural fields. However, the concentration of dissolved P in runoff is generally quite low due to the high level of P sorption and precipitation. One exception would be for runoff events immediately or shortly after applying P fertilizers or runoff from animal feedlots. Some factors contributing to soil erosion and surface runoff include long slopes in fields farmed without conservation structures, tillage or crop rows up and down moderate or steep slopes, inadequate canopy or crop residue cover, lack of windbreaks, intensive tillage, and over-irrigation.

The amount of P loss with leaching through the soil profile is much less than P loss with erosion and surface runoff in most soils and landscapes. In coarse-textured soils or in moderately textured soils with sustained P application in excess of crop removal (very high soil test P), fertilizer or manure applications can increase subsoil P concentrations and leaching to groundwater or surface waters through subsurface tile drainage. Also, P leaching can be a concern on coarse-textured soils that are frequently flood-irrigated or regions with high rainfall. Therefore, P leaching can result in water quality impairment in some situations.

Phosphorus Soil Testing

Soil testing is a very useful tool to assess P requirements for crops. Several test methods are used in different regions of the country because some adapt better to different soils. The most widely used tests are Bray-1, Mehlich-1 (in the southeast), Mehlich-3, Morgan (in the northeast), and Olsen (mainly in the northern Great Plains and western states). Most of these tests are well adapted to acid to neutral soils, but the Olsen is better suited for high-pH, calcareous soils. Soil samples are generally collected from the upper 6 to 8 inches of soil because P from fertilizers and manure will stay in this upper layer, most crop rooting and uptake occurs in this soil layer, and this sampling depth usually better predicts P fertilization needs. All soil-test methods need to be correlated and calibrated with crop yield response in order to give a meaning to the test result in terms of crop sufficiency. Different methods and sampling depths result in different test results, and even the same method may have a different calibration in soils with contrasting mineralogy and chemical properties.

Research has been and continues to be conducted in different regions to correlate and calibrate soil test methods. Figure 2 shows the general relationship between soil-test P levels and crop yield. Soil test levels are generally distributed into interpretation categories referred to as very low, low, medium (or optimum), high, and very high (or excessive). The "critical" level or range separates soil-test values for which there is a high probability of large to moderate crop response to fertilization from values for which there are small and infrequent responses. The critical level can vary with the test method, crop, soils, and climate; and sometimes even with the philosophy of researchers that establish interpretations and recommendations. For example, the Bray-1 P level considered adequate for crops, and at which no fertilization is recommended, vary from about 12 to 30 ppm for forages or grain crops across the U.S. In addition, because nutrient and crop prices influence the profitability of nutrient application and crop production, economic considerations together with producers' management and business philosophies further influence the optimum soil-test levels for crops. The optimal soil-test P level from an economic perspective will depend largely on the nutrient and fertilizer price ratios, producer management, and other enterprise decisions.
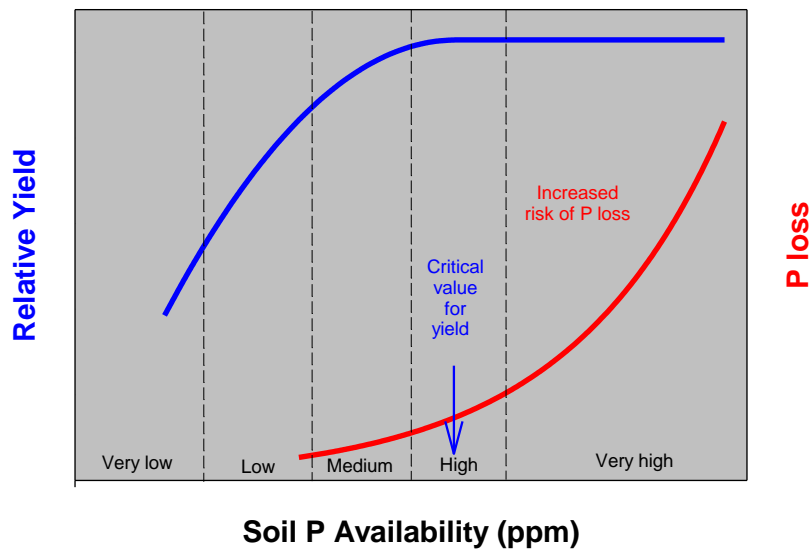
Soil P Availability (ppm)

Figure 2. Schematic representation of the relationship between relative crop yield and P loss.

Interpretation of soil-test P values for water quality issues must be different than for crop production. There is general agreement that soil-test levels higher than adequate for crops may significantly increase the risk of P loss and water quality impairment. As an example, Figure 2 also provides a schematic representation of the relevance of soil-test P values for crop yield and risk of P loss. There is no agreement on what this threshold should be for different regions or production systems. Also, most scientists agree that the soil-test P level is only one of several factors that affect P loss and transport form agricultural fields. Therefore, risk of loss should be considered in a comprehensive P risk assessment tool, such as the P index.

Phosphorus Interpretation and Recommendations Concepts

Soil test laboratories, universities, and crop consultants provide guidelines for application rates based on soil P test results. Interpretation of test results and the recommended fertilization rates vary greatly across regions due to different crop, soil, or economic relationships related to crop response to nutrient application but also concepts and assumptions concerning nutrient management. The concepts of sufficiency level and buildup/maintenance for P and other immobile nutrients have been discussed in soil fertility circles for several decades.

According to a strict sufficiency level concept, the nutrient application rate for any given soil test P level should be the one that results in maximum yield or maximum economic yield. The amount of nutrient to

apply is determined from many field trials on different soils over many years. This approach emphasizes short-term profitability from fertilization; high returns per pound of fertilizer applied, and reduced risk of fertilizer over-application by accepting a moderate risk of yield loss. It requires frequent use of soil-testing and a research data base that adequately predicts a crop response under good or normal conditions.

A strict build-up and maintenance concept emphasizes increasing soil-test levels to an optimum level in a short period of time by applying rates higher than those for a one-year rate needed to achieve maximum yield or maximum economic yield. This approach reduces the risk of yield loss due to insufficient nutrient levels, emphasizes long-term profitability from fertilization, and supports the maintenance of optimum or slightly higher than optimum soil-test levels. It may not require frequent soil testing, but requires knowledge of fertilizer rates needed to maintain soil-test values over time, which usually is based on calculated P removal with crop harvest. A yield response or profit to maintenance fertilization usually is not expected.

The interpretation and fertilizer recommendations systems used across the U.S. seldom strictly follow these two concepts, and actually combine both to different degrees. For example, recommendations by the University of Illinois are closer to the buildup/maintenance concept, those in Minnesota are closer to the sufficiency level concept, and those in Iowa are intermediate. Kansas, however, provides interpretations for both concepts. The main reason for use of the buildup and maintenance approach is that many soils retain applied P but do not necessarily "fix" much P in forms unavailable for crops, and this allows for both buildup and drawdown as management options within the cropping system. For example, Figure 3 provides an example of long-term soil-test P trends over time for various fertilization rates in a typical Iowa soil with a corn-soybean rotation. Data in this figure also demonstrates two important characteristics of soil-test P and fertilization relationships observed in many soils of the U.S. (but not necessarily all). One is that with prevailing crop and fertilizer prices, moderate soil-test P buildup happens even with economically optimum rates applied to low-testing soils. This is explained by only partial plant P uptake of applied fertilizer, P recycling to the soil with crop residues, and soil properties that keep applied P mostly in crop-available forms over time. The other important characteristic is that it usually takes higher P application rates to maintain a high soil-test P level than low or medium levels. This occurs because of increased P concentration of harvested products with increasing soil-test P (luxury P accumulation) and increased P loss through erosion, surface runoff, or leaching through the soil profile.

The keys for developing sound soil-test P interpretation and nutrient application guidelines includes information on crop response to fertilization and calibration of soil-test methods; profitability of fertilization for different soil-test interpretation categories; long-term soil-test P trends as affected by

fertilization, yield levels, removal, and plant-tissue P concentrations; and impacts of soil-test P levels on water quality. Additional consideration of management philosophies, land tenure, and attitudes toward risk (related to yield loss or gain, short-term or long-term profitability, and environmental impacts) can influence development of soil-test P interpretations and P fertilization practices suitable to a large variety of soils, production conditions, and producer management philosophies.
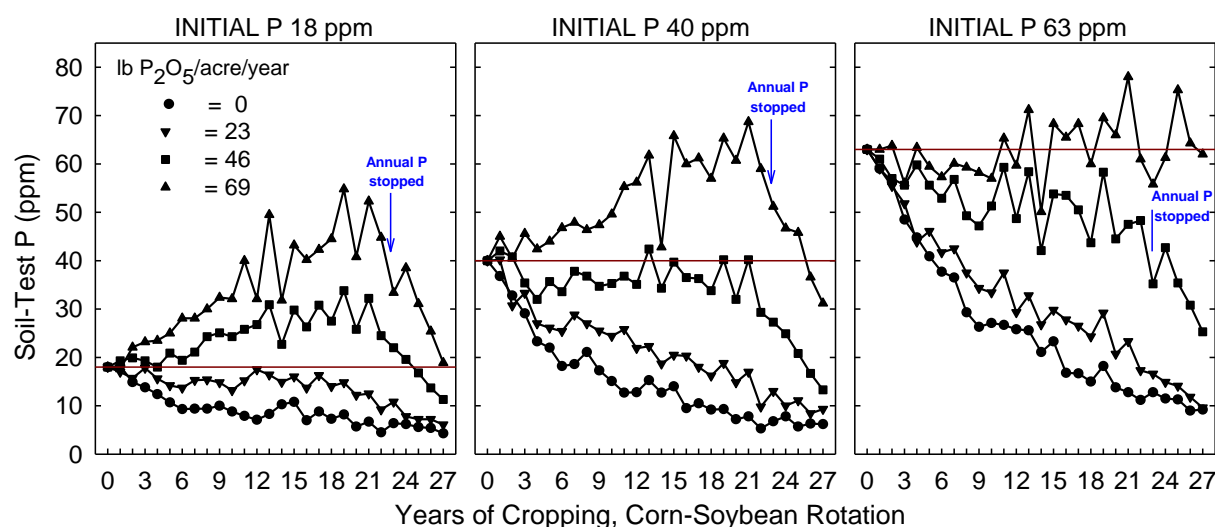

Figure 3. Change in soil-test P (Bray-1) over time with different initial soil-test levels and annual P fertilizer rates in a corn-soybean rotation. Adapted from Mallarino, A.P. 2009. Long term phosphorus studies and how they affect recommendation philosophies. p. 6-12. In North-Central Extension-Industry Soil Fertility Conf. Proceedings. Nov. 14-15. Vol. 25. Des Moines, IA.

Phosphorus Fertilizer and Manure Management

Proper management of P applications is a key for optimizing yield, profitability, and water quality. There are some considerations regarding P source, timing, placement, and rate that producers should consider in order to maximize P use efficiency.

Phosphorus sources

The two most commonly used commercial P fertilizers in the U.S. are MAP (monoammonium phosphate) and DAP (diammonium phosphate). There is no strong research data indicating different efficacy for these products as long as the total P and N rates applied, and the application method and timing are the

same. The slightly different manufacturing processes and different temporary pH when applied to the soil do not result in clear P efficiency differences. Nitrification of ammonium in both fertilizers may result in more acidic pH when using DAP, but this difference is negligible for normal P application rates and given the much higher impact of the comparatively higher N fertilization for cereals.

Use of triple superphosphate (sometimes referred to as concentrated superphosphate) in the U.S. has decreased greatly during the last two decades, and is difficult to find in many regions. This excellent P source, and also simple superphosphate (which contains sulfur), are very important P sources in other parts of the world, however. Use of ammonium polyphosphate and other polyphosphates in fluid fertilizers is very common in the U.S. (such as in 10-34-0 and other mixtures). This P source hydrolyzes rapidly in soil to phosphate after application (even partially during long storage) and, therefore, undergoes similar sorption and precipitation reactions described for other P sources. Rock phosphate, which is comprised of apatite and fluorapatite, is used only infrequently in the U.S. due to the low solubility of these two minerals, especially at high pH. Organic producers frequently use this form of raw, unprocessed P mineral as a nutrient source, but at very high rates and pulverized into fine particles due to its low solubility and low available P concentration. Rock phosphates that are most suitable for direct application are used extensively in other parts of the world, however, mainly for forages and pastures in acidic soils.

Applying manure to cropland sometimes presents different management issues and options from those discussed above for P fertilizers. If manure is applied to meet crop N needs, more P may be applied than is necessary to meet crop P needs. However, this varies greatly with the animal species and both feeding and manure handling systems due to large impacts on the N:P concentration ratio in manure and the plant availability of the manure N. Therefore, long-term manure applications may increase soil test P levels well above critical levels, especially when applied to continuously to cereal crops to meet N fertilization requirements. The crop-availability of manure P varies less than N, is less prone to large losses and the significant transformations typical with manure N. However, plant P availability is affected by the animal species and diet. Suggested manure P crop-availability values vary greatly across the U.S. Iowa research has shown, for example, that the crop-availability of manure P compared with inorganic fertilizer ranges from 60 to 100 % for beef or dairy manure and 90 to 100% for poultry or swine manure.

Manure management has become more of an issue the last few decades as crop and animal operations have become concentrated in various regions of the country and because of public and government concerns about manure management impacts on water quality. Environmental concerns related to confined animal feeding operations (CAFOs) have become an issue in the humid regions of the U.S. Phosphorus from animal manure should be managed as carefully as P fertilizer, with practices including:

representative manure samples analyzed to determine nutrient concentrations; choose the manure application rate according to crop nutrient requirements and for the crop availability of all manure nutrients (not just for P); for manure P application rates consider the nutrient needs of crop rotations rather than just individual crops; allocate manure to fields or within-field areas based on soil tests and crops to be grown; consider the risk of P loss for the field or within-field areas by using a P risk assessment tool (such as the P Index); and do not apply manure to snow-covered, frozen, or water-saturated sloping ground when runoff risk is high.

Application Rate and Placement Method

Applying P fertilizer at rates higher than crop production requirements according to soil-test calibrations and concepts discussed before is unwise from both environmental and economic viewpoints. There is no agronomic justification for building P soil test levels higher than crop sufficiency levels. Phosphorus losses in surface runoff have been shown to increase with increased P application rates. Therefore, once the crop sufficiency levels have been reached, P applications should be made only as dictated by soil testing and crop removal.

Phosphorus banding is recommended over broadcast and incorporated applications in soils that strongly retain or transform applied P into forms that have low crop availability. Because banding reduces the interaction of applied P with soil, P plant availability is enhanced and may increase use efficiency. Most of the soils of the U.S. Corn Belt and eastern U.S. do not retain P so strongly, however, and research has shown no large or consistent differences among P application methods (surface broadcast, broadcast and incorporated, banded) with tillage or no-till management, except for soils with small acreage and for starter fertilizer under some conditions. Even in these regions, however, banded P near the root zone almost always enhances early crop growth, and tends to be more efficient at extremely low soil-test P levels and with sub-optimal P application rates. In other regions or under special situations, banding is a more efficient practice and provides benefits that more than offset the additional application cost. These situations include soils with very high soil retention capacity, low rainfall regions, crops with a taproot type of root system, or when root growth is limited. Figure 4 shows a generalized schematic representation of the different types of outcomes for broadcast and band P application. Reasons for the differences in response relate mainly to soil properties, but also the crop and management practices. Local research should be used to help guide decisions for best P placement and application methods for different soils and crops.
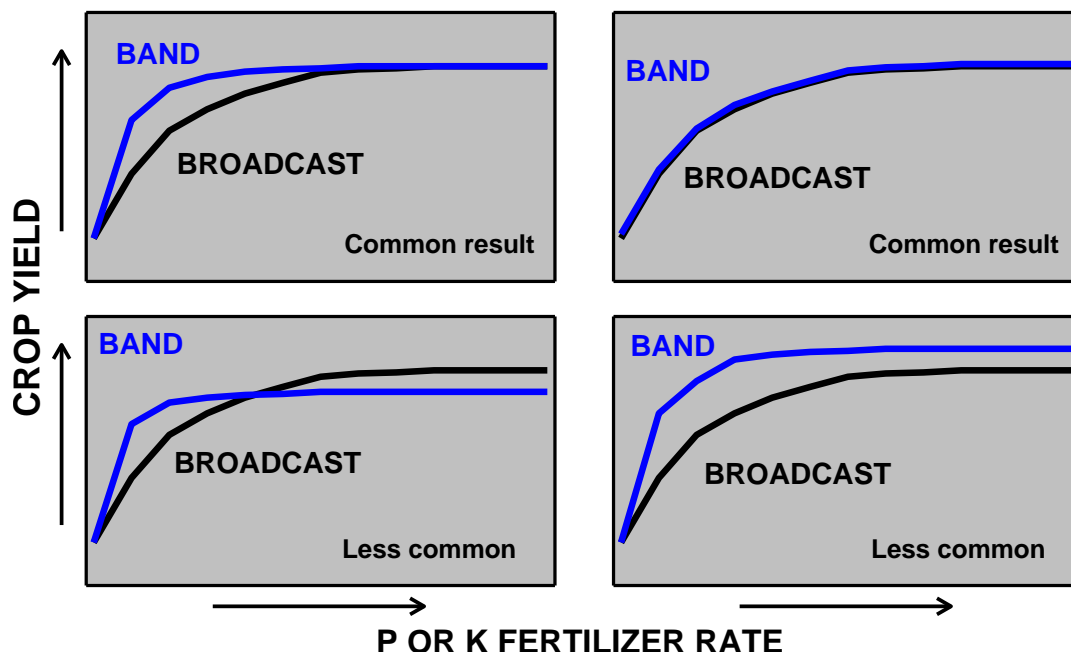
*Figure 4. Idealized possible differences between broadcast and band
P placement methods depending on crops and soil properties.
Adapted from Black, C.A. 1992. Soil fertility evaluation and control. Lewis Publishers.*

Phosphorus placement may have important implications for risk of P loss with soil erosion and surface runoff. The main concern with surface application of P is the increase in soil test P at the soil surface; at the soil-runoff water mixing zone and where water or wind erosion occurs. The surface soil P buildup may result in short-term (after a large runoff event shortly after application) or sustained long-term contribution to risk of P loss. The main concern with P incorporation by tillage is the risk of increasing the rate of soil erosion in sloping lands. Subsurface P application, without reducing P use efficacy by crops, increasing soil or water loss, or an inordinate increase in application costs, would be an ideal management practice for P.

Total runoff P loss may or may not be reduced with incorporation or subsurface injection of manure or fertilizer P compared with surface application because loss also depends on the slope, soil hydrology, P rate, and impacts of incorporation or injection on erosion and surface runoff. Generally, dissolved P in runoff is higher with surface P application if the runoff event occurs shortly after application. However, the increased risk with surface application decreases in the days and weeks following application.

Figure 5 demonstrates the effects of P rate, incorporation into the soil, and days after P application on the risk of P loss with surface runoff. Reduced P loss occurs with lower P rates, a delay in runoff events after

application due to time for retention by soil constituents, and incorporation into the soil. Similar results were observed for inorganic fertilizer and poultry manure. The P loss can be greatly reduced by incorporation of large P amounts into the soil when the tillage operation does not significantly increase erosion and surface runoff mainly with runoff events shortly after application.
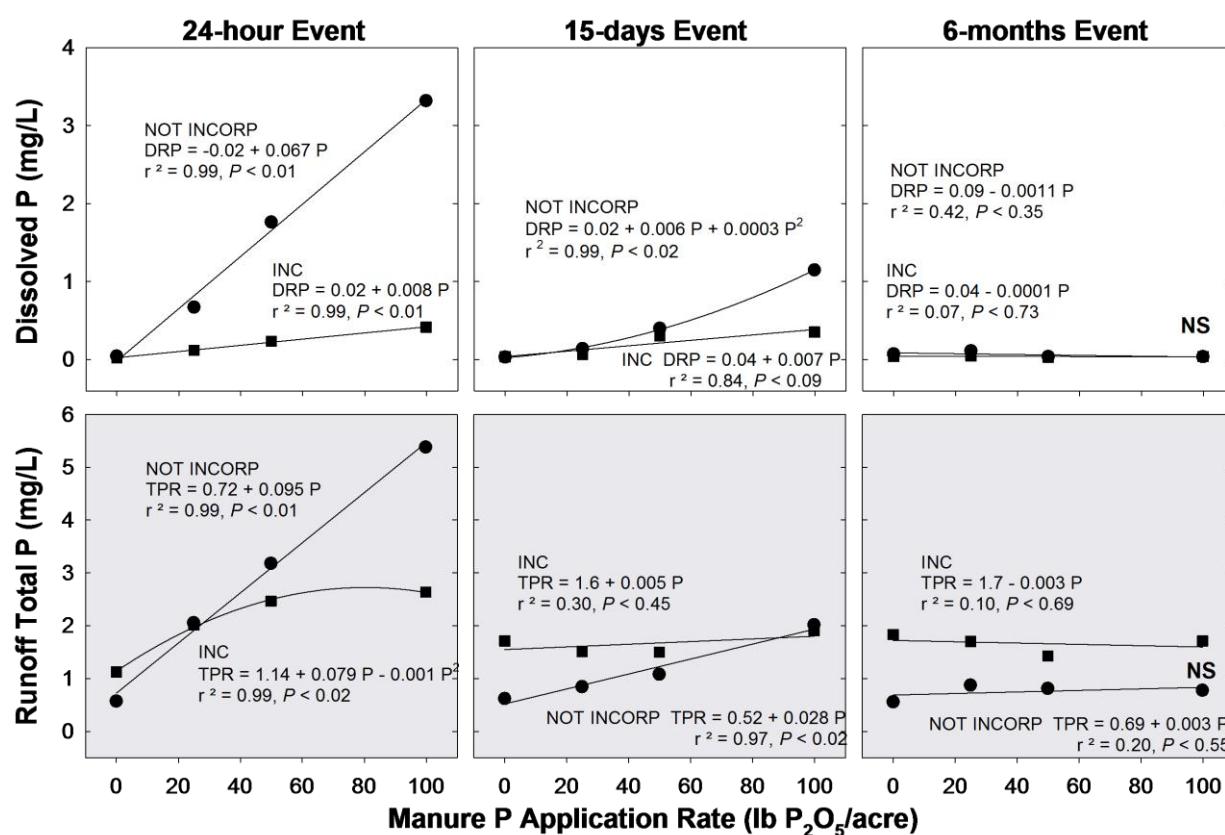

Figure 5. Effect of liquid swine manure P application rate, incorporation, and time (days after P application) of simulated rainfall on runoff P loads (NS indicates no interaction between P rate and incorporation). Adapted from Allen, B.L., and A.P. Mallarino (2008). J. Environ. Qual. 37:125-137.

Time of Application

From a nutrient use efficiency perspective in humid regions, the time of P application before the crop planting date generally is a much less important factor than the time of N application. With the exception of regions that have soils with very high P retention capacity, the timing of P application before planting has little or no impact on P use efficiency by crops. This fact justifies, for example, widespread fall P application for summer crops in the Corn Belt and the Great Plains and also application every other year for some rotations. In soils that retain or transform applied P into forms of low crop availability, however,

application well in advance of crop growth may reduce P use efficiency and there are often large differences due to placement method (less efficiency with broadcast and incorporated application, for example). On the other hand, in-season P application is not recommended, except for forages crops and pastures, which is in clear contrast to N sidedress application. Many years of research has shown that an adequate P supply is important early in plant growth, to stimulate development of photosynthetic leaf area and increase grain sink size to maximize yield and P use efficiency.

The time of P application to the soil surface or of tillage to incorporate broadcast P may have a significant impact on runoff P loss shortly after application. As was shown in Figure 5, P loss with surface runoff from surface P application decreases significantly with a delay in the runoff event. A few days are needed so that soluble P reacts with the soil and the phosphate concentration in solution decreases. Therefore, the importance of incorporation and the P loss are higher when the P is applied during periods of high probability of rainfall and surface runoff or with significant snow cover. The probability of large runoff events typically is greatest in the spring due to snowmelt in northern areas and frequent high-intensity rainfall in most humid regions of the U.S.

Variable rate P application

Dense soil sampling from many fields has shown very large within-field spatial variability of soil-test P and crop yields. Precision agriculture technologies available to producers or custom applicators facilitate application of fertilizer and manure at rates adequate for different parts of a field based on soil-test P and estimated P removal. Iowa research has shown that grid or zone soil sampling methods combined with variable rate application of fertilizer or manure P may not always increase crop yield or increase profits compared with traditional application methods because the average effects on yield and amount of P applied depends on the overall level and distribution of soil-test P values. Also, soil testing seldom is performed on an annual basis, there is always a certain degree of sampling error (especially in fields with high small-scale variability), and research has shown that relationships between P removal and soil-test P are good over several years but not necessarily from year to year. Therefore, even with annual variable-rate application, use of this technology is not perfect. However, on-farm research has shown that variable-rate application of P fertilizer or P-based manure almost always minimizes or avoids P application to high-testing areas, reduces soil test P variability within fields, and, as a consequence improves P use efficiency and reduces risk of P loss by minimizing P application to high-testing field areas. Figure 6 shows, as an example, that use of variable-rate technology is an effective tool to manage P better. The change in soil-test P was measured after applying P-based liquid swine manure for corn after three corn-soybean rotation cycles. Similar results were observed with fertilizer application. In addition, variable-

rate P application can be practically implemented on the basis of P-index ratings for field zones, not just based on soil test P or estimates of P removal. Variable rate application of fertilizer P is common in the Great Plains and the Corn Belt, and custom manure applicators also are beginning to apply manure at variable rates.
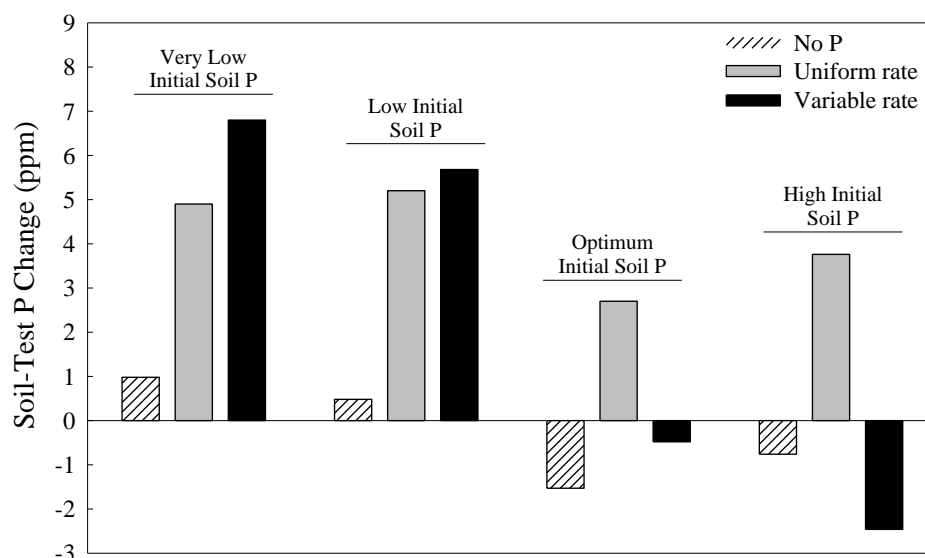

Figure 6. Effect of uniform application and soil-test phosphorus (STP) based variable-rate application of liquid swine manure on STP change within a field for various initial STP interpretation classes. Adapted from Mallarino, A.P., and J.S. Schepers. 2005. Role of precision farming in phosphorus management practices. p. 881-908. In T. Sims et al. (eds). Phosphorus: Agriculture and the Environment. Agronomy Series 46. ASA, CSSA, SSSAJ, Madison, WI.

Summary

Proper P management is essential for many reasons: to maximize the profitability of crop production, maximize efficiency of a non-renewable resource, reduce impacts of P use in crop production on surface water quality, and avoid increased regulation. Phosphorus management is somewhat simpler than for N in humid regions, due to differences in chemical transformations, no gaseous phase or volatilization, and less influence of environmental factors on processes that control crop-available forms and losses. Also, although the vast majority of P in soils is unavailable to plants because it is bound in insoluble P minerals or sorbed strongly to soil particles, soil sampling and testing is more reliable and useful than testing for N and other nutrients. The goal of sound P management in most regions of the U.S. should be to keep the

soil-test P level at optimal ranges for maximum economic crop yield and utilize application methods and timing that optimize P use efficiency and economic profitability, and minimize water quality impairment.

Substantial within-field variability of P soil-test levels and P removal with harvest in most agricultural areas justifies the use of appropriate soil sampling, soil testing, application methods, and variable-rate application technology to increase P use efficiency and reduce the risk of P loss to water resources. The large variation across the U.S., and even within states, due to many factors means that best P management will also vary. Therefore, any list of best P management practices always will need to be tailored to a specific area, and likely will be incomplete in regard to meeting all potential P management issues. Following is a list that encompasses the most important concepts underlying P management strategies.

Management Practices for P Fertilization:

1. Sample soil as frequently and as densely within fields as economically possible and use appropriately calibrated soil-test methods based on research for each state or region.

2. Consider yield levels and crop P removal across and within fields to help maintain optimum soil-test P levels in conjunction with soil testing.

3. Fertilize P deficient soils using environmentally and economically sound agronomic guidelines. In general, soils testing 'high' or "very high" will not respond economically to additional P and should not receive fertilizer except for starter in certain known and specific conditions.

4. Divide large, non-uniform fields into smaller fertility management units based upon yield potential, soil tests, and relevant soil properties.

5. Credit all available P from manures and other organic sources when deciding the P application requirements for crop.

6. Refer to local research and guidelines concerning P placement methods to optimize P use efficiency, the profitability of nutrient application, and water quality protection.

7. Incorporate or inject high rates of inorganic or organic P sources into the soil where the risk of surface runoff or soil erosion is high.

8. Use manure nutrient analysis and a P risk assessment tool such as the P Index in order to utilize as much manure nutrients as much as possible without increasing the risk of P loss and water quality impairment.

Case Study

There are many different P management strategies for crop production that are used by producers across the U.S. It is impossible to give one example representative for all geographic areas, crops, and current management systems concerning options for improved P management. These would vary with soil type, crop, rotation, climate, available fertilizer or manure, application equipment, and producer management philosophy. The following example describes a P management system being used for a specific farm in the U.S. Corn Belt, and includes possible practices the producer could consider to improve crop use efficiency and economic return from P application while minimizing losses from fields that could impair water resources.

Example scenario

- A 1,000 acre farm in Western Iowa.

- Soils are prairie-derived, well drained, and formed in loess on convex slopes and ridges. In general topsoil texture is silty clay loam and slopes range from 0 to 15 percent.

- The farm has fields with continuous corn and corn rotated with soybean.

- The producer uses chisel-plow and disk tillage in about half of the fields and no-till in the other half, and he has not built terraces.

- The farmer has a large confined swine production operation. Liquid swine manure is broadcast in the fall after crop harvest and before soils freeze or are covered with snow. The manure is applied based on the manure N concentration and the corn N fertilization needs assuming 90% manure N availability as suggested by Iowa State University manure nutrients management guidelines (220 lb total N for continuous corn and 165 lb total N/acre for corn after soybean).

- The only P or K fertilizer applied in the farm is a small rate of N-P-K starter always applied for corn.

- Soil testing for P and K seldom is used.

- Potassium deficiency is not likely in this farm and in most of the western Iowa region because soils have naturally high soil-test K levels.

- In wet years, and especially in the fields with steeper slopes, the producer has noticed high surface runoff after rainfall events. He has implemented no-till management in the fields with the steepest slopes, but erosion can be observed in several fields.

This example scenario is not uncommon where nutrient management with manure is a challenge due to multiple nutrients and emphasizes the potential benefits from development of an improved P management plan. Following are some management options to consider. This set of agronomic practices is an example of a properly designed nutrient management plan and would contribute to increased crop production by enhancing P use efficiency and minimize environmental problems related to P losses.

- It is important from the agronomic and environmental perspectives to have an estimation of available soil P and K. This is crucial to adjust nutrient application rates in order to meet crop requirements and/or prevent water contamination issues. In this specific case, the producer should adopt a soil sampling and testing strategy because application of N-based manure for corn after soybean may apply sufficient P for the corn crop, but may supply insufficient P for the soybean crop or supply excessive amounts for the rotation. Or, if enough manure is not available to treat all fields, the low starter rate will not supply adequate P and K for high yielding crops.

- Application of an insufficient amount of manure nutrients will limit profitability and application of an excessive amount will increase soil P beyond optimum levels and will therefore increase the risk of P loss. With continuous corn, application of N-based manure each year undoubtedly will increase soil P to unacceptable levels concerning risk of P loss and water quality impairment. Soil sampling and testing strategies should be implemented based on either a zone sampling approach considering topography, soil map units, yield level, or other field information; or on a grid sampling approach, which in Iowa is based mostly on cells 2.5 acres in size. This information would allow the farmer to know what parts of the farm or fields do not require additional P application, where additional P is needed, or where soil P test levels are so high that there is a risk to water quality. The frequency of soil sampling should be not less than 4 years; ideally every 2 years for the corn-soybean rotation and also the same frequency for continuous corn given the high P loads with annual manure application.

- Once soil P tests results are available, the next step is to plan manure application priorities in order to improve as much as possible use of the manure P resource for crop production profitability, and minimize chance of soil P buildup to levels above optimum for crops. According to Iowa State University swine manure P has 90 to 100% availability for crops.

Therefore, the producer should continue applying manure in fields or field areas with optimum or lower P levels, which most likely will be for some of the fields managed with a corn-soybean rotation. This allocation may also require manure be hauled to fields that historically have less frequent manure application. Because N-based manure rates applied to corn almost always supply sufficient P for the corn crop, complementary inorganic P fertilizer may be needed for the soybean crop. The producer also should avoid or reduce manure applications in areas with already high P tests, and apply additional inorganic N fertilizer for corn as needed. If there is large within-field variation in soil-test P levels, the producer could use variable-rate manure and fertilizer application equipment to improve nutrient management within fields.

- The risk of P loss with runoff can be also reduced, and the manure-N use efficiency can significantly be increased, by injecting the manure instead of broadcast applying in fields with no-till management. Also, the producer could use low soil disturbance coulters and knives, which are becoming more available and affordable, to further minimize soil erosion and P loss. And, any P fertilizer needed for soybean in low-testing no-till areas could be applied in subsurface bands, either with planter starter attachment or deep-banding before planting. Iowa research shows that P banding seldom increases crop yield compared with a broadcast application in no-till, but this practice can reduce the risk of P loss with surface runoff.

- If the producer still wants to apply manure in areas testing above optimum, he should use the Iowa P Index to determine if applying additional P to those areas increases the risk of P loss to unacceptable levels. Using the P Index will indicate if additional P can be applied, and if it can be applied, it will suggest the most effective soil or P management practices to assure the risk of P loss does not increase. Given the conditions for this farm (sloping ground), controlling erosion and surface runoff should be the most effective way of decreasing P loss. The adoption of terraces, contour cropping, and/or no-till in additional fields with surface runoff would reduce erosion and P loss, and also will increase the agronomic efficiency of the production system and over time perhaps the profitability of the system as well.

- The producer should also evaluate the possibility of eliminating the application of starter P in areas with high P soil tests, especially with the corn-soybean rotation, because the low probability of grain yield increases from starter P in those conditions.

Chapter 4:
Potassium Management

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Introduction

Potassium (K) is abundant in most soils, but the vast majority is unavailable to plants. Plants require K for photosynthesis; synthesis of ATP (an energy exchange compound), many carbohydrates, and proteins; translocation of sugars, and nitrogen (N) fixation in legumes. Adequate K supply strengthens plant stalks and stems, thus helping reduce lodging, and also increases resistance to several diseases through a variety of mechanisms. Typical K-deficiency symptoms develop first in the older leaves and may consist of yellow or white spots on the leaf edges (as in alfalfa, for example), chlorosis and necrosis of the leaf edges (as in corn and soybean), or chlorosis of leaf tips (as in wheat).

When compared with other macronutrients, K total plant uptake is generally second only to N, and in some crops such as sugar beets and potatoes K uptake exceeds N uptake. Annual K removal from fields depends greatly on the plant part harvested, crop, and yield level; and ranges from 50 to 500 lb K_2O/acre. Table 1 shows an example of guidelines concerning K concentration per unit of yield for several crops. Commercial K fertilizer analysis has historically been expressed as the oxide form (K_2O) rather than the elemental form (K). Therefore K uptake and removal values are usually expressed as K_2O per unit of yield. Using the ratio of their molecular weights, the amount of K_2O can be converted to K by dividing by 1.2. To estimate K_2O uptake, multiply the yield by the amount in the table per unit of crop yield harvested.

In contrast to phosphorus (P), the K concentration and removal with grain harvest of cereals is a much smaller proportion of the total plant uptake. Most grain crops reach the maximum K uptake before physiological maturity, and the total K contained in aboveground plant parts can even decrease by grain maturity. Figure 1 shows, as an example, the total K uptake by wheat and its distribution among plant parts during the growing season. Therefore, if most of the plant material is removed at harvest (such as for

corn silage or biomass for bioenergy), K removal can result in a severe depletion of soil available K. Also, because the absorbed K ions are not incorporated into plant organic compounds and are soluble in water, leakage of K from vegetative plant tissue or crop residues is an efficient recycling mechanism to the soil.

Table 1. Potassium amounts in harvested portions for selected agricultural crops.

Crop	Unit of Yield	Pounds K_2O per unit of yield
Corn	bu	0.3
Corn silage	bu grain equivalent	1.3
Soybean	bu	1.5
Oat and Straw	bu	1.0
Wheat	bu	0.3
Sunflower	100lb	0.7
Alfalfa	ton	40
Tall fescue	ton	66

Source: Iowa State University Extension publication PM 1688.

Plant uptake can also influence the recycling of available K from deep in the soil. Deep-rooted plants can act as nutrient pumps by transferring K from the subsoil to the surface layers. This process makes previously inaccessible K available for shallow rooted crops.
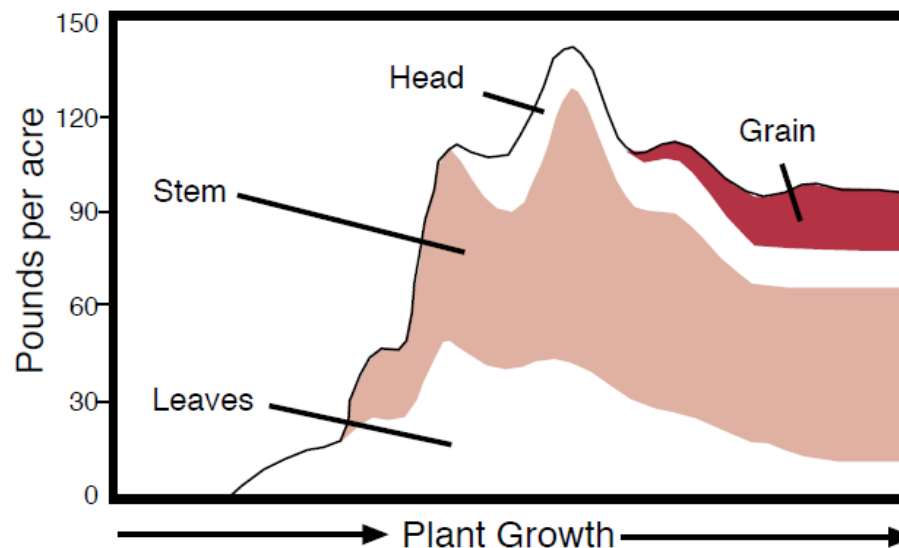
Figure 1. Potassium accumulation during growing season for hard red spring wheat. Adapted from Jabosen et al. (1992). Montana AgResearch 9:23-26.

Potassium application and management does not result in water quality concerns as with N and P. An understanding of K reactions in soils, cycling, and availability for crop is important to improve K use efficiency, to meet crop K needs in a profitable way, and to help with K management decisions.

Potassium Processes in the Soil-Plant System

Forms of Soil Potassium

The vast majority of soil K is contained in unweathered primary minerals such as feldspars and micas (muscovite, biotite, and others). The top layer of most soils contains thousands of ppm of mineral K, but the K in the crystal structure of these minerals is released very slowly over dozens or hundreds of years and has no relevance for crop nutrition. Other soil K pools include dissolved K^+ ions (solution K), exchangeable K, and slowly exchangeable K (often referred to as nonexchangable K in textbooks). Readily plant-available K includes the solution and exchangeable K fractions, and there is a fast equilibrium between these two fractions in response to K additions and plant uptake or leaching. The exchangeable K fraction contains hydrated K^+ ions weakly sorbed to the negatively charged surfaces of mineral soil particles and organic matter, and can rapidly replenish the solution K pool as K is taken up by plants. Plants can only directly use K from the soil solution, yet solution K concentrations range from only 1 to 10 ppm except shortly after fertilization, and the exchangeable K fraction in U.S. soils may range from about 20 to 1,000 ppm. The slowly exchangeable K is held within clay layers by stronger bonds and is not readily exchangeable or available to plants in the short term (days or weeks). In soils of the U.S., the amount of K held in this fraction varies greatly, and may range from about 100 up to 2,000 ppm.

Potassium Exchange and Reactions in Soils

When solution K is depleted due to plant uptake or leaching, K desorbs from the soil particles and enters the solution. When the amount of solution K is increased by fertilization or K leaching from crop residues, added K will also be held on the soil exchange capacity (CEC) sites. Fine-textured soils with high CEC generally have large exchangeable K concentrations and a strong capacity to maintain a sufficient K supply to the soil solution and for plant uptake throughout the growing season. Low CEC soils often lack the capacity to sorb sufficient K reserves to satisfy crop requirements over a growing season.

Exchange reactions involving the slowly exchangeable K fraction are important in the long term (weeks to years), and can dominate processes affecting the long-term crop availability of K mainly in soils with

predominant mica (illite) or vermiculite clay types. A portion of the K in this fraction may become plant available during the growing season and over the years; conversely, some added K may become strongly retained and nonexchangeable. Both processes are highly influenced by the opening (peeling apart) and closing of sheet-like clay crystal structures near fracture borders in response to drying-wetting, freezing-thawing, changes in soil aeration, or long-term weathering (Figure 2).
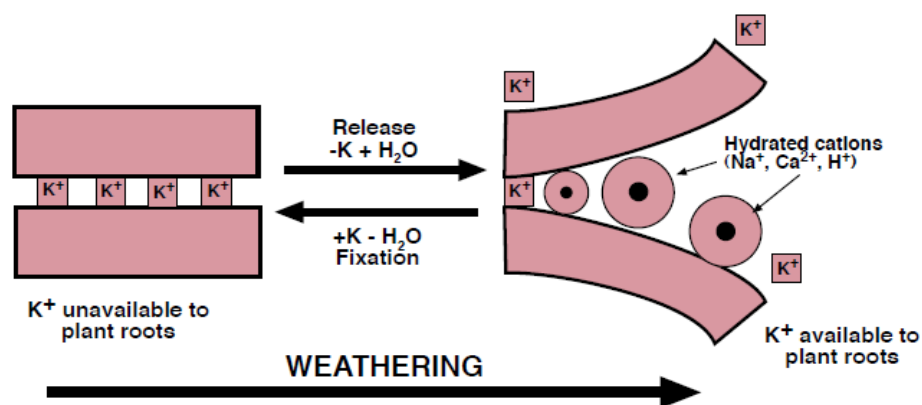

Figure 2. The opening and closing of layered clay minerals releases K into solution and also can retain K in a form that may be unavailable to plants. Adapted from McLean (1978), Potassium in Soils and Crops.

Potassium retention and release by clay, and its availability to plants can be affected by soil pH. As the pH increases (i.e., with increased lime application, for example) in very acid soils having exchangeable aluminum (Al), which are common in the southern and southeast regions of the U.S., the soil capacity to retain K (and added calcium) in an exchangeable form increases mainly because the liming transforms exchangeable Al into insoluble forms. In acid soils without exchangeable Al, the effect of a pH increase is less clear concerning availability to plants. As the pH increases due to liming, the soil CEC is increased and H^+ ions are removed from cation exchange sites, and more exchange sites are available for holding K^+ and calcium ions (Ca^{2+}) in an exchangeable form. However, high amounts of Ca^{2+} can reduce crop uptake of K, and the pH increase can cause the collapse of expanded clay layers and trapping of K ions in the non-exchangeable form.

Soils with high K-fixing capacity typically show a smaller soil-test K (STK) response to fertilizer application than other soils because a portion of the supplied K can quickly bind to clays in a nonexchangeable form. A soil with high K-retention capacity will generally be capable of sustaining available K levels to a crop over many years of production, thereby buffering the crop removal of K. This property has been called the 'K supplying power' of a soil. A sandy soil and a clay loam soil may have

the same initial exchangeable K levels, but their response to crop uptake and removal of K will be different because sands have low CEC and, therefore, a lower K supplying power than clay loams (Figure 3).
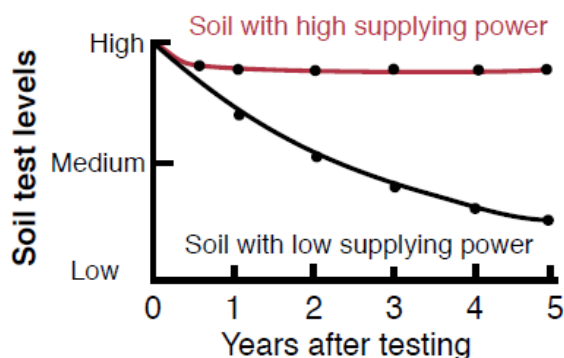

Figure 3. Soils with the same initial K level may have very different abilities to supply K to crops over time. Adapted from Hoeft et al. (2000), Modern Corn and Soybean Production.

Potassium: A Relatively Immobile Nutrient

As a result of K exchange reactions and retention in soils, K moves only short distances through soil and only slightly more than P. The amount of K that reaches the root surface with water mass flow is not sufficient to supply plant needs, and K ion diffusion through the soil solution is the main mechanism of plant K uptake. This characteristic has several important consequences. Factors that limit the rate of K diffusion and both the rate of root growth and the size of the root system can limit K uptake. These include cold temperature and low moisture (which limit diffusion and root growth), soil physical properties that inhibit root growth, and diseases or pests that impair root function. Therefore, induced K deficiency may occur even with presumably adequate soil-test K levels. In these situations, placement that puts applied K near young plant roots may increase plant growth and yield compared with broadcast application.

The amount of K loss with leaching through the soil profile is much less than K loss with erosion and surface runoff in most soils and landscapes. In coarse-textured soils or in moderately textured soils with sustained high K applications, K can move through the profile and increase subsoil K concentrations or leach to groundwater or surface waters through subsurface tile drainage. Therefore, although K does constitute a water quality problem, minimizing soil erosion and excess application to coarse textured soils will help maximize K utilization by crops.

Potassium Soil Testing

The primary goal of soil testing for K is to estimate the supply of K available to a crop. Solution and exchangeable K are the most important forms for plant growth, but the estimate of exchangeable K is far more important than the solution K fraction. The STK methods used in the U.S. measure solution K and most of the exchangeable K. The most widely used methods extract K with the ammonium acetate and the Mehlich-3 methods, but a few states use the Bray-P1, Morgan, or Mehlich-1. In contrast to P, the measurement of extracted K can be done by various laboratory procedures that give the same result Only the top six to eight inches of soil is generally tested for K because the surface soil is the most significant source of K for most plants, although in a few states a shallower sampling depth is recommended for pastures and no-till. The relationship between STK and relative yield response in the U.S. has been a subject of significant research (Figure 4). Soil test levels are categorized into low, medium (or optimum), or high, and sometimes also into 'very low' and 'very high' (or excessive) categories. At STK levels below the 'critical level or range' (usually medium or optimum) the probability that a yield increase will result from fertilizer addition is high. Above the critical level, small or no yield responses to K fertilization would generally be expected.
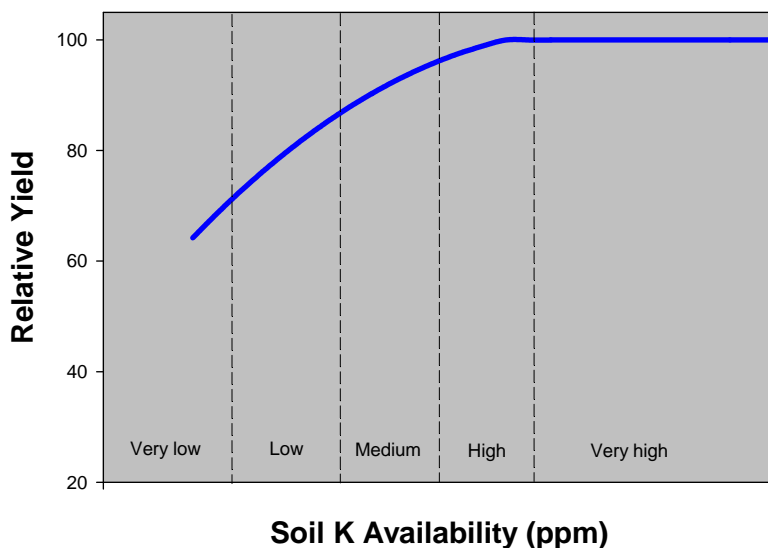

Figure 4. Relationship between soil-test K level and crop yield.

The STK and exchangeable K levels can change significantly during the year due to effects of crop uptake, soil moisture and rainfall, and different rates of recycling of K in crop residues. This happens also for other nutrients, but is especially the case for K. As an example, Figure 5 shows how STK changes due

to crop uptake and also soil moisture. Figure 6 shows how the rapid recycling of K from crop residues, which is faster and of greater magnitude than with P. Soil STK levels are usually highest and more stable a few weeks or months after crop harvest and with normal moisture, and before plant uptake becomes substantial. Over the growing season, K is removed from solution and exchange sites by plants, so STK will be lowest from mid-season to crop physiological maturity. Therefore, the time of year that soils are sampled is critical for effective K management and must be consistent over time in order to monitor the K fertility of a site over time. Different states may have different sampling date recommendations as soils, climate, and crops vary greatly across the U.S.
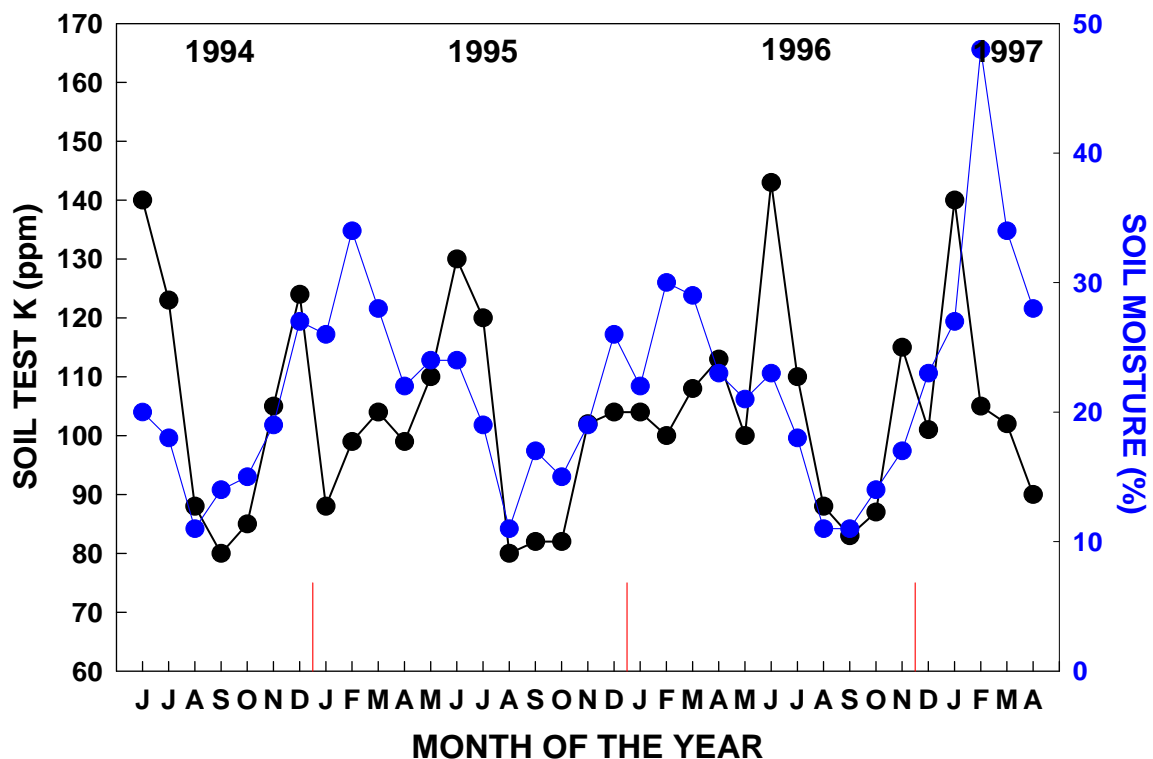

Figure 5. Relationship between soil moisture and soil-test K levels in an Illinois soil (Dixon Springs Agricultural Center). Soil-test K data adapted from S.A. Ebelhar and E.C. Varsa. 1999. Tillage and potassium placement effects on potassium use efficiency in a corn-soybean rotation. Illinois Fertilizer Conference Proceedings. January 25-27, 1999. University of Illinois, Urbana-Champaign. Moisture data adapted from T. R. Peck (University of Illinois, unpublished).
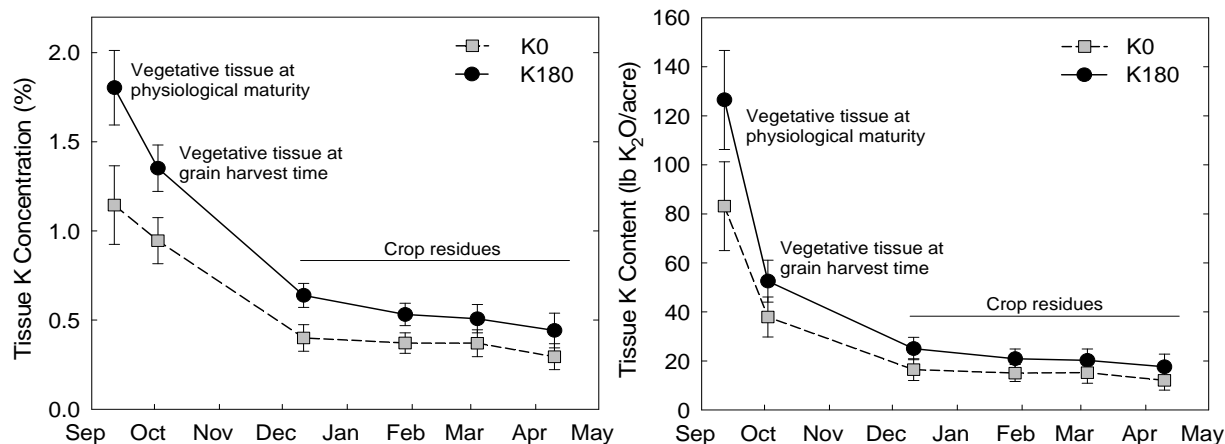
Figure 6. Concentration and amount of potassium in soybean plant tissue (except grain) from physiological maturity until grain harvest and in residue until the following spring for two K application rates. Adapted from R.R. Oltmans and A.P. Mallarino (2011). Identification of reasons for high temporal soil-test potassium variation. p. 65-73 In North-Central Extension-Industry Soil Fertility Conf. Proceedings. Nov. 16-17. Vol. 27. Des Moines, IA.

Potassium Fertilizer Recommendation Concepts

The interpretation of soil-test results in terms of sufficiency for crops and the amount of nutrient to apply are determined from many field trials on different soils over many years. Interpretations of STK results concerning fertilization rates vary greatly across regions due to different crops, soils, or economic issues related to crop response to nutrient application. Also, interpretations differ due to different concepts and assumptions concerning nutrient management in relation to the crop production system. The concepts of sufficiency level and buildup/maintenance for P, K, and other immobile nutrients have been widely discussed in soil fertility circles.

According to a strict sufficiency level concept, the soil nutrient availability should be determined by soil testing and the nutrient application rate for a given STK level should be the one that results in maximum yield or maximum economic yield. This approach emphasizes short-term profitability from fertilization, high return per pound of fertilizer applied, and reduced risk of fertilizer over-application by accepting a moderate risk of yield loss. It requires frequent use of soil-testing and a research data base that accurately predicts the nutrient need for different soil-test values. A strict build-up and maintenance concept emphasizes increasing soil-test levels to a desirable level in a short period of time by applying rates higher than those needed to achieve maximum yield or maximum economic yield. This approach reduces

the risk of yield loss due to insufficient nutrient levels and emphasizes long-term productivity and profitability from fertilization. It may not require frequent soil testing or accurate soil-test calibration, but requires knowledge of fertilizer rates needed to maintain soil-test values over time, which usually is based on measured or estimated K removal with crop harvest. A short-term yield response or profit to maintenance fertilization usually is not expected.

The soil test interpretation and fertilizer recommendation systems used across the U.S. seldom strictly follow these two concepts. For example, recommendations by the University of Illinois are closer to the buildup/maintenance concept, those in Minnesota are closer to the sufficiency level concept, and those in Kansas provide recommendations for both concepts. The main reason that allows the use of the buildup and maintenance approach for K is that many soils retain applied K but do not "fix" it in forms unavailable for crops, and this allows for both buildup and drawdown as management options within the cropping system. For example, Figure 7 provides an example of long-term relationships between K removed with harvest and STK for several typical Iowa soils managed with corn-soybean rotation. Data in this figure shows high temporal variability of STK (much more than for P), but shows a linear relationship between K removal and STK over the long term.

The keys for developing sound STK interpretation and K application guidelines includes appropriate information for crop response to fertilization, calibration of soil-test methods, and profitability of fertilization for different soil-test interpretation categories; long-term STK trends as affected by fertilization, yield levels (because of removal), and K concentration of harvested plant parts. Additional consideration of management philosophies, land tenure, and attitudes toward risk (related to yield loss or gain, short-term or long-term profitability, and environmental impacts) can influence utilized STK interpretations and K fertilization practices suitable to a large variety of soils, production conditions, and producers. Applying K fertilizer at rates higher than crop requirements or to soil testing higher than recommended is unwise from economic and resource conservation perspectives. There is no agronomic or economic justification for building STK levels higher than sufficient for crop needs.
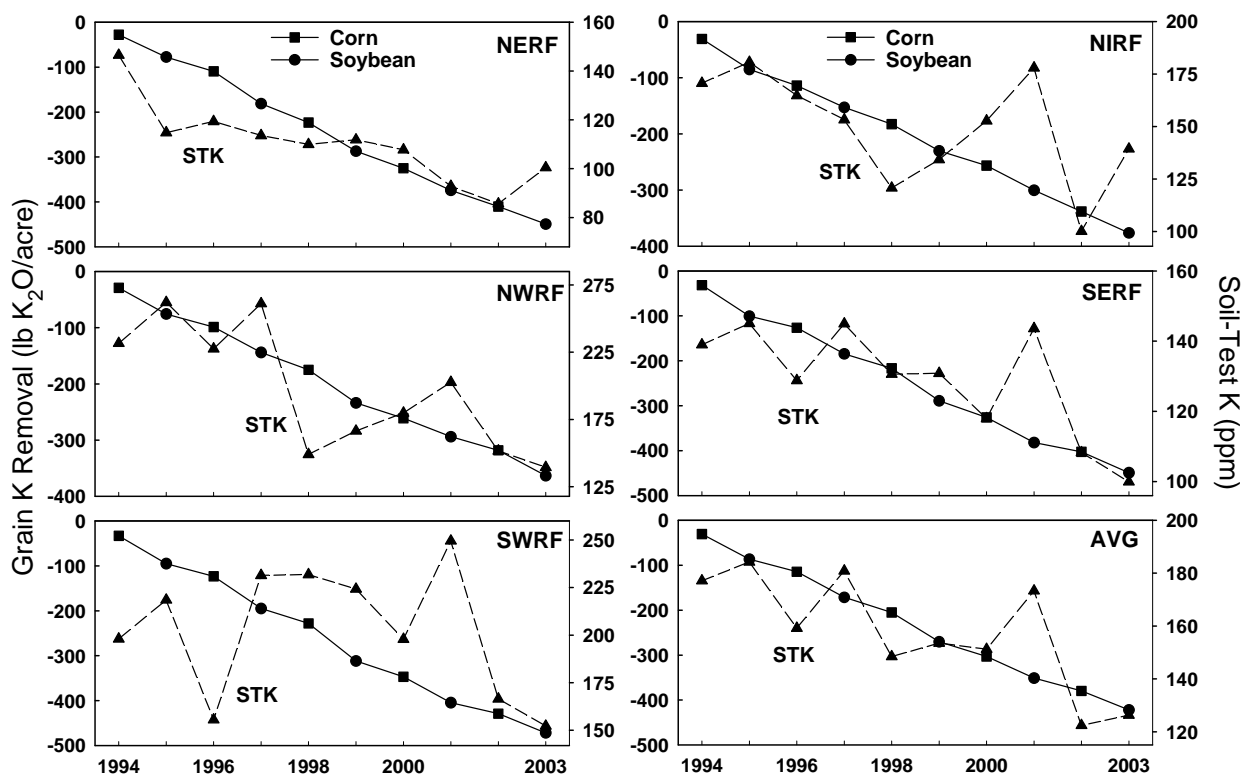
Figure 7. Soil-test K and cumulative K removal long-term trends for five Iowa sites and the average. From Mallarino et al. (2011). Factors determining high temporal soil-test potassium variation and soil sampling and testing alternatives. In Proceedings, North Central Region Soil and Plant Analyst Workshop. Feb. 23-24, 2011. Bettendorf, IA. Available at http://ncera-13.missouri.edu/publications.htm.

Fertilizer and Manure Potassium Management

Potassium Sources

Potassium fertilizer is available commercially mainly as potassium chloride (KCl, 0-0-60), potassium sulfate (K_2SO_4, 0-0-50), and potassium nitrate (KNO_3, 13-0-44). The potassium is all water soluble for these sources. These sources (especially potassium nitrate) have the potential for inhibiting plant growth due to salt effects (the plant cannot get enough water from the soil) if applied in excess and close proximity or with the seed. Potassium chloride accounts for over 95% of all K fertilizer sold in the U.S. because it is mined from raw KCl deposits, and minimal processing and transportation make this the most economic K source. Potassium sulfate is primarily used where Cl toxicity or sulfur (S) deficiency is a problem. Potassium nitrate also is a source of N, but is expensive and is widely used only for foliar sprays of K application to fruits and vegetables.

Potassium in organic sources, manures and sewage sludge, occurs predominantly as soluble inorganic K^+ and is readily available for crop uptake. In animal manures, the K concentration ranges between 0.2 and 2% of dry matter, so large application rates are required to meet crop needs.

Placement Method and Timing

There are many ways of applying K to crops and most considerations, except potential salt effects, are similar to those for P fertilizers. Band applications concentrate nutrients at or near the root zone, which is important for young plants with limited root systems, particularly in cold and/or compacted soils. The "starter" effect from K is much less than for N and P, however, and too much K fertilizer close to the seed can reduce seed germination and injure roots due to high salt concentrations. Band K should be placed beside and below the seed level to reduce potential damage or by using very low rates if it is applied to the seed furrow. Band K applications can be more effective than broadcast application in soils with a strong capacity to retain added K in forms of low plant availability. This may be the case in soils with very high clay content or soils with significant levels of vermiculate in the clay fraction. Otherwise, and in most regions, broadcasting K fertilizer before planting is a convenient and low-cost way for applying high amounts of K fertilizer. Research with corn, mainly in Iowa and Minnesota, has shown that deep banding of K can be more effective than other placement methods, especially for ridge-till and sometimes for no-tillage and strip-tillage. The research demonstrated that the cause of increased efficiency of this method does not necessarily relate only to STK stratification typical for these systems, and that is explained by water availability deeper in the soil profile when the top few inches of soil are dry.

With the exception of regions that have soils with very high K retention capacity, the timing of K application before planting has little or no impact on K use efficiency by crops. This fact justifies, for example, widespread K application in the fall for summer crops in the Corn Belt and the Great Plains, and also application every other year for some rotations. In soils that retain or transform a significant proportion of applied K into forms of low crop availability, however, application long in advance of crop growth may reduce K use efficiency and often there are large differences between placement methods (less efficiency with broadcast and incorporated application, for example).

Variable Rate Potassium Application

Dense soil sampling in many fields has shown very large within-field spatial variability of STK, crop yield levels, and crop response to K fertilization. Figure 8 shows an example of the variation in corn yield response to K fertilization for field areas 10 to 25 acres in size that had different STK values. Precision

agriculture technologies available to producers or custom fertilizer applicators facilitate application of fertilizer and manure at rates adequate for different parts of a field based on STK and estimated K removal. Grid or zone soil sampling methods, combined with variable rate application of fertilizer or manure K, may not always increase crop yield or increase profits compared with traditional uniform rate application, because the average fertilization effect on yield and amount of K applied depends on the overall level and distribution of STK values. Also, soil testing seldom is performed on an annual basis, there is always a certain degree of sampling error (especially in fields with high small-scale variability), and research has shown that short-term relationships between K removal and STK are very variable. Therefore, even with annual soil sampling and variable-rate application, use of this technology faces challenges for K management. However, variable-rate application of K fertilizer minimizes or avoids K application to high-testing areas within fields, reduces STK variability, and as a consequence, improves K use efficiency. Variable rate application of K fertilizer is now common in the Great Plains and Corn Belt.
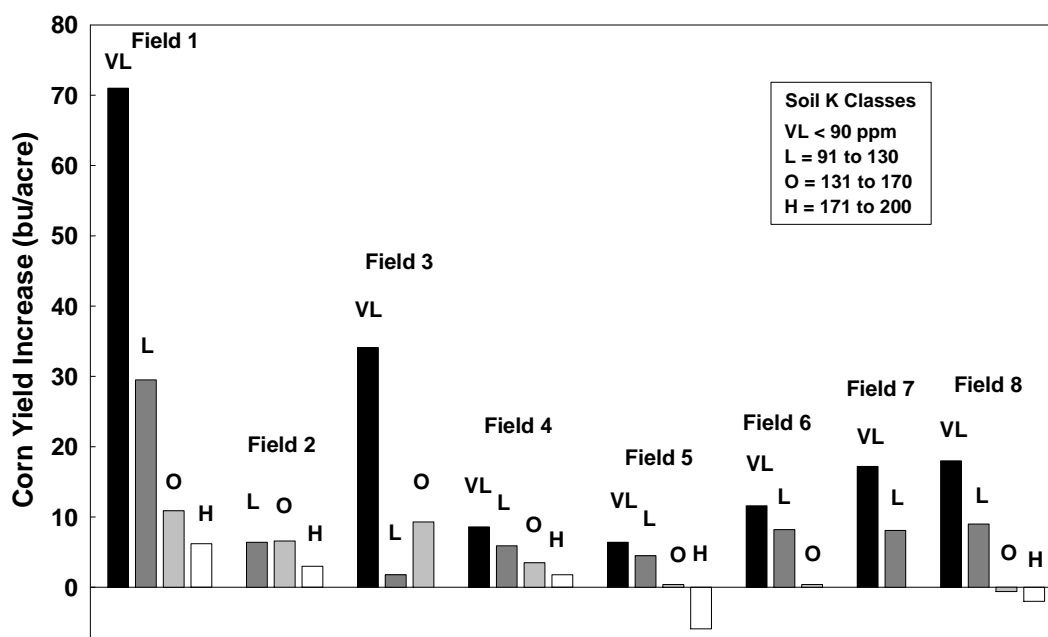

Figure 8. Within-field soil-test K variability and yield response variability from eight representative strip trials conducted in Iowa (field identifiers are arbitrary codes). From A.P. Mallarino and D.J. Wittry (2006). Variable-rate application for phosphorus and potassium: impacts on yield and nutrient management. p.219-224. In The Integrated Crop Management Conf. Proceedings. Nov. 29-30, 2006. Iowa State Univ. Extension. Available at

http://www.agronext.iastate.edu/soilfertility/info/mallarino_Variable-PK%202.pdf

Summary

Effective K management requires not only a thorough understanding of K reactions in the soil, but also an awareness of how climate, aeration, and moisture can affect the capacity of a plant to access the large reserves of soil K. Potassium exists in large, albeit finite amounts in soils, but the readily available forms can be depleted during short period of high crop demand or over long-term crop production.

Proper management of K is essential to maximize the profitability of crop production as well as maximize the efficiency of a non-renewable resource. Potassium management, as well as P management, is somewhat simpler than for N in humid regions due to relatively easier to predict chemical transformations and no gaseous phase or volatilization problems. Also, although there is more temporal variability of STK and uncertainty with soil testing than for P, soil sampling and testing for K is still a useful diagnostic tool. The goal of sound K management in most regions of the U.S. should be to keep the STK level at optimal ranges for maximum economic crop yield and utilize application methods that optimize K use efficiency and profitability. Substantial within-field variability of STK and K removal with harvest in most agricultural areas justifies the use of appropriate soil sampling methods and variable-rate application technology to increase K use efficiency.

Best Management Practices for K Fertilization:

Any list of best K management practices will need to be tailored to a specific region because of large variation in crops, soils, and production systems; and likely will be incomplete in regard to addressing all potential issues. However, the following list includes the most important concepts underlying K management strategies.

1. Sample soil as frequently and densely as possible, and use appropriately calibrated soil-test methods based on research for each state or region.

2. Consider yield levels and crop removal between and within fields to help maintain optimum soil-test K levels in conjunction with soil testing.

3. Fertilize K deficient soils using economically sound agronomic guidelines. In general, soils testing 'high' or "very high" will not respond economically to additional K and should not receive fertilizer except for a small amount of starter fertilizer in certain specific conditions.

4.   Divide large, non-uniform fields into smaller fertility management units based upon yield potential, soil tests, and relevant soil properties.

5.   Account for crop available K applied with manures and other organic sources when deciding on K application requirements.

6.   Refer to local research and guidelines concerning K placement methods to optimize K use efficiency and the profitability of nutrient application.

Case Study

Several K management strategies and philosophies are used by producers across the U.S. One example representative for all geographic areas, crops, and current management systems is not possible. Therefore, the following situation and suggested options for improved management apply to a specific farm in the U.S. Corn Belt. However, many issues and possible practices the producer could consider to improve crop K use efficiency and economic return from K application apply to other regions.

Example scenario

•   An 800-acre dairy farm in northeastern Iowa.

•   Soils are well drained, moderately permeable, are of loam, silt loam, or silty clay loam texture, and slopes range from 2 to 12 percent.

•   The farm has fields with continuous corn and others in a rotation consisting of three years of alfalfa, two year of corn, and then soybean one year. About one-half of the corn is used for silage that is fed to dairy cattle.

•   The producer uses chisel plow in approximately one-half of the fields and no-till in the other half.

•   Some corn fields receive high rates of dairy manure, including for corn after the last alfalfa production year. Large quantities of manure are produced in the overall farm operation, which is applied without using manure nutrient analyses or soil testing.

•   For many years the farmer has assumed that sufficient amounts of nutrients are applied with the dairy manure, including K, so only occasional fertilizer application is used. This fertilizer is mainly N for the continuous corn and some broadcasts K fertilizer (as potassium chloride) to some fields with alfalfa.

•   The dairy manure is broadcast and incorporated by chisel plowing and disking in fields managed with tillage (all with continuous corn), but is not incorporated or injected in fields managed with no-tillage.

•   In recent years, especially after harvesting some high yielding corn silage, the farmer has noticed older corn leaves on the lower part of plants with yellow or brown edges in spots, and also wonders about apparently increasing within-field variation of yields of both corn and alfalfa.

The farmer's recent observations are consistent with likely K deficiency given the crop and nutrient practices that he has been using. This scenario could be a frequent situation in geographic areas with crops that remove large amounts of K when manure and soil analysis are not used as it should, and the manure is not managed appropriately. With the high nutrient removal with alfalfa and corn silage harvest, it is likely that the amount of K applied is not adequate to maintain soil test K at optimum levels. This, together with uneven or not careful manure application, will lead to extreme variation in soil tests across and within fields, and limited crop yields at least in some areas.

Following are some new management options to consider:

•   It is very important from the agronomic and economic point of view to monitor soil nutrient levels routinely. This is crucial in order to adjust nutrient application rates to meet crop requirements, maximize profitability, and avoid potentially high risk of water quality impairment due to excess N and P loss from fields. In this specific case, it is very likely that the spotty K deficiency symptoms in corn, and large within-field crop yield variability, is due to continued uneven application of dairy manure without consideration of K being applied and varying yields. For example, corn silage harvest removes almost four times more K than grain only harvest. Harvest of a high yielding alfalfa crop can result in even more K removal than a high yielding corn silage crop. While soybean is a minor crop in the rotations, soybean grain harvest will remove more K than corn grain harvest. Therefore, the producer should adopt a soil sampling strategy for monitoring soil test levels, K in particular, and within-field soil test variability. An ideal sampling strategy would be a 2.5 acre grid sampling on all fields, or a less dense zone sampling

approach that considers at least soil map units and topography. Some measurement of within-field yield variation would be very useful, although this is easy and of relatively low cost only for grain yield with yield monitors and GPS. The soil sampling frequency should reflect the crop rotation. For example, sampling before each new alfalfa seeding and before the first-year corn after alfalfa, and every two to three years in the continuous corn. The soil test information would allow the farmer to know what fields and field areas require supplemental K fertilizer application, and if excess manure P is being applied to some fields or field areas.

•   The farmer should have a regular manure sampling and analysis program so the amount of nutrients applied can be appropriately determined. In fact, regular soil and manure analyses are beginning to be required by many NRCS programs and state agencies in charge of preserving environmental quality.

Once a K soil test map of the farm is carefully studied, the next step would be to target dairy manure or K fertilizer application in field areas with lower K levels and avoid/reduce applications in areas with high K levels and/or excessive soil-test P levels (if they exist). Consideration should be made for the needed N, P, and K. For example, if soil test P is very high, and K soil test is low, then fertilizer K should be applied instead of manure. If the field is rotating from alfalfa to first year corn, then manure application should be avoided, or only a low rate should be applied, since first-year corn after alfalfa crop requires little or no additional N. Application of manure or fertilizer can be accomplished by using conventional manure/fertilizer application practices, or variable rate application equipment depending on the degree and scale of P and K spatial variability and the availability of variable-rate technology equipment.

•   The dairy manure should be injected when it is applied to fields managed with no-tillage. This will increase manure N use efficiency (by reducing ammonia volatilization) and will reduce the risk of P loss with surface runoff. Known crop availability of N, P, and K in dairy manure, and the diversity of cropping and harvest systems being used in this dairy farm (and in most farms that include animal production), present a serious challenge concerning maximum use of the manure resource while attending to crop nutrient needs and risk of water quality impairment due to excess N and P application.

•   In order to properly maintain adequate K supply for all crops and minimize the risk of excessive N and P loss, the farmer has to appropriately consider manure and inorganic fertilizer application rates, avoid application of N at rates much higher than needed by each corn crop, and use an environmental P risk assessment tool (such as the P Index). Use of the P Index helps to determine what fields or field areas testing high in P can have application of manure to supply N and K, and will not result in excessive risk of P loss and water quality impairment.

Chapter 5:
Sulfur Management

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Introduction

Sulfur (S) is often classified as a "secondary" plant essential element, mainly due to a smaller plant requirement but also because it is less frequently applied as a fertilizer and in smaller amounts compared to other nutrients like the "macronutrients" nitrogen (N), phosphorus (P), and potassium (K). However, if deficient, S can have a dramatic effect on plant growth and crop productivity – more than the classification "secondary" would imply.

Sulfur is a constituent of three amino acids which are essential to protein synthesis and represent approximately 90% of the S content in plants. Sulfur is also necessary in the formation of chlorophyll, vitamins, enzymes, and aromatic oils. As a constituent of amino acids, sufficient S is essential for high protein content in forages. Research has shown that S plays an important role in crop quality such as wheat grain for making bread and protein content of forages and grains. Breadmaking varieties of wheat have approximately 10% more S in grain than non-breadmaking varieties, although total plant S uptake is similar. Two important factors related to breadmaking are loaf volume and dough extensibility. Both of these factors are directly related to S concentration in grain, which in turn is dependent upon available S in the soil.

Sulfur deficiencies are on the rise in the U. S. and throughout the world. Three global trends are responsible for increasing S deficiencies:

1) The shift in modern fertilizers to more concentrated, higher-analysis products containing little to no S (historically S was a co-product of the manufacturing process);

2) The reduction of sulfur dioxide (SO_2) emissions from burning coal and oil, which decreases atmospheric S additions; and

3) The steady increase in crop S uptake and removal due to high-yielding varieties and more productive management.

Plants require significant S, with uptake varying considerably between crops. For example, alfalfa is a greater S demanding crop than corn. Also, the plant component harvested affects S removal. Harvesting all above ground material will result in more S removal. For example corn grain versus corn silage, stover removal or grazing, and multiple forage crop harvest. Table 1 lists the S removal per unit of yield, and can be used for estimating S removal. Crops take up S in the sulfate (SO_4^{2-}) form. They do not take up elemental S. Sulfate-S usually represents less than 10% of total S in the upper soil profile, with most S contained in the soil organic matter.

Sulfur deposition from the atmosphere can represent a significant S input, especially in locations down-wind from sources, such as coal-burning facilities, metal smelters, geo-thermal areas, and urban areas. Atmospheric sulfate-S deposition ranges significantly, but usually is between 3 to 11 lb S/acre. In addition, plants can absorb sulfur dioxide directly from the air. Figure 1 shows a recent U.S map with sulfate wet deposition mainly due to industrial activity. Also, irrigation water can be a significant source of plant available S.
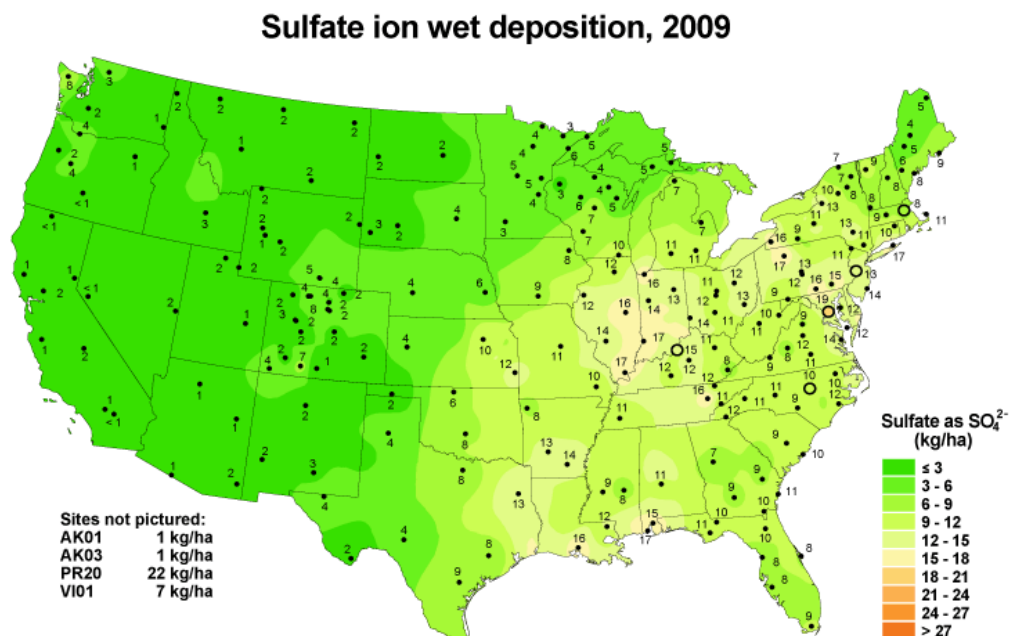

Figure 1. Sulfate wet deposition for the U.S. in 2009.
Source: National Atmospheric Deposition Program/National Trends Network. http://nadp.sws.uiuc.edu.

Table 1. Sulfur amounts required by common agricultural crops.

Crop	Unit of Yield	Pounds of S per unit of yield
Corn	bu	0.07
Corn silage	ton	0.58
Soybean	bu	0.10
Oat and Straw	ton	4.50
Wheat	bu	0.08
Barley	bu	0.08
Alfalfa	ton	5.00
Clover	ton	3.00

Adapted from Modern Corn and Soybean Production. 2000.
MCPS Publications.

Sulfur deficiency looks similar to N deficiency (yellowing and interveinal chlorosis), but because S is not very mobile in the plant, the younger leaves tend to show the deficiency first versus the older leaves as in N deficiency. With severe deficiency, the entire plant will have yellowing and reduced growth or spindly stems. Efficient N utilization requires adequate S because both are needed to form proteins in the plant. Sulfur is also needed for N fixation by legumes. Effective management of S requires an understanding of the processes that determine its availability to crops and the methods to manage soils with inadequate S levels.

Basic Sulfur Processes in the Soil-Plant System

Mineralization and Immobilization

Organic S compounds held in plant and microbial residues collect in the soil organic matter (OM) and represent the largest S pool in many soils. Over 90% of the total S in these soils exists in the organic form, except in soils where accumulations of gypsum ($CaSO_4$, calcium sulfate) are significant. Microorganisms decompose the OM and release plant available S through the process of mineralization, similar to that with N cycling. About 1 to 3% of organic S is mineralized each year, contributing 4-13 lb/acre of inorganic sulfate-S annually. The amount of S made available to plants annually via mineralization depends on the soil OM content and conditions suitable for mineralization. Therefore, practices to maintain or increase soil OM can help with plant available S supply.

Immobilization is the microbial process of converting inorganic sulfate-S to organic materials, and is essentially the reverse of mineralization. Microorganisms use available S from the soil and convert it into

proteins and other organic compounds. Although this process removes S from the available pool, the S is still in a reserve pool that could eventually become available to plants via mineralization.

Since mineralization and immobilization are primarily biological processes, factors affecting microbial growth will influence these S transformations. Important factors include soil temperature, soil moisture, pH, C:S ratio, aeration, and residue composition. The highest mineralization rates will occur under aerated, warm, and moist conditions with near neutral pH levels because these conditions are optimal for microbial activity. Conversely, cold-dry soils will have slow mineralization and low production of sulfate-S.

The N:S ratio is relatively stable in soil OM, remaining near 8:1; however the C:S ratio is more variable and strongly affects relative mineralization and immobilization. If residues and organic matter lack sufficient amounts of S, microbes will pull the needed available S from the soil and thus reduce plant available S.

Sorption and Precipitation

Inorganic S occurs in solid phases in the soil as sorbed S or S-containing minerals. Sorption of sulfate increases as anion exchange capacity (AEC) and clay content of soils increase. Highly weathered and acid soils dominated by positively charged Fe/Al oxide will have a high AEC and therefore sorb significant sulfate. Also, because sulfate interacts with soil clays, soils will retain sulfate, including sulfate accumulation in the subsoil where clay content is high in many soils.

Inorganic S-containing minerals represent an important S pool in some soils. Sulfur is also present in numerous primary and secondary minerals, which release either sulfate or sulfide (S^{-2}) as they weather. Gypsum, for example, is widely distributed in arid and semi-arid soils where precipitation is too low to leach the mineral out of the profile. In moderately humid regions, gypsum accumulates in the subsoil, forming a S-rich layer often in close proximity to calcium carbonate ($CaCO_3$) layers. Although the surface layers of soils may have low levels of plant available sulfate-S, sulfate in the lower soil profile maintains an adequate supply of S within the rooting depth. Early in the growing season, subsoil S may not be available to crops because it is out of reach of the growing roots. Later in the growing season, when plant roots have grown deeper, adequate S can then be accessible to crops.

Sulfur Losses

Sulfur loss from moderately to well-drained soils, other than by crop removal, is through leaching of sulfate. Sulfate is a negatively charged ion (SO_4^{-2}, an anion), and therefore not held on the cation exchange complex. Leaching is the physical removal of sulfate by water moving through the profile, like that with nitrate. Sulfate, however, is not subject to denitrification. The areas with the highest risk for sulfate leaching are associated with high precipitation and coarse texture soils. Excessive irrigation following fertilizer application can move sulfate through the soil profile and eventually out of reach of plant roots. In semi-arid climates, sulfate often collects in the subsoil, as described earlier, because there is insufficient water to move sulfate out of the profile.

Testing for Sulfur Sufficiency

Sampling soil, plant, and irrigation water are methods for determining S fertilization needs. Soil testing the topsoil for plant-available S has been and continues to be debated because testing for extractable sulfate-S or other S forms has a poor relationship with S sufficiency for crops, and is not reliable in soils of many regions for predicting yield response to applied S. Other suggested soil tests for S include measuring the organic S content and estimating mineralization during the growing season. For example, a study from Iowa has shown no value of extractable soil sulfate-S (0-6 inch depth) for predicting corn yield increase from S application (Figure 2), and several land-grant universities do not recommend sulfur application based on soil testing. A low testing soil may still supply a crop with adequate S because of ample S below the testing depth (i.e., subsoil sulfate or gypsum layer), significant organic S mineralized during the growing season, or high S levels in shallow groundwater. At issue is that soil tests by themselves cannot integrate all of the potential sources and variation in supply of plant-available S.
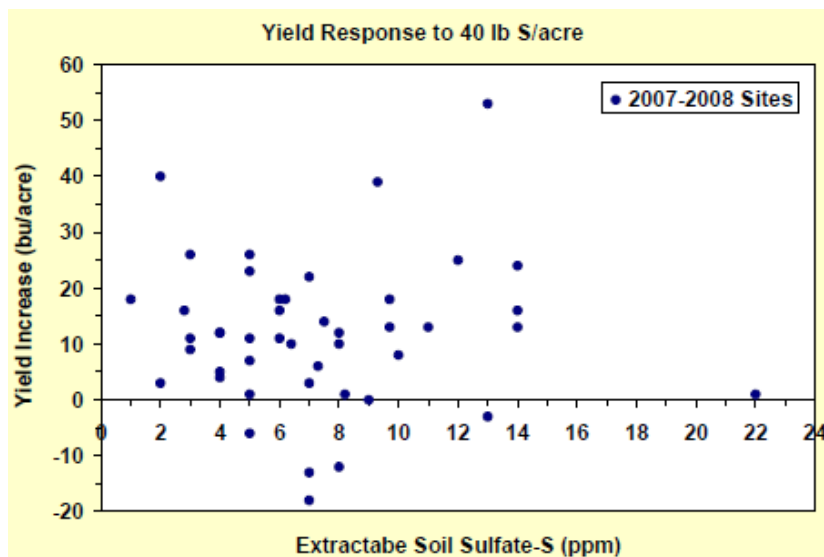
Figure 2. Corn grain yield response to S application as related to extractable soil sulfate-S concentration (0-6 inch soil depth) in the no-S control. Adapted from Sawyer, J.E., D.W. Barker, and G. Cummins. 2009. Dealing with sulfur deficiencies in crop production: the Iowa experience. p. 64-73.In North-Central Extension-Industry Soil Fertility Conf. Proceedings. Nov. 18-19. Vol. 25. Des Moines, IA.

Plant tissue testing can also be used to determine sufficiency of plant-available S. Samples are analyzed for total S concentration or the N:S ratio. These plant tests for S have greater reliability than soil testing in some crops. For example, the S concentration in the top six inches of alfalfa at early bud state (Figure 3). In research with corn in the same area of Iowa, plant S concentration of ear leaves at silking could not indicate a specific critical concentration.

In some crops and geographic areas, the plant N:S ratio has been successfully used as an indicator of S status. For example, the critical ratio for wheat is about 16:1, so, assuming adequate N supply, ratios greater than 16:1 would indicate a S deficiency in the plant (Figure 4). Unfortunately, deficiencies indicated by tissue tests in some crops taken during the growing season cannot easily be corrected until the following year. In other crops with multiple harvests per growing season, like alfalfa, deficiencies can be corrected after any harvest.
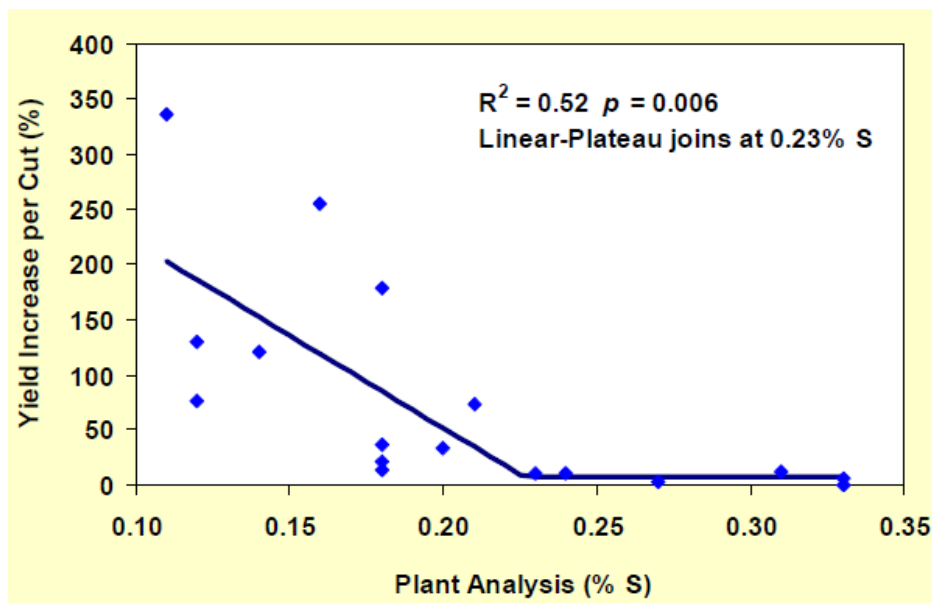
Figure 3. Yield increase per cut from S fertilization relative to the alfalfa plant tissue S concentration (6-inch plant top) with no S applied. Adapted from Sawyer, J.E., D.W. Barker, and G. Cummins. 2009. Dealing with sulfur deficiencies in crop production: the Iowa experience. p. 64-73.In North-Central Extension-Industry Soil Fertility Conf. Proceedings. Nov. 18-19. Vol. 25. Des Moines, IA.

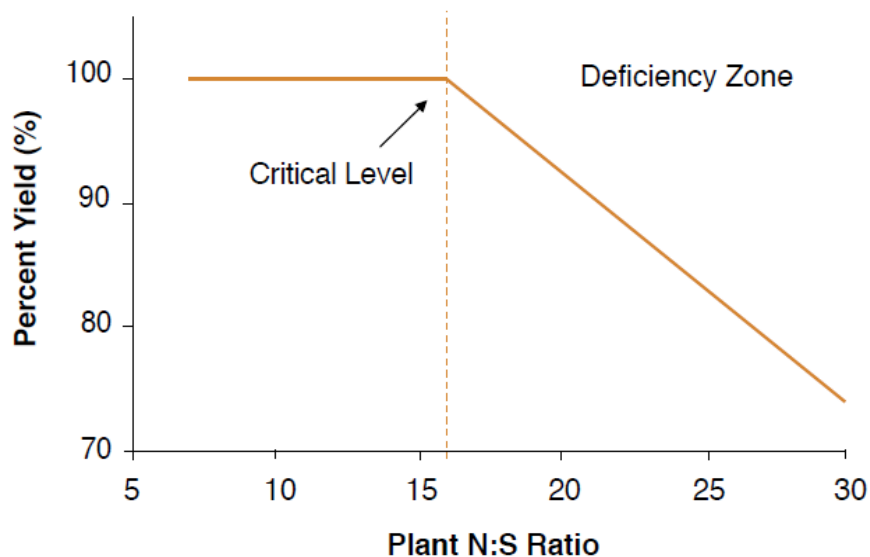*Figure 4. Relationship between relative yield of wheat and plant tissue N:S ratio. Adapted from K. Spencer and J.R. Freney (1980). Agron. J. 72:469-472.*

Basis for Sulfur Fertilizer Recommendations

Yield responses to S occur most commonly in crops with higher S requirements such as alfalfa, canola, and corn; when most of the plant material is removed; in sandy or eroded soils; and soils low in organic matter or with low or very low sulfate-S content in the profile. Unlike N-P-K, S fertilization guidelines do not exist in many regions of the U. S. The existing S fertilization recommendations often are based on plant testing (for specific crops when reliable) or local yield response trials, and suggestions often include consideration of soil properties and other conditions commonly associated with response to S application. This is explained by the great complexity of S cycling and factors affecting plant available S levels; no single diagnostic method or recommendation system seems to be appropriate for all crops or regions. Therefore, diverse S management strategies have been implemented in different production areas, supporting the need to use locally developed information. Following are examples that represent some of the various approaches that universities and other research institutions are recommending to manage S fertilization.

The University of Wisconsin recommends the use of a S availability index (SAI) to determine relative plant available S. This index is comprised of: (soil test SO_4^--S x 4) + Subsoil-S + precipitation-S + (% OM x 2.8 lb/acre) + available manure-S. For the SAI, values greater than 40 are considered adequate with no S application needed, and less than 30 considered low with application of 10-50 lb S/acre recommended (with rate depending of the placement method and crop). If the SAI is between 30 and 40, a tissue test is recommended to determine if additional S is needed. In other states, such as Alabama, S recommendations are more conservative in terms of preventing S deficiencies and suggest that all crops receive 10 lb S/acre per year except cotton which would receive 20 lb S/acre. In the Great Plains, a soil test critical value has been determined for canola. Soils with less than 5 ppm sulfate-S should be fertilized with 15 lb S/ac in an optimal N-P-K blend. In the same region, the critical soil test level for wheat and other small grains such as barley and oats is only 3 ppm SO_4-S and fertilizer recommendations for deficient areas range between 10 and 15 lb S/acre.

Sulfur Fertilizer Application

Proper management of S applications is a key for optimizing yield and profitability. There are some guidelines regarding S source, timing, placement, and rate that producers should consider in order to maximize S use efficiency.

Sulfur Sources

There are several forms of S fertilizers available to producers, some with very different S solubility and crop-availability in the short term. The most common S fertilizers used in the U.S. are listed in Table 3. The major factors in choosing a S fertilizer are the analysis, availability to plants, acidifying effect of the material, fertilizer compatibility, and cost. Ammonium sulfate, ammonium thiosulfate, gypsum, potassium sulfate, and epsom salt (magnesium sulfate) are commonly used S sources because they quickly release sulfate for plant use. Therefore, these fertilizers can be applied before, at, or after planting. Elemental S, on the other hand, must be microbially oxidized to sulfate before plants can utilize it. The rate of oxidation depends on particle size, incorporation, temperature, moisture, and soil properties. Dispersible, granular elemental S can be broadcast to increase surface area and exposure of S, and thereby accelerate oxidation. This form of S must be applied well before the growing season if it is expected to supply the crop with S; otherwise some readily available S should be included. Another factor with application of elemental S is the acidifying affect it may have on the soil. Most soils are buffered and should not have pH affected by low rates typically applied to provide S for crop production, but sandy soils are more susceptible to acidification. Ammonium sulfate acidifies soil at about twice the rate as commonly used N fertilizers. Therefore, if it is applied as a N source, the soil pH decline may be large but the effect on soil pH will be minimal when it is applied based on crop S need.

Manures are a good source of S, and can eliminate the need for S fertilizer application. Also, many locally produced byproducts contain S, and can be an effective source of plant-available S. Examples include products from lysine manufacturing, soapstock processing, and wallboard. In some cases, application of a byproduct can supply adequate S for many years of crop production.

Table 3. Commonly used S fertilizers.

Fertilizer Source	Formula	Analysis (N-P-K-S)
Ammonium sulfate	$(NH_4)_2SO_4$	21-0-0-24
Ammonium thiosulfate (ATS)	$(NH_4)_2S_2O_3$	12-0-0-26
Gypsum	$CaSO_4 \cdot 2H_2O$	0-0-0.5-17
Epsom salt	$MgSO_4 \cdot 7H_2O$	0-0-0-14
Granular elemental S	S + bentonite	0-0-0-90
Potassium magnesium sulfate	$K_4SO_4 \cdot 2MgSO_4$	0-0-22-23
Potassium sulfate	K_4SO_4	0-0-50-18

Timing/Placement

The demand for S by a growing crop is not constant through the growing season, with the highest uptake associated with the periods of rapid growth. Timing S fertilizer applications so that they provide a plant-available supply when the crop needs it is the desired goal. Plants subject to deficiency during a high demand period may not recover to achieve full yield potential even with high S rates applied too late or when a form such as elemental S is not applied far enough ahead of crop need. Conversely, application of a sulfate form (or one that changes quickly to sulfate such as thiosulfate) well in advance of crop uptake can be subject to losses in soils with high leaching potential (coarse textured soils with excessive rainfall). In those soils, application close to or at planting would be desirable. Sidedress applications can be beneficial for correcting deficiencies, but should be a readily plant available form (such as sulfate or thiosulfate) and applied before large plant uptake. For crops with multiple harvests, like forages, there are multiple opportunities for application – at seeding or after any cutting. Applied S must be in the rooting zone for plant uptake, therefore banding or incorporation into the soil is desirable. Surface applications must be in a sulfate form so movement into the soil can take place with rainfall. Some S fertilizers may cause seedling injury and should not be placed in furrow, with thiosulfate an example.

Application Rate

Sulfur fertilizer application rates should be based on expected optimal economic return. Those rates vary among regions, crops, and years, so local research is important to determine economic response. For example, in a set of S rate trials with corn in Iowa, the maximum response rate for 21 fine-textured soil sites was 17 lb S/acre, with an economic optimum rate at 16 lb S/acre (Figure 5). However, for 7 coarse-textured soil sites, the maximum response rate was higher at 25 lb S/acre, with an economic optimum rate at 23 lb S/acre. The economic optimum S rate is near the maximum response because the fertilizer cost (rate times price) is low compared to the yield return (yield increase times corn price).
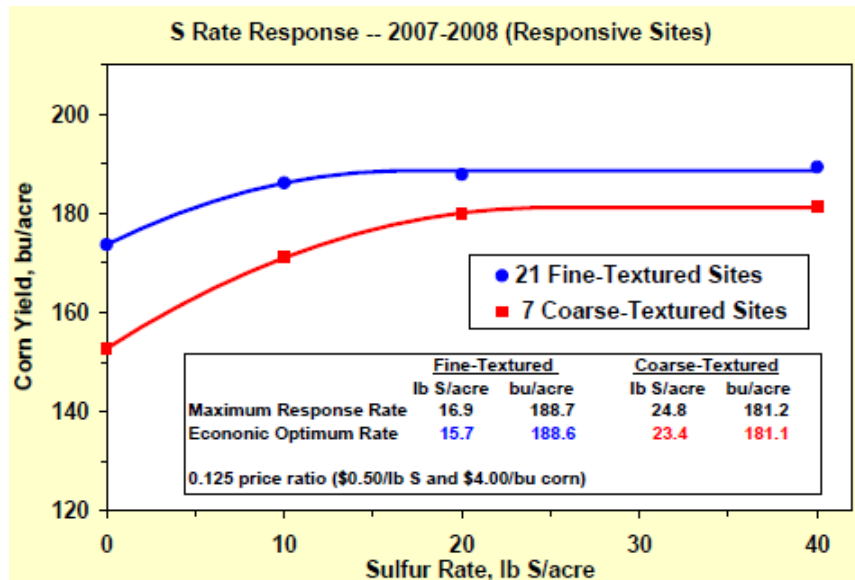
Figure 5. Corn grain yield response to S application rate at responsive sites. Adapted from Sawyer, J.E., D.W. Barker, and G. Cummins. 2009. Dealing with sulfur deficiencies in crop production: the Iowa experience. p. 64-73.In North-Central Extension-Industry Soil Fertility Conf. Proceedings. Nov. 18-19. Vol. 25. Des Moines, IA.

Another example of crop response to increasing rates of S application is presented in Figure 6 for research in Alabama with cotton. In this case, cotton yield reached maximum values with S applications of 20-35 lb S/acre.
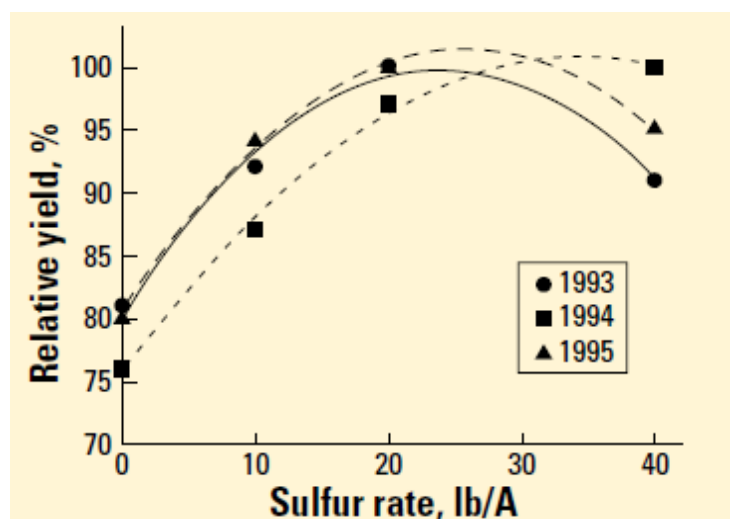

Figure 6. Cotton lint yields as affected by the rate of S on a Lucy loamy sand in Alabama. Adapted from Mullins, G.L. 1999. Cotton response to sulfur on a Coastal Plain soil. p. 64-73.In Better Crops. 83(4) 4-5.

Research to date has not fully documented the variability of S deficiency within fields or the potential for variable-rate S application. Work with alfalfa in Iowa clearly showed differential response in poor and good coloration/growth areas, indicating that it would not respond to S application across entire fields. Similar expression of S deficiency and yield response within fields has been observed in corn. However, until more is known about economically delineating S deficiencies or access to tools for determining deficiency, it is likely most prudent to simply fertilize entire fields when deficiency exists rather than attempt site-specific applications because of the relatively low cost of S fertilization. Site-specific management is possible, but increases production costs and reliable methods are needed to "map" S sufficiency across a field.

Summary

Effective S management requires not only a thorough understanding of S transformations in soil, but also an awareness of how several factors can affect the plant availability of S and potential deficiency. These include temperature, moisture, soil organic matter, erosion, tillage system, landscape position, soil texture, rooting depth, subsoil sulfate, past S inputs, atmospheric deposition, and cropping system. Although S deficiencies have been relatively infrequent in the past, the frequency of deficiencies is increasing and the need for S fertilization is increasing. Sustained high crop yields, with few if any S inputs, has resulted in greater chance of deficiency. Sulfur plays a major role in crop growth, yield, and quality, and improves the effectiveness of other nutrient inputs like N, P, and K. Therefore, S needs to be considered for developing successful nutrient management plans.

Chapter 6:
Calcium and Magnesium Management

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Introduction

Calcium (Ca) and magnesium (Mg) are considered secondary macronutrients because they are less commonly yield limiting than the macronutrients (N, P, and K), yet are required by crops in relatively large amounts. Calcium and Mg occur in the soil as soluble 'divalent' ('double-charged') cations (Ca^{2+} and Mg^{2+}), on cation exchange sites, and in primary minerals. The major processes in Ca and Mg cycling are plant uptake, exchange, precipitation, weathering, and leaching. Calcium and Mg dynamics in the soil are quite similar to K. Like K, plants absorb the soluble ionic forms from soil solution (Ca^{2+} and Mg^{2+}), which is then replenished from exchangeable and mineral Ca and Mg. The most notable difference between the Ca and Mg nutrient cycles and K is the absence of clay fixation with Ca and Mg.

Calcium as an Essential Nutrient

Calcium is essential for plant growth, cell division, and cell enlargement. It is a component of cell membranes and is important for developing the root system, shoot tips, and storage organs. Calcium aids in pollen development and helps plants retain foliage. Calcium strengthens cell walls, helping to reduce bruising and plant disease. An adequate supply of Ca produces food crops which are less susceptible to handling damage and have a longer shelf life. Fruit and vegetables will also have a higher nutritional value. Crops deficient in Ca can have growth disorders. Since Ca does not move readily within the plant, Ca deficiencies appear in the younger tissues. Calcium deficiencies may result in the death of the plant's growing point. It may also cause blossoms and buds to drop prematurely. Calcium quantities in the harvested portions of common agricultural crops are presented in Table 1.

Calcium is usually the dominant basic cation in soil cation exchange reactions, typically accounting for more than 70% of base saturation. Base saturation represents the percentage of the cation exchange

capacity (CEC) occupied by basic cations (Ca, Mg, K, and Na), and increases with increasing soil pH. Exchangeable Ca exists in equilibrium with the soil solution, replenishing soluble Ca used by plant uptake or lost by leaching. Leaching can be significant in coarse-textured soils where substantial water moves through the profile. The formation of many calcareous soils occurred by Ca accumulation with leaching from the topsoil, soil developed from calcium carbonate ($CaCO_3$) parent material, or carbonates deposited as water carrying dissolved carbonates accumulated in low landscape areas and then water evaporated leaving the solid carbonaceous materials. These Ca-rich 'calcic' areas can be comprised $CaCO_3$ or gypsum ($CaSO_4$). Calcium is made available to plants by dissolution of these minerals or in the long term through weathering of primary minerals such as feldspars and micas.

A low exchangeable Ca content in soil often causes acidity problems due to low base saturation, before actual Ca nutrient deficiency becomes an issue. Where soil acidity is a problem, liming soils with limestone ($CaCO_3$ and $MgCO_3$) is a common practice and thus supplies plant available Ca. Soils with neutral to basic pH are buffered at high pH levels by both Ca on the exchange complex (as the dominant part of the base saturation) and Ca in bicarbonates and carbonates (free lime).

Because of its divalent (2^+) charge, Ca acts as an ionic 'glue' (electrostatic attraction with negatively charge clay particles), thus promoting aggregation of soil particles through a process called flocculation. Soils with high levels of sodium (Na), referred to as sodic soils, promote dispersion which is the opposite of flocculation. When the monovalent (single-charged) Na^+ ions reach a high proportion of the cations on clay negative exchange sites (the CEC), the weak (and single) positive charge of the Na^+ ion is not strong enough to overcome the negative charges of clay particles, which then repel each other. The result of dispersion is a structureless soil with insufficient aeration, permeability, and water-holding capacity for optimum plant growth. Additions of Ca in the form of gypsum are frequently used for reclaiming sodic soils because it counters the effects of Na by adding Ca^{2+} ions, exchanging Ca^{2+} for Na^+ on the soil exchange site, allowing leaching of Na from the soil, and thus promoting aggregation critical for soil productivity. Gypsum is used instead of lime as the Ca source as often soil pH does not need to be increased, which does not occur with gypsum application.

Magnesium as an Essential Nutrient

Magnesium plays a critical role in nearly all parts of plant metabolism and protein synthesis, is an activator of enzymes, and an essential constituent of chlorophyll. It also aids in the formation of sugars, oils and fats. Deficiency in Mg leads to reduced photosynthesis, which limits crop yields. Plants require less Mg than Ca, but deficiencies are more common because less Mg exists in the soil solution and on the

soil exchange complex. Magnesium deficiency usually appears on older plant leaves first; the leaf tissue between the veins turns yellow or reddish in color, while the veins remain green. Severe deficiencies will cause leaf margins to curl. Magnesium quantities in the harvested portions of common agricultural crops are presented in Table 1.

Mineral forms of Mg are relatively resistant to weathering and represent a large fraction of total soil Mg. These include biotite, horneblende, olivene, and most 2:1 clay minerals. Magnesium can also be present in calcareous surface and subsurface soils as magnesium carbonate ($MgCO_3$), frequently along with $CaCO_3$. Although Ca and Mg share the same exchange processes, Mg sorbs less strongly than Ca to soil colloids (still Mg sorbs much more strongly than monovalent cations) and therefore is more prone to leaching, particularly in sandy soils. As a divalent cation, Mg^{2+} competes with Ca^{+2}, K^+, and NH_4^+ for plant absorption and cation exchange sites. As with Ca, Mg helps with soil flocculation and soil structure, but to a lesser extent. Magnesium deficiencies generally occur when the other cations dominate the soil exchange complex along with low Mg concentrations. A common Mg deficiency problem in cattle is called grass tetany, or hypomagnesaemia. This deficiency is due to insufficient Mg in forage fed to livestock. Often feeds are supplemented with Mg salts to supply adequate Mg. In soils with low available Mg, lime application to acidic soils (except with pure calcitic lime) often supplies adequate Mg (as the $MgCO_3$ component of lime along with $CaCO_3$); or fertilizers are applied such as potassium-magnesium-sulfate and epsom salt ($MgSO_4$) if soil pH is already at adequate levels. Magnesium concentration in forages can also be reduced when high rates of K are applied, increasing the chance of low forage Mg levels and development of grass tetany.

Table 1. Calcium and magnesium quantities in harvested portions of common agricultural crops.

Crop	Unit of Yield	Pound of Ca per unit of yield	Pound of Mg per unit of yield
Corn	bu	0.01	0.05
Soybean	bu	0.18	0.18
Oat and Straw	ton	4	4
Wheat	bu	0.03	0.15
Barley	bu	0.03	0.05
Alfalfa	ton	28	5
Clover	ton	28	7

Adapted from Modern Corn and Soybean Production. 2000. MCPS Publications.

Calcium and Magnesium Soil Testing

An often used approach for determining if the soil supply of Ca and Mg is sufficient to meet crop needs is to extract soil with ammonium acetate or Mehlich-3 (the same procedures used to determine soil test K) and evaluate the amount measured against critical levels. Because most U.S. soils contain more than adequate levels of Ca and Mg for most crops, no reliable or generally accepted critical level has been established. Therefore, although an estimate of exchangeable Ca and Mg sometime is routinely measured, many universities do not publish soil test Ca or Mg interpretations. There are exceptions, and an example is Ca testing for potato production due to issues with tuber density. Another example would be soil testing to help avoid development of grass tetany, where knowledge of soil test Mg and K would be useful when high rates of K are needed. Also, soils typically have large available levels of both nutrients because Ca and Mg are replenished by limestone application. If someone is interested in the soil CEC level, then routine soil testing can be used to estimate CEC by summing the dominant exchangeable cations (Ca^{2+}, Mg^{2+}, K^+, H^+, Na^+).

The Ca:Mg ratio or the basic cation saturation ratio concepts (meq/100g charge concentration based ratio) was developed many years ago as a means to identify an optimal level of these two nutrients or other cations for crop production. However, numerous research studies have shown that the Ca:Mg ratio or ratios of several cations is not a viable basis for fertilization with Ca, Mg, or other cations. Having sufficient levels of exchangeable Ca and Mg (through soil testing) is the proper method of evaluation where reliable field calibrations are available, rather than trying to manipulate ratios. Fortunately, in most U.S. soils Ca and Mg levels are adequate and the ratio of these nutrients are not an issue for availability of either nutrient as the parent material the soil developed from or local limestone sources supply both nutrients in adequate proportions. Also, adequate levels of plant-available Ca and Mg are maintained without need for fertilization either because the soil has a large inherent supply capacity or because of liming to maintain adequate soil pH for crop production.

Calcium and Magnesium Sources and Application

Application of Ca and Mg occurs most commonly through liming practices. With limestones classified as either calcitic or dolomitic, there is application of both Ca and Mg as these are contained in all limestones. Therefore, as long as acidic pH problems are corrected through liming, Ca and Mg supply will be maintained and at amounts more than removed with crop harvest. Once removal has occurred with years of crop production, and with concurrent low soil pH, liming once again supplies needed Ca and Mg. Soils

that have naturally high pH (neutral to basic pH), and those with free lime (calcareous), have more than adequate levels of these nutrients.

Even though limestone is the main source of Ca and Mg for crops, there are several fertilizers or amendments that contain these nutrients. Table 2 presents the most common sources of Ca and Mg. Within this list, limestone requires a special consideration since it is never a pure material but a mixture of Ca and Mg carbonates (with higher Ca concentration in the calcitic limestone and higher Mg concentration in the dolomitic limestone). Therefore limestone, no matter the type, is a source of both Ca and Mg.

Table 2. Most frequently used calcium and magnesium sources.

Source	Formula	Element concentration)
Calcium		--- % ---
Calcium chloride	$CaCl_2$	36
Calcitic limestone	$CaCO_3$	Approx. 32
Dolomitic limestone	$CaCO_3 + MgCO_3$	21 to 30
Gypsum	$CaSO_4 \cdot 2H_2O$	50
Magnesium		
Dolomitic limestone	$CaCO_3 + MgCO_3$	6 to 11
Magnesium sulfate	$MgSO_4 \cdot H_2O$	17
Potassium magnesium sulfate	$K_2SO_4 \cdot 2MgSO_4$	11

Summary

Secondary nutrients such as Ca and Mg are no less essential to plant growth than the primary nutrients. However, the mineralogy and texture of many U.S. soils maintain high levels of available Ca and Mg. An exception would be sandy soils in association with fertilization need of certain crops, for example potato, or interaction with application of other nutrients like K. Because plants require relatively small amounts of these nutrients and leaching is a minor loss, Ca and Mg deficiencies are rare but do occur in specific soil conditions and crops. In addition, liming soils to neutralize acidity and increase soil pH also add plant available Ca and Mg, thus reducing the probability of deficiency and need for fertilizer application.

Chapter 7:
Micronutrient Management

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Introduction

Micronutrients are those essential elements required in small quantities for plant growth and reproduction. The quantity needed varies with plant species and the specific element. Seven essential elements are considered micronutrients, and include boron (B), copper (Cu), chlorine (Cl), iron (Fe), manganese (Mn), molybdenum (Mo), and zinc (Zn). To better understand the relative amounts needed by plants, we can look at the crop removal rate. For example, harvest of a 150 bu/acre corn grain crop will remove approximately 135 pounds of N, 53 pounds of phosphorus (P_2O_5) and 40 pounds of potassium (K_2O) per acre. In comparison to these macronutrients, the removal amount for the micronutrients B, Cu, Fe, Mn and Mo, and Zn are only 0.06, 0.06, 0.10, 0.09, 0.03 and 0.15 pound per acre, respectively. While the needed micronutrient amounts are small, without them plants would not grow and reproduce.

Traditionally, the most important sources of micronutrients for crop growth have been those naturally present in soil and amounts added as impurities in fertilizers and pesticides. Specific soil and related crop situations, however, result in deficiency of one or more micronutrients and potentially serious limitation to crop production. An example is iron deficiency chlorosis in soybean, which coincides with soils having alkaline pH and free carbonates. In some areas, deficiencies of micronutrients have been diagnosed frequently and producers are taking a closer look at their general availability. For high yields and positive economic return to crop production, it is important to correctly recognize and correct micronutrient deficiencies. When micronutrients become a limiting factor, other inputs such as seed, water, fertilizer, etc. are less efficiently utilized and may be wasted. Table 1 lists the amount of each micronutrient (except chlorine) taken up by several crops.

Table 1. Approximate per acre micronutrient uptake by corn, soybean and alfalfa.

Micronutrient	Corn	Soybean	Alfalfa
	150 bu	60 bu	6 ton
	---------------------------- lb/acre ----------------------------		
B	0.16	0.1	0.3
Cu	0.1	0.1	0.06
Fe	1.9	1.7	1.8
Mn	0.3	0.6	0.6
Mo	0.008	0.01	0.02
Zn	0.27	0.2	0.24

Source: http://www.ces.purdue.edu/extmedia/AY/AY-239.html

A brief description of the importance of each micronutrient is presented below, along with the situations in which micronutrient deficiencies are more likely to occur and a general description of fertilization practices.

Boron

A primary function of B is related to cell wall formation, so B deficient plants may have stunted growth. Since B is not readily translocated from older to actively growing tissues, when deficiency occurs the terminal bud can stop growing and will die if the deficiency persists. Sugar transport in plants, flower retention and pollen formation, and germination also are affected by B deficiency. Boron deficiency symptoms first appear at the growing points. This results in a stunted or bushy appearance near the top of the plant, yellowing of newer leaves, barren ears due to poor pollination, hollow stems and fruit (hollow heart), and brittle, discolored leaves and loss of fruiting bodies.

Boron deficiencies are found mainly in sandy soils, in regions of highly weathered soils, low soil organic matter, exposed subsoil, and pH above 7.0. Organic matter contains much of the B in soils. Boron is present in the soil solution mainly as the undissociated boric acid form $B(OH)_3$, or the ionized form $B(OH)_4^-$ at high pH values, and these are the predominant B forms taken up by plants. The B forms are somewhat mobile in soil and can be leached from the root zone, but they move less than other anions like nitrate or chloride. Sorption by clays and association with organic matter will help retain B in soils and provide sources of available B for crops. Boron deficiencies are more pronounced during drought periods when root activity is restricted in the upper profile where available B is typically higher. Crops more sensitive to B deficiency include alfalfa.

Boron fertilizer application can correct deficiencies, but the application rate, method and crop should be carefully considered because toxicity can easily occur. Band application in the seed furrow generally is not recommended because high B concentration can be toxic to seedlings and also can result injury to developing plants. Crops most sensitive to B deficiency include alfalfa, canola, and sugar beet; and many crops are sensitive to B toxicity.

Copper

Copper is a component of enzymes that play a key role in photosynthesis, respiration, lignin synthesis, and carbohydrate and N metabolism. Copper deficiency results in stunting of plants, and since Cu is required for lignin synthesis, deficiency affects cell wall strength and prevention of wilting. Copper deficiency symptoms include reduced nodulation and N fixation in legumes, delayed flowering and maturity; pollen sterility; dieback of leaf tips, stems, and twigs; yellowing of leaves; stunted growth; and pale green leaves that wither easily.

Copper deficiencies are mainly found on organic soils, sandy soils, and soil with pH above 7.5. Copper uptake decreases as soil pH increases. Plants roots take up Cu as the Cu^{2+} ion. Copper uptake by plants can be reduced by excessive P and Fe availability. Cool and wet conditions favor Cu deficiency. Crops more sensitive to Cu deficiency include corn, wheat, and oat.

Broadcast application of Cu mixed with N, P, or K fertilizers is a common application method. Since Cu is slowly converted to unavailable forms in most soils, an application can correct deficiencies for several years with the exception being very sandy soils. Repeated application should be monitored closely for total Cu application, however, and further application discontinued when suggested maximum rates have been applied. If Cu is applied in bands, sprayed to foliage, or from a chelated material, the application rates can be lower than with broadcast applications.

Iron

Iron is involved in the production of chlorophyll in plants; therefore, Fe deficiency (called iron chlorosis) is easily recognized on sensitive crops by yellowing of leaves due to low levels of chlorophyll. Iron also is a component of many enzymes associated with energy transfer, N reduction and fixation, and lignin formation. Iron is associated with S containing compounds that catalyze several other reactions. Leaf yellowing first appears on the younger upper leaves in interveinal tissues. Severe Fe deficiencies cause leaves to turn completely yellow or almost white, and then brown and tattered as leaf tissues die.

Iron deficiencies are found mainly on high pH soils (usually above pH 7.2 and with free carbonates) due to low Fe solubility, in sandy soils, and in organic soils. Cool, wet soil conditions enhance Fe deficiency, especially with marginal levels of available Fe. Poorly aerated or compacted soils also reduce Fe uptake by plants. Uptake of Fe is adversely affected by very high levels of available P, Mn, and Zn in soils; and in soybean Fe chlorosis is aggravated by high concentrations of soil nitrate. Plants roots take up Fe as the Fe^{2+} (ferrous) and Fe^{3+} (ferric) ions, and as a component of organic complexes of low molecular weight. Plant species vary significantly in their sensitivity to low Fe supply. Sensitive crops include soybean and grain sorghum.

Due to soil interaction that greatly reduces Fe solubility and plant availability, foliar or planter-band applications often are the most effective Fe fertilization methods. Research has shown that variety selection is typically a more effective solution than Fe fertilization.

Manganese

Manganese is involved in enzyme activation for plant photosynthesis, N metabolism, and synthesis of various compounds. Interveinal chlorosis is a characteristic Mn deficiency symptom in many plants, and has similar appearance as Fe deficiency chlorosis. In severe deficiency situations, brown necrotic spots appear on leaves and there is premature leaf drop. Delayed maturity is another deficiency symptom in some species. White or gray spots on leaves of some cereal crops are typical signs of Mn deficiency, such as "grey speck" in oat due to tissue breakdown.

Plant roots take up Mn mainly as the Mn^{2+} ion. Manganese deficiencies mainly occur on organic soils with pH above 5.8, high pH mineral soils with free carbonates (calcareous), soils with poor drainage and high organic matter levels, saturated conditions with poor aeration, sandy soils, and over-limed soils having low cation exchange capacity. Crops sensitive to Mn deficiency include soybean, oat and wheat.

Due to interaction with soil that greatly reduces Mn solubility and plant availability, foliar or band applications often are the most effective Mn fertilization method. A common foliar treatment is application of manganese sulfate, but use of chelates is becoming more common. Use of a chelated Mn fertilizer for foliar or band application allows for lower application rates compared with broadcast application. In marginally deficient soils, banding acid forming fertilizers with the planter can prevent or alleviate Mn deficiency by solubilizing soil Mn compounds.

Molybdenum

Molybdenum is involved in enzyme systems related to symbiotic N fixation in legumes, N and S metabolism, and protein synthesis. Molybdenum has a significant effect on pollen formation, so fruit and grain formation are affected in Mo deficient plants. Because Mo requirements are very low, most plant species do not exhibit Mo deficiency. Deficiency symptoms in legumes mimic N deficiency because of the primary role of Mo in N fixation. Unlike most other micronutrients, Mo deficiency symptoms are not confined to the youngest leaves because Mo is mobile in plants. The characteristic Mo deficiency symptom in some crops is irregular leaf blade formation known as whiptail, but interveinal mottling and marginal chlorosis of older leaves also have been observed.

Molybdenum deficiencies are found mainly on very acid, highly weathered, sandy soils in humid regions. Plant roots take up Mo as the MoO_4^{2-} ion. Molybdenum availability and uptake by plants increases with increasing soil pH, which is the opposite of other micronutrients. Liming acidic soils is the most practical and cost-effective way of correcting Mo deficiency and acidity problems at the same time. However, if fertilization is needed, a low Mo rate usually is applied banded with the planter or as a seed treatment.

Zinc

Zinc is an essential component of enzymes important for energy production, carbohydrate metabolism, protein synthesis, and growth regulation. Zinc is not mobile in plants, so Zn deficiency symptoms occur mainly in new growth early in the season. The most visible Zn deficiency symptoms are short internodes, a decrease in leaf size, and a broad band of bleached tissue that goes across leaf veins.

Zinc deficiencies are mainly found on sandy soils low in organic matter, eroded soils with exposed high pH subsoil, soil pH above 7.3, severe root growth restrictions, and organic soils. Plant roots take up Zn mainly as the Zn^{2+} ion. Crops sensitive to Zn deficiency include corn, grain sorghum, and soybean. Zinc deficiencies occur more often during cold, wet spring weather, which is related to reduced root growth and activity as well as less microbial activity and thus less Zn release from soil organic matter. Uptake of zinc can also be adversely affected by application of high P fertilizer rates when soil Zn availability is marginal.

Application to the soil is a common method of applying Zn fertilizers. There are many Zn fertilizers available, with choice depending on the intended application method (broadcast or banded), rate desired, and solubility of the fertilizer. Zinc oxide is the least soluble form and must be finely ground

for enhanced availability. Zinc sulfate, oxysulfate, and zinc-ammonia complex are inorganic sources that provide varying degrees of available Zn. Zinc chelates enhance availability due to lower Zn^{2+} ion interaction with the soil. In marginally deficient soils, banding acid forming fertilizers with the planter can prevent or alleviate Zn deficiency in high-pH soil by solubilizing soil Zn compounds.

Chloride

The chlorine (Cl) elemental form is not found in soils or plants, and it is present as the chloride ion form (Cl^-). Plants take up the chloride ion. Because Cl^- is a mobile anion within the plants, most of its functions relate to osmotic effects (stomatal opening, for example) and electrical charge balance in several physiological functions. Wilting and restricted, highly branched root systems, are the main Cl^- deficiency symptoms, which are found mainly in cereal crops. The role of Cl^- in decreasing the incidence of various diseases in small grains is perhaps more important than its nutritional role.

Most soils contain sufficient levels of Cl^- for adequate plant nutrition. However, Cl^- deficiencies have been reported on sandy soils in humid regions or soils derived from low Cl^- containing parent materials. Crops sensitive to Cl^- deficiency include wheat, potato, and barley, but a few crops (tobacco, for example) are very sensitive to high Cl^- levels. There are few regions with Cl^- deficiency, mainly because Cl^- is applied to soils with KCl, the predominantly used K fertilizer. However, in regions with naturally high available soil K (such as in the central and northern Great Plains), no Cl^- containing K fertilizer is normally applied so Cl^- deficiency is more common.

Diagnosing Micronutrient Deficiencies

Diagnosing a micronutrient deficiency can be a difficult process because diagnostic tools, such as soil or plant analysis, are less reliable than for the macronutrients (as explained below).

<u>Soil sampling and testing</u>

Soil tests aid in determining whether a particular nutrient is responsible for poor crop production and provides the basis for deciding the type and amount of fertilizer needed to correct a nutrient deficiency. Soil samples collected for laboratory analysis must consist of a number of cores and a number of samples from the field. Various soil extractants are calibrated for use in different geographic areas and can extract widely different amounts of micronutrients. Therefore, for proper interpretation of test results, one must use the test calibrated for a particular region, soil, nutrient, and crop. The reliability of most micronutrient

soil tests, compared to other tests like P and K for example, is very low. Also, some soils with low micronutrient levels in the surface layer may not respond to fertilization because they have higher levels of the nutrient in the subsoil. Therefore, confirmation of a deficiency with trial nutrient application, tissue testing, and visual symptoms is helpful to confirm deficiency.

Tissue sampling and testing

Plant tissue tests can aid in determining if a particular nutrient is responsible for poor crop growth. When a deficiency is detected by tissue testing, a reduction in yield due to restricted crop growth has likely already occurred. As with soil analysis, plant tissue tests must be calibrated with field fertilization trials. Calibration of tissue tests is far more complex than for soil tests because measured nutrient concentrations vary considerably with the stage of plant development and the portion of the plant sampled. Special care is required in taking plant tissue samples, including soil contamination. Tissue test interpretation should be based on calibrations with yield response for specific crops, plant part sampled, and stage of plant growth. An appropriate number of samples should be collected to appropriately represent the field area of interest. Fresh samples should be taken quickly to a lab or air-dried to remove excess moisture before they are shipped to a lab. Collecting soil and plant tissue samples at the same time can aid in determining if a micronutrient is deficient.

Micronutrient Fertilizer Sources

Micronutrient fertilizers are applied to the soil or foliage. Foliar or planter-band applications often are more effective than broadcast applications to the soil because the nutrient is applied directly to the foliage or for some micronutrients (not Cl^-) banding minimizes reactions of soluble forms with the soil that reduces crop availability. The decision regarding whether to use a foliar or soil application, and associated product, will depend on the nutrient, production system, potential soil interaction, and cost of material and application. In addition, because toxicity can occur easily for some micronutrients (such as B), the fertilizer form, placement, and rate should be carefully considered and based on reliable local research information.

Table 2 lists common micronutrient fertilizers and analyses. There are four main categories of micronutrient fertilizers: inorganic, synthetic chelates, natural organic complexes, and fritted glass. Common inorganic fertilizers include oxides, sulfates, and oxysulfates.

Sulfates, due to their high solubility and low cost, are the most common metallic micronutrient salts used as fertilizers. Table 2 gives some examples. The sulfate fertilizer forms can be applied as a granular material or dissolved in liquid fertilizers. Oxides, due to being relatively insoluble, must be finely ground to be effective and more quickly converted to plant available forms when applied to soil. Application well in advance of crop need also increases effectiveness. Oxysulfates are mixtures of oxides and partially dissolved oxides, commonly dissolved with sulfuric acid. Solubility should be greater than 40% to be effective agronomically.

Some micronutrient metals can be complexed with ammonia. The most common is Zn-ammonia complex, which in the soil converts to plant available Zn^{2+}. The Zn-ammonia complex mixes readily with liquid fertilizers.

Chelates are formed by coordinate bonding between an organic chelating agent and the micronutrient metal ion. Chelating agents can be synthetic organic compounds (manufactured) or natural (citric acid, lignosulfonates, phenols, and polyflavinoids). Examples of synthetic chelating agents are EDTA, HEDTA, EDDHA, and DTPA. Chelates generally have higher stability, provide less metal micronutrient interaction with the soil, and are preferred for applications to soil. Chelated micronutrients also are commonly used for foliar application. Due to the enhanced effectiveness, chelates are used at lower rates than other micronutrient fertilizer forms.

Fritted glass micronutrients are specialty fertilizers not widely used, but can be useful for highly leachable soils in areas with high rainfall. They are produced by combining the micronutrient with silicates and then fired in a furnace. The fritted glass matrix controls the release of the micronutrient, and these fertilizers can contain multiple micronutrients.

Manure contains all plant essential nutrients, and like macro- and secondary nutrients, is a valuable source of micronutrients. Therefore, manured fields typically do not have micronutrient deficiencies nor require micronutrient applications.

Table 2. Some example common micronutrient fertilizer sources.

Micronutrient	Fertilizer Name	Formula	Nutrient Percentage (elemental basis)
B	Sodium tetraborate	$Na_2B_4O_7 \cdot 5H_2O$	14
	Boric acid	H_3BO_3	17
	Solubor	$Na_2B_8O_{13} \cdot 4H_2O$	20
Cl	Potassium chloride	KCl	47
Cu	Copper sulfate	$CuSO_4 \cdot 5H_2O$	25
	Copper chelates	Various	Varies
Fe	Ferrous sulfate	$FeSO_4 \cdot 7H_2O$	20
	Ferric sulfate	$Fe_2(SO_4)_3 \cdot 4H_2O$	23
	Iron chelates	Various	Varies
Mn	Manganese sulfate	$MnSO_4 \cdot 3H_2O$	27
	Manganese chelates	Various	Varies
Mo	Ammonium molybdate	$(NH_4)_2MoO_4$	49
	Sodium molybdate	$Na_2MoO_4 \cdot 2H_2O$	39
Zn	Zinc sulfate	$ZnSO_4 \cdot H_2O$	36
	Zinc oxide	ZnO	78
	Zinc-ammonia complex	$ZnSO_4 \cdot NH_3$	10
	Zinc chelates	Various	Varies

Practical Recommendation Summary

Due to the low plant nutrient requirement, crop specificity for deficiency, and soil/climate/nutrient interaction, for many crops and geographic regions practical experience with micronutrient deficiencies is often the best system for determining micronutrient application need. And, given the often poor reliability of soil and plant tissue testing for micronutrients (mainly for soil testing), the large variety of conditions that affect micronutrient supply to crops, and the large variety of fertilizer sources, the following steps are recommended to identify and correct a micronutrient deficiency.

- Ensure that poor crop growth in a field or portion of a field is not the result of a macronutrient or secondary nutrient deficiency, compaction, excess moisture, drought, salinity, disease or insect problem, or herbicide injury.

- Find out if a micronutrient deficiency has been identified before in a particular crop or soil type in the area.

- Examine the affected crop for known specific micronutrient deficiency symptoms.

- Take separate soil and plant tissue samples from affected and unaffected areas for complete analysis, and analyze samples for other nutrients in additions to micronutrients.

- If most indications point to a micronutrient deficiency, apply the micronutrient to a specific, clearly marked, affected area in order to observe results and compare with non-treated areas.

- In choosing a micronutrient fertilizer, consider the solubility, safety concerning damage to seedlings or foliage, advantages and disadvantages for foliar or soil application such as potential for interaction with soil, and cost.

- Consider that other crop inputs such as pesticides, lime, or manure can supply micronutrients or may affect the availability of micronutrients present in the soil. For example, liming acid soils is a very cost effective way of increasing crop availability of Mo, but excess lime application to soil that is slightly acid to neutral pH, or liming alkaline soils, can decrease the availability of Cu, Fe, Mn, Zn and sometimes B.

Chapter 8:
Soil pH and Lime Management

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Introduction

Soil pH is a measure of the soil solution's (soil water) acidity and alkalinity. By definition, pH is the negative logarithm of the hydrogen ion concentration $[H^+]$, i.e., $pH = -\log [H^+]$. Soils are referred to as being acidic, neutral, or alkaline (basic), depending on their pH values on a scale from 0 to 14. A pH of 7 is neutral, less than 7 acidic and greater than 7 alkaline. Because pH is a logarithmic function, each unit on the pH scale is ten times less acidic or basic than the unit above or below it. For example, a solution with a pH of 6 has a 10 times greater concentration of H^+ ions than a pH of 7, and 100 times higher concentration than pH 8. Soil pH is influenced by both acidic- and basic-influencing ions in the soil. Common acidic cations (positively charged ions) are hydrogen (H^+), aluminum (Al^{3+}), and iron (Fe^{2+} or Fe^{3+}); whereas common basic cations include calcium (Ca^{2+}), magnesium (Mg^{2+}), potassium (K^+), ammonium (NH_4^+), and sodium (Na^+).

Many factors influence the pH of a soil or subsoil. These include parent material the soil was derived from; length of weathering and soil formation; climate; organic matter mineralization; NH_4^+ fertilizer rate and nitrification to NO_3^-; cropping system and crop harvest; and land use and management. Of the management practices for crop production, application of fertilizers or organic sources that contain ammonium (NH_4^+) or compounds that transform into NH_4^+ once applied to the soil and the cropping system will have the largest influence on increasing soil acidity. Nitrification of NH_4^+ to NO_3^- from any fertilizer or manure source, or mineralization of organic-N compounds such as from manure, produces H^+ ions, thus lowering soil pH. Frequency of crops in a rotation that require N application, and frequency of crops with high N fertilization requirement, will affect acidification rate. An example is continuous corn versus corn-soybean rotation. Some manure sources contain liming materials, eggshells and limestone with poultry manure as an example, and may offset acidity from nitrification or even increase soil pH.

Most agricultural soils in dry climates have alkaline conditions with average pH values ranging from 7 to 8.5. This is primarily due to the presence of basic cations associated with carbonates and bicarbonates found naturally in those soils and irrigation water. When sodium (Na) is abundant, which sometimes is the case in dry climate areas, soil pH can be as high as pH 10. Due to relatively low precipitation, often less than evapotranspiration, there is little leaching of basic cations resulting in a relatively high degree of base saturation (percentage of the cation exchange complex occupied by basic cations) and pH values greater than 7. In contrast, acidic conditions occur in soil derived from parent material high in elements such as silica (rhyolite, granite, sandstone), high levels of sand with low buffering capacities (ability to resist pH change), and in regions with high precipitation. High precipitation causes increased leaching of basic cations, low base saturation and therefore low soil pH.

Soil pH affects plant growth directly and also indirectly by affecting availability of essential nutrients, levels of phytotoxic elements, and microbial activity. Figure 1 shows relatively how nutrient availability and microbial activity are affected by soil pH. The availability of Fe and zinc (Zn), for example, is severely reduced in high-pH soils. Even though Fe is present in large quantities in soils, much greater than Zn, its availability to plants (in a form plants can take up) is limited by reactions that form insoluble compounds at high pH.

Most plants have a wide range of pH where they can grow and survive, but have optimal growth and production in a fairly narrow range. For example, a legume crop like alfalfa can grow and survive in soil pH's ranging from 5.0 to 8.1, however, forage yield will be greatly reduced in low-pH soils (less than 6.0) and is optimized with soil pH only slightly acidic to neutral. Other crops, like cranberries, for example, are adapted to acidic soils and will not grow well in soils with a pH above 6.0. Soil pH modification, therefore, must be tailored to the crop or cropping rotation. Optimum soil pH ranges, which depend on the crop and geographic region, have been established for crops. Examples are given in Figure 1.
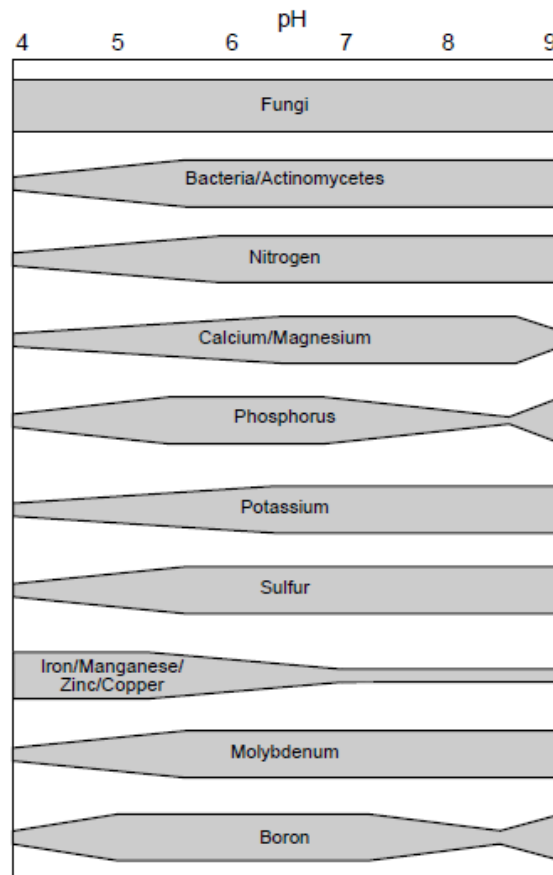
Figure 1. Nutrient availability and microbial activity as affected by soil pH; the wider the band, the greater the relative availability or activity (Adapted from Brady, N. The Nature and Properties of Soils, 10th ed. Macmillan Publ. Co., New York, 1990).

Negative Effect of Acidic Soils

Knowing the soil pH helps identify the kinds of chemical reactions that are likely to be taking place. In general, the most important reactions from the standpoint of crop production are those dealing with solubility of essential and non-essential elements. As indicated in Figure 1, the relative availability of several essential nutrients is greatly reduced at low pH. Phosphorus (P) is an important example. Toxicity from Al^{3+}, Mn^{2+}, and H^+ is a major cause for crop failure in very acidic soils. Aluminum and Mn are a problem in acidic soils because they are more soluble at low pH. There are always large quantities of Al present in soils because it is a component of clays. When the soil pH is above 5.0 to 5.5, soluble Al^{3+} is low and Al remains in a solid combination within clays and other elements, and therefore is not harmful to plants. As the pH drops below those levels, Al containing materials began to dissolve and Al^{3+} increases in soil solution and on the soil cation exchange complex. Because of its nature as a cation

(Al^{+3}), the amount of dissolved aluminum is 1,000 times greater at pH 4.5 than at 5.5, for example. Toxic levels of Al^{3+} harm the crop by negatively affecting root activity. As a result, plants are unable to absorb water and nutrients normally and will appear stunted and exhibit nutrient deficiency symptoms, especially such as those for P. Often the field also will appear to be under greater stress from pests, such as weeds, because of the poor crop growth and inability to compete.

The relationship between pH and dissolved Mn^{2+} is similar to that just described for Al^{3+}, except that Mn^{+2} only increases 100 fold when the pH drops from 5.5 to 4.5, and levels are greatly affected by the oxidation/reduction conditions of the soil. Toxic levels of Mn interfere with the normal growth processes of the above ground plant parts, usually resulting in stunted, discolored growth, and poor yield.

Iron reactions are similar to that for Al and Mn where Fe solubility increases as soil pH decreases and is very low at high soil pH (Figure 1). Iron toxicity, however, in low-pH soils is not a major problem for most crops (as it is for Al and Mn toxicity), but can be for some crops (rice, for example). Iron deficiency in high-pH soils is widespread for some Fe-sensitive crops (soybean, for example) and is therefore a cause of concern in many agricultural systems.

Testing for Soil pH

Soil pH is best measured in soil-water slurries, with soil to water ratios of 1:1 (most common in most of the U.S.), 1:2, or in a saturated soil paste. Soil pH values are measured with a pH electrode placed into either the slurry or paste. This pH is designated as the water pH and is an indication of what is called the active acidity or acidity in soil solution. Though most soil testing laboratories utilize water for pH determination, some will use a dilute salt solution (such as KCl or $CaCl_2$). The dilute salt is used to mask the effects of naturally occurring soluble salts or recent fertilizer application on pH measurement. By adding a slight concentration of salts, more exchangeable H^+ ions are brought into solution from the exchange complex, with the measured pH generally 0.5 to 1.0 units lower than measured using a water slurry. Also, differing soil-water ratios produce slightly different pH values; a reading obtained from a 1:1 soil:water ratio is generally 0.15 to 0.25 pH units higher than that of a saturated paste extract, but lower than a 1:2 ratio. Therefore, it is important to be aware of the soil pH test being used and to be consistent between methods to ensure comparable data over time. Soil testing laboratories typically denote the pH test method used on their soil test reports.

Table 1. Range and suggested optimum soil pH values for optimum growth of selected crops

Crop	Optimum Soil pH range	Suggested optimum pH
Alfalfa	6.2-7.5	7.0
Barley	5.5-7.0	6.5
Corn	5.5-7.0	6.5
Soybean	5.5-7.0	6.5
Wheat	5.5-7.0	6.5

Source: Havlin et al., 2005. Soil fertility and fertilizers. Upper Saddle River, N.J: Prentice-Hall, Inc. 499 p.

Soil sampling: Methods, Timing, and Frequency

Collecting an appropriate soil sample for pH determination is the first and most critical step in determining liming needs. Improper sample collection and handling can lead to incorrect recommendations. It is generally suggested to collect at least 12 cores from the recommended depth (this varies by region) at random locations across the area of interest and place them in a clean, plastic container for shipment to the lab. Timely soil sampling is important because limestone requires time to neutralize soil acidity. Sampling and limestone application should be completed several months in advance of crop growth to provide time for pH adjustment. In addition, soil pH fluctuates during the year, thus soil sampling should be conducted at the same time during the season.

The frequency of soil sampling to determine lime requirement will depend on soil properties, crop, the source and amount of N applied, and the quality and type of liming material used. Under intense cereal production using high rates of N fertilizer, sandy soils will rapidly increase in acidity. Finely ground liming materials will result in a more rapid increase in pH, but also a more rapid decrease in pH over time. Sampling at least every three to five years is recommended.

There is increased interest in within-field site-specific pH measurement and variable rate lime application due to the often large variation in soil pH. This is especially true in fields with variable soils, for example, fields where acidic soils are intermixed with carbonate containing (basic) soils. Dense grid soil sampling approaches and variable rate technologies are being adopted at a rapid rate by producers. Results from samples collected from producer's fields and field-scale research have shown very high pH variation within fields and even within soil map units. Figure 2 shows soil pH spatial variability from a very dense grid sampling for a field having several soil types in central Iowa. Taking into account the degree of the spatial variability for most agriculture soils in the U.S. and cost of sampling, soil analysis, and limestone, the 2.5-acre soil sampling approach is the one most frequently recommended for making prescription maps for variable rate liming. However, less dense

grid sampling schemes or zone sampling, for example by soil type, are also used in areas where soil property variation dominates soil pH spatial variability. Also, remote sensing sometimes can be used to establish sampling zones for pH. For example, soybean iron deficiency chlorosis in high-pH, calcareous soils can be used to verify the pH is calcareous and map calcareous areas within fields.
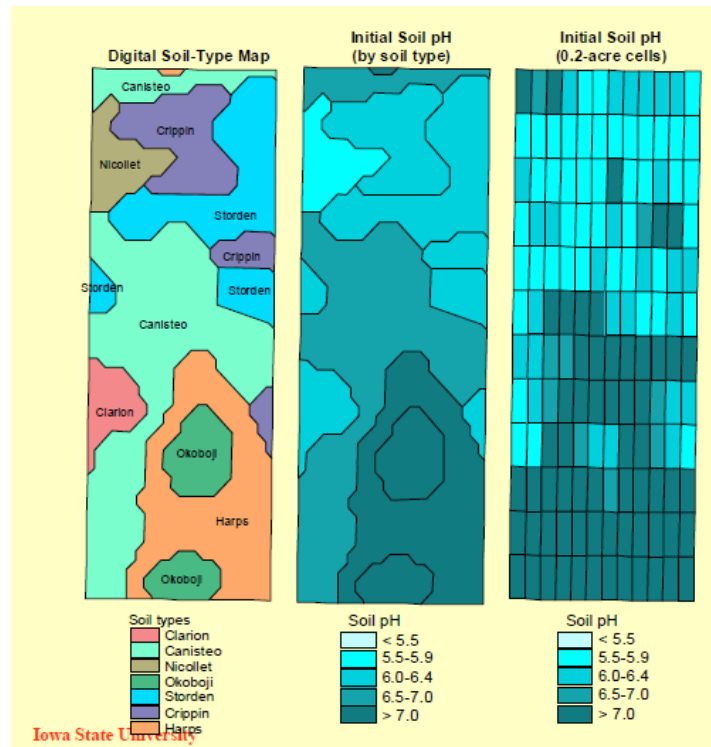

Figure 2. Example of soil pH spatial variability using a zone or grid soil sampling approach for a central Iowa field with several soil types. Adapted from Bianchini and Mallarino, 2002. Agron. J. 94: 1355-1366.

Managing Soil pH for Alkaline Soils

Alkaline soils have pH above 7.0, which means the exchange complex is saturated with basic cations. In soils with pH 7.2 to 8.5, pH is controlled by dissolution of free lime (calcium and magnesium carbonates). In soils with pH 8.5 to 10.5, pH is controlled by exchangeable Na and dissolution of sodium carbonate. Therefore, decreasing pH of alkaline soils is difficult due to the need to neutralize free lime (carbonates) or Na salts and reduce base saturation. In field situations, this is impractical (except perhaps for high-value horticultural crops) due to the high cost for large application of acidifying amendments and potential salt buildup from those applications. For example, a soil containing 1% lime (carbonates) in the top 7 inches would require 68 ton/acre of concentrated sulfuric acid to neutralize the carbonates before

alkalinity could be reduced. In most cropping situations, alkaline soil pH is not modified, but instead crop, nutrient sources and production practice decisions are based on knowledge of field conditions.

Soil pH reduction can be achieved in localized (small areas); for example garden or landscape areas for plants that require low pH. In such cases, a common amendment to acidify soil is elemental sulfur (S). Elemental S is oxidized by microbes to sulfate (SO_4^{2-}), with production of H^+ ions which then neutralize free lime or lower base saturation on the exchange complex. Ferrous sulfate ($FeSO_4$) and aluminum sulfate [$Al_2(SO_4)_3$] can also be used to lower pH by contributing acidic cations. The amount of an acidifying material required depends on the volume of soil to be treated, free lime content, soil cation exchange capacity, desired pH and acidifying effect of the material applied. Salt issues can develop if the amount of acidifying material applied is large, and element toxicity is possible when materials containing Al are used.

Managing Soil pH for Acidic Soils

Soil acidification is one of the most common agronomic problems in humid and highly productive areas of the U.S. In non-alkaline soils, application of N fertilizers and many manure sources continually causes a steady increase in soil acidity. The most common method for neutralizing soil acidity and increasing soil pH is to apply limestone. Liming materials are most often carbonate containing materials, such as $CaCO_3$, and $MgCO_3$. Limestone (and other liming materials) react with carbon dioxide and water in the soil to yield bicarbonate (HCO_3^-), which reacts with H^+ and Al^{3+} to form either water (for H^+) or insoluble compounds (for Al^{3+}). These reactions take acidic cations off the exchange complex and out of solution, thereby increasing base saturation and raising soil pH.

The amount of limestone material to apply depends on the amount of reserve soil acidity to be neutralized and the quality of the liming material. The quality of liming materials is determined by two factors. One factor is the ability to neutralize acid (purity), called the calcium carbonate equivalent (CCE). As CCE increases, the material purity increases and the acid neutralizing ability increases. The second factor is the particle size analysis. Finer limestone particles react faster due to increased surface area. The combination of these two factors is the effective neutralizing value (ENV). This quality factor has different names in different states, but in all cases is providing the ability of liming materials to be effective in neutralizing acidity and raising soil pH. In some states regulations require this quality measure to be supplied with the product label.

Most agricultural limestones are ground Ca and Mg carbonates, and have a mix of particle sizes from small to large. For example, in Iowa, the particle sizes effective in neutralizing soil acidity and used for

the quality measure (effective calcium carbonate equivalent, ECCE) are 60, 8 and 4-mesh screen sizes (mesh size is the number of screen wires per inch; the larger the number, the finer the screen opening). The quality measure (ECCE as in Iowa) is then a combination of the fineness efficiency from the percent of material passing each mesh size, the CCE and moisture content. The mix of particle sizes is important so there are adequate fine materials (passing the 60 mesh) and coarser materials (passing 8- and 4-mesh) to ensure rapid pH improvement and stabilization of pH for several years.

Rate of Limestone Application

The amount of limestone needed to adjust soil pH depends on the desired level for a particular crop, the initial soil pH and the soil cation exchange capacity (the soil clay and organic matter content which determine the soil buffer capacity or resistance to pH change). Although, soil pH is used to determine whether or not soil acidity limits crop growth and liming is needed, it does not directly estimate lime requirement (amount of lime to apply). Several analytical methods have been developed to determine lime requirement. These methods include soil incubation, direct titration and use of buffer solutions. Long-term soil incubations with $CaCO_3$ have been used for research studies and to calibrate other lime requirement methods, but are impractical for use by routine testing laboratories. Direct titrations are laborious and may require days to complete, so they are not practical for use in routine soil testing.

Buffer pH methods were developed to provide a faster assessment of lime requirement in a routine lab setting. A buffer solution resists pH change when exposed to acidity, and provides a linear decrease in pH when the soils potential acidity (acidity on the exchange complex) reacts with the buffer. The decrease in pH of the buffer solution is what is measured after mixing the buffer with soil and provides an estimate of the amount of lime required to neutralize the acidity of the soil in order to reach a desired pH. There are several buffer pH solutions in use. In the Midwest U.S., the Shoemaker-McLean-Pratt (SMP) buffer has been the method adopted in many states. However, that buffer solution contains hazardous chemicals and needs special and expensive disposal by soil testing laboratories. Therefore, new buffers, such as the Mehlich and Sikora buffers, were developed and are currently being used because they do not contain hazardous chemicals and are more environmentally friendly.

In some states, instead of using a buffer pH method, the lime requirement is calibrated from measured soil pH and the soil cation exchange capacity (CEC can be determined by lab measurement or knowledge of the soil's textural class and color, both reflect the soil clay and organic matter content).

The liming rate need is estimated from the measured water pH and relationship to lime rate for various soil types.

In addition to these methods, some states (especially in the southeast U.S.) have developed fast direct titrations methods that use a single addition of a strong base to determine lime requirement. These methods are based on the assumption that the relationship between the addition of a liming material and soil pH is linear between pH 4.5 and 6.5.

Timing of Limestone Application

Although limestone can be applied at any time, several factors should be considered when planning an application. Most importantly is the length of time required for pH correction to take place. Crops with more sensitivity to low pH, such as forage legumes, should have pH corrected well in advance of seeding. Soil moisture is critical for the reaction of limestone with soil acidity, thus rainfall patterns can also be used as a guide for application timing. Soils should be sufficiently firm to support heavy equipment and minimize compaction. If subsoil pH is low, a long period will be required for the limestone to effect a change in the soil pH with depth. Coarse limestone particles react more slowly and may take several months to correct pH. Incorporation into the soil will provide faster reaction and pH adjustment within the tillage zone. Surface application, for example in no-tillage, will have most impact on pH near the soil surface. When a more rapid pH correction is needed, the use of finely ground limestone or an agricultural ground limestone with good quality (considerable fine materials) should be considered.

Liming Method

Dry bulk limestone is typically applied using fertilizer spreader trucks. The density of the spreading pattern declines with increasing distance from the truck. In addition, minimizing dust and achieving a uniform spreading pattern can be increasingly difficult with finely ground limestone products. A moisture content of 7 to 10% in fine limestone helps minimize dust and achieve a uniform spreading pattern.

Variable Rate

Application of lime using variable rate technology has grown in popularity over the last decade, because it helps growers avoid applying liming products in field areas having lower-than-optimum pH and reduces or avoids application in areas with high pH. This methodology increases liming efficiency and therefore profitability.

Liquid, fluid, or suspension lime is a combination of very fine limestone (100 mesh or smaller) in water with 1 to 2% clay to form a suspension that is about 50 to 60% solids. Some drinking water treatment byproducts are similar as they result from rapid throughput of water treated with finely ground calcium oxides. These materials are typically spread using a tank truck equipped with a boom and high-volume nozzles. With proper calibration, this enables very uniform product application with no dust. Fluid lime does not react differently than finely ground dry limestone, but because of the fineness of grind the rate of application should be adjusted to avoid over-liming and resulting too-high pH.

Liming Materials

A variety of agricultural liming materials, most frequently calcitic and dolomitic limestone, are readily available in the U.S. (Table 2). Agricultural liming materials are defined as follows:

1. Agricultural liming materials mean a product whose Ca and Mg compounds are capable of neutralizing soil acidity.

2. Limestone means a material consisting essentially of Ca carbonates or Ca and Mg carbonates capable of neutralizing soil acidity.

3. Dolomitic limestone means those materials of which sixteen percent or more of the neutralizing value expressed as Ca carbonate is derived from Mg carbonate.

Table 2. Typical acid neutralizing value, expressed as calcium carbonate equivalent (CCE), of liming materials and the quantity of each liming material necessary to achieve acid neutralization equivalent to one ton (2,000 pounds) of pure pulverized calcium carbonate.

Liming Material	CCE	Equivalent to one ton pure limestone
	- % -	----- lb -----
Calcium carbonate	100	2000
Calcitic limestone	85-100	2350-2000
Dolomitic limestone	95-109	2100-1830
Burned lime	150-175	1330-1140
Hydrated lime	120-135	1670-1480
Basic Slag	50-70	4000-2900
Baked oyster shells	80-90	2500-2200

There are other liming materials, such as CaO or $Ca(OH)_2$, but they are not commonly used due to high reactivity and corrosiveness. Also, there are drinking water treatment by-products and other by-products that provide liming capability.

Summary

- Soil pH is considered the single most important chemical property of soil because it affects plant growth and nutrient availability in many different and complex ways.

- Limited solutions exist for reducing pH in high pH soils because they are impractical or uneconomical.

- Soil acidity reduces plant nutrient availability and increases toxicity of some elements. Therefore, neutralization of soil acidity has positive effects on crop productivity.

- Lime application is the most common way to neutralize acidity in soils and there are many lime sources that vary in type, neutralization capacity (purity) and particle size. Agricultural ground limestone is the most commonly used liming material.

- Although several methods can be used to determine liming rates to achieve optimum pH for crop growth, buffer solutions, single titrations with a base and indexes that include soil characteristics such as soil pH and organic matter, clay, or CEC, are the most widely used approaches.

- The large within-field spatial variability in soil pH and lime requirement commonly found in many U.S. regions greatly justifies dense soil sampling and variable rate technology for limestone application.

Chapter 9:
Soil Sampling

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Developed in cooperation with Lara Moody, TFI; John Davis, NRCS; and Steve Phillips, IPNI.

Introduction

Soil testing is one of the most useful and commonly used tools to estimate the crop availability of many nutrients. Therefore, the accuracy of a nutrient recommendation depends on how well soil samples represent a field or areas within a field. The amount of plant available nutrients can vary considerably across and within fields due to natural variation of physical and chemical characteristics of the soils and also due to variation in crop management practices that over time influence the amount of available nutrients. Natural variation arises from different soil-forming processes (such as parent material and weathering) or losses/deposition (erosion) that lead to accumulation or loss of nutrients or processes that differently affect nutrient availability. Management factors that often influence nutrient availability include tillage, crops grown, harvest system, fertilization and liming and irrigation among others. It is typically necessary to collect multiple samples from a field to accurately assess the fertility status. Recommended soil sampling procedures can vary significantly between geographic regions, for specific nutrients and specific purposes. The information provided here relates to routine testing for soil pH and immobile nutrients such as phosphorus (P) and potassium (K), but also is relevant for mobile nutrients such as nitrate nitrogen (N). Specific sampling recommendations should be followed for each nutrient and region. Sampling procedures have been published by most Land Grant universities and some regional research and extension soil testing committees. Useful considerations relevant to soil sampling for P to assess the risk of water quality impairment were prepared by the Organization to Minimize Phosphorus Losses from Agriculture (SERA-17) and published in "Soil sampling methods for phosphorus" by Mallarino, Beegle, and Joern (2007, www.sera17.ext.vt.edu) and "The importance of sampling depth when testing soils for their potential to supply phosphorus to surface runoff" by Vadas, Mallarino, and McFarland (2005, www.sera17.ext.vt.edu).

Soil Sampling Strategies

Five main factors generally should be considered when taking soil samples:

1. Sampling depth.

2. Time of year when samples are collected.

3. Number of soil cores per composite sample.

4. Number and distribution of samples across a field.

5. Sampling frequency.

The nutrient of interest, the soils present and the crop rotation can influence the specific sampling practice and importance of each of these factors. Proper consideration of each factor for each specific field or region is needed to best estimate the nutrient availability in the soil and to develop reliable nutrient application recommendations.

1. Sampling Depth

A major misconception among nutrient management planners and producers is that a soil sample should be collected from the depth where the nutrient level is higher. For example, such a criterion would result in very shallow sampling for P and K with no-till management since both nutrients are relatively immobile in the soil and tend to accumulate near the soil surface. Instead, the most important criterion to decide the appropriate sampling depth is the depth that best estimates plant sufficiency and best predicts crop response to nutrient additions or best determines the risk that nutrients are transported offsite. Sometimes the best sampling depth is the one where the nutrient accumulates, such as for nitrate, but for other less mobile nutrients that often is not the case. This is one of the main reasons the soil sampling depth is an important issue and that is specified in the calibration of soil test methods. Therefore, it is very important that soil samples used for nutrient recommendations should be taken at the same depth that is used in the research for soil-test calibration and interpretations to generate the nutrient recommendations.

For tests like pH, P, K, and many secondary and micronutrients, the depth is typically the surface 6 to 8 inches of soil. For nitrate, the sample depth may be the surface 12 inches (for tests like the Pre-Sidedress Nitrate Test, PSNT) or the rooting zone depth for profile nitrate (3 to 5 feet). For soil pH, an exception involves sampling in no-till or systems with very shallow tillage. For estimating lime requirements for no-till management or pastures, a shallower surface sample (0-2 or 0-3 inches) often is recommended because, except in sandy soils, it is too costly or impractical to apply lime to change pH of subsurface soil layers. Use of a deeper sampling depth may result in lime application rates that cause excessively high pH

of the surface soil layers which could affect, for example, herbicide activity and/or carry-over, the availability of various macro- and micro-nutrients and crop disease or pests incidence. While not typically cost effective for crop production, one could sample by depth increments (like every 2 to 3 inches) to assess the degree of nutrient stratification and better assess nutrient availability. Due to economic and practical reasons, however, soil-test interpretations and fertilization recommendations are not made from this type of soil sampling.

2. Time of Year to Sample

In northern regions with frozen or snow-covered soils, soil sampling after crop harvest in the fall, or before planting in the spring, are the most common sample timings. Sampling in the fall is most common, however, because fertilizer or manure is often applied in the fall. In regions with mild winters and more than one crop per year, the soil sampling usually is done before the most nutrient demanding or profitable crop. With the exception of pastures and sampling for N for some crops, soil sampling while crops are growing is seldom used because test results do not provide the best estimate of nutrient availability or fertilizer cannot be applied due to practical reasons. The most common in-season sampling for N is the test for soil nitrate to estimate sidedress N fertilization for corn and for N application for wheat at the tillering stage. In addition, sampling some time before planned lime, fertilizer, or manure applications allows sufficient time for the laboratory analyses to be completed and recommendations developed. Suggestions regarding soil sampling for nitrate vary considerably, so local recommendations on specific sampling and use of nitrate testing should be followed.

Because of seasonal variation in soil-test levels, soil sampling should occur at about the same time of the year each time a particular field is sampled. Also, the sampling time should be the same that was used for the soil test calibration. This is particularly important in humid or irrigated regions for the most mobile nutrients nitrate, chloride (Cl), and sulfur (S), and sometimes also for K, manganese (Mn), iron (Fe), and pH. Potassium recycling with crop residue, or grazing cattle, and the equilibrium between soil K pools of different K availability are highly affected by rainfall and alternating freezing and thawing. Although Fe and Mn are immobile nutrients in soils, changes in oxidation/reduction conditions due to moisture and chemical or microbiological processes often result in large temporal variability. Soil pH can vary significantly during the year depending on rainfall due to movement of soluble salts and microbial processes such as nitrification of ammonium fertilizers.

3. Number of Soil Cores per Composite Sample

A sufficient number of soil cores should be collected per composite sample to correctly represent the area being sampled. Recommendations about numbers of cores per sample vary considerably, mainly because of variation in small-scale nutrient variability across nutrients and fields, and range from about 8 to 20 cores per sample across regions and states. Non-uniform nutrient application, such as banding of fertilizer or manure and grazing, often creates high small-scale nutrient variability. Samples taken from a recent band can greatly overestimate the overall fertility level of a field or field area. Broadcast fertilizer or manure application also can create high small-scale nutrient variability with improper equipment use and careless spreading. The small scale variability can be very high, especially in no-till fields. Figure 1 shows an example of the soil-test variability of immobile nutrients that can be expected at various scales, which was obtained from a study of soil-test P variation in several Iowa fields with long histories of fertilizer or manure application. There was very high spatial variability at a very small scale (samples taken every 6 inches) and at a moderate scale (10-core composite samples taken at 10-foot intervals) in manured or high-testing fields. Often there was relatively high variability at moderately low soil-test levels. For example, soil-test P results from single-core samples taken at 6-inch intervals often encompassed two or three interpretation classes.
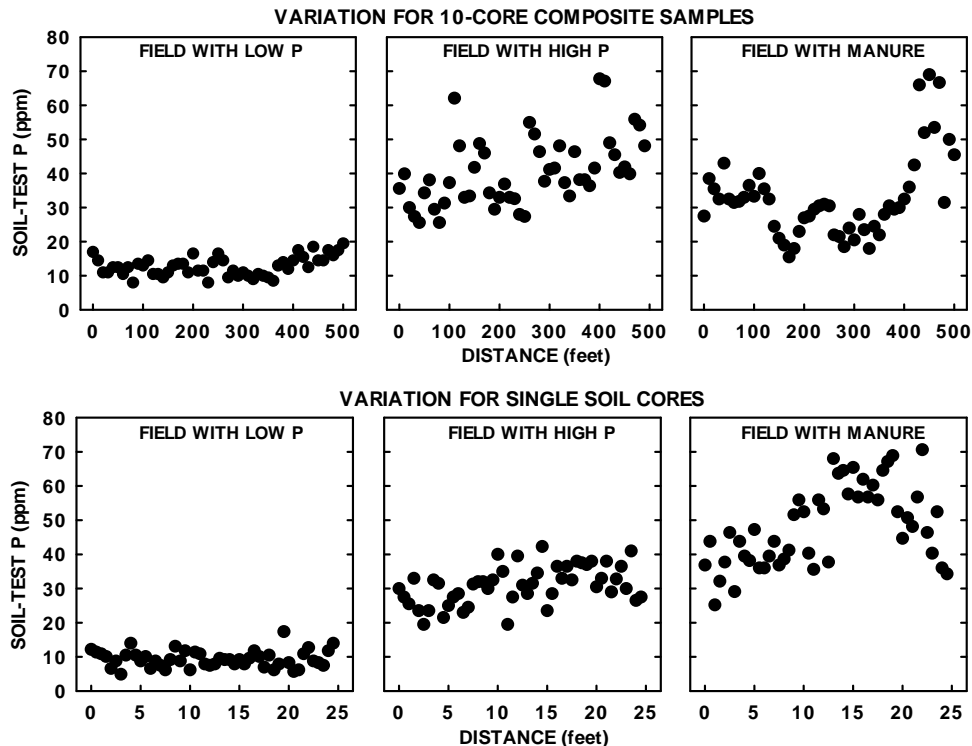
Figure 1. Soil-test P variation for composite or single-core soil samples taken at different scales from three typical Iowa fields. Adapted from Mallarino, A.P. 1996. Spatial variability patterns of phosphorus and potassium in no-tilled soils for two sampling scales. Soil Sci. Soc. Am. J. 60:1473-1481.

Even one or two soil cores with very high nutrient levels can significantly skew the average test result for a composite sample value, and may result in too low nutrient application rates for a major portion of the area sampled. Therefore, there is benefit from taking 15 to 20 soil cores per composite soil sample for most nutrients and most field conditions. Research has shown that the accuracy of soil-test results increase as the number of cores included in composite samples increases. The example in Fig. 2 shows that collecting 20 cores would result in a difference of 15 to 20% from the true average value for the sample area. Although the magnitude of the error varies greatly from field to field depending on the small-scale variability, the error always decreases exponentially with increasing number of cores. This exponential relationship means there is a large gain in accuracy when the numbers of cores are increased from very few cores, but a small gain when many cores are already collected.
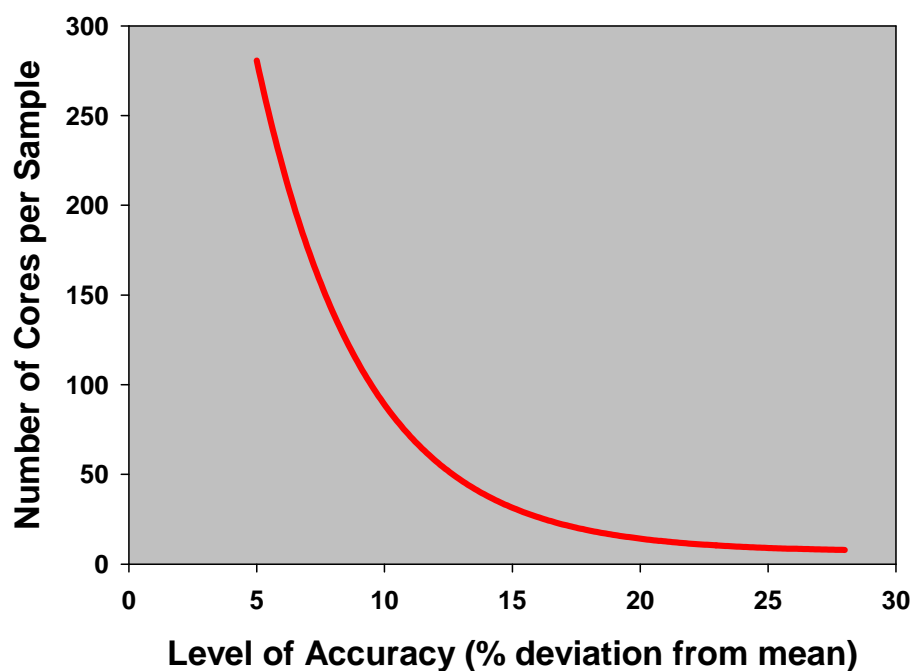
Figure 2. Number of cores required for a composite soil sample for soil-test P determination according to different accuracy levels. Adapted from Swenson, L.J., W.C. Dahnke, and D.D. Patterson. 1984. Sampling for soil testing. North Dakota State Univ., Dept. of Soil Sci., Res. Rep. No. 8.

4. Number and Distribution of Samples across a Field

The most appropriate number of samples and location distribution across a field depends on the magnitude of the variability, but should also involve consideration of cost/benefits and how the fertilizer or manure will be applied. More samples always result in better estimates of nutrient availability, but the crop response to fertilizer addition may not offset the increased sampling and testing costs. Also, a dense sampling approach cannot be economically justified when the nutrient application rate will be the same across the field no matter differences in test results. In relatively uniform fields or areas smaller than about 20 to 25 acres, a single composite sample from cores taken in a random or zigzag manner often is sufficient. Larger fields often have higher variability and are usually subdivided into smaller sampling areas. Non-uniform fields can be subdivided on the basis of obvious differences, such as slope position or soil type, or past management such as incorporating past multiple fields into one larger field. However, even small fields can be highly variable in P and K with long histories of fertilizer or manure application.

Historically, the objectives of soil sampling have been to determine the average nutrient status of a field or field areas with clearly different soil types or topography. The development and adoption of precision

agriculture technologies have revolutionized soil sampling and nutrient application, however, by allowing for better measurement and management of within-field nutrient variability. Technologies well adapted to soil sampling [such as global positioning devices (GPS) and on the go measurement of apparent electrical conductivity (EC)], estimating yield and nutrient removal with harvest (yield monitors), and nutrient application (variable-rate technology) are widely used in many regions of the U.S. Instead of focusing on an entire field, producers can now diagnose fertility levels and crop nutrient removal and manage areas within fields. Knowledge of factors influencing soil nutrient level variation, such as soil type, topography, cropping history, manure application, fertilizer application, yield levels, land leveling for irrigation, and others will help determine the most effective sampling and nutrient application approaches.

Therefore, several soil sampling methods are available, each adapted better to different nutrients and conditions, and having advantages or disadvantages. In general, there are three soil sampling approaches that are being used or can be used: The traditional sampling "by soil map unit and topography", grid sampling and zone sampling.

Sampling by soil map unit and topography

Most commonly referred to as "sampling by soil type", this is the approach most universities and soil testing laboratories have recommended for decades. The approach recognizes the impact that soil parent materials, topography, and other soil formation factors have on the level of crop available soil nutrients. Therefore, soil survey map units, which always consider soil series and often both erosion and slope phases, are used to delineate different sampling areas within fields. The approach includes separating sampling areas based on different crop, soil and nutrient management practices, and also considers the presence of old or current animal feeding locations, homesteads, or watering ponds that could result in nutrient variation. Also, the approach sometimes recommends sampling separately two or three areas of an apparently uniform soil map unit or field.

An example of this sampling approach is shown in Figure 3. This 80-acre field was originally farmed as four, 20-acre fields that were managed differently. First, identify the areas that are odd or dissimilar. Areas A and B probably have very high fertility levels. Area C would be expected to have a higher soil pH than the remaining original fields. Areas D and E would be different soils and could have vastly different soil pH, organic matter (OM), and fertility levels than the adjoining soils. Old fence lines are to be avoided. The original fields should be sampled separately, unless a previous comprehensive sampling has shown no fertility differences. Samples 1 and 2 are taken because the soils differ, sample 3 would be sufficient for the original 20-acre field, samples 4 to 6 represent three different soils, and samples 7 and 8 each represent about 10 acres of an apparently uniform area.
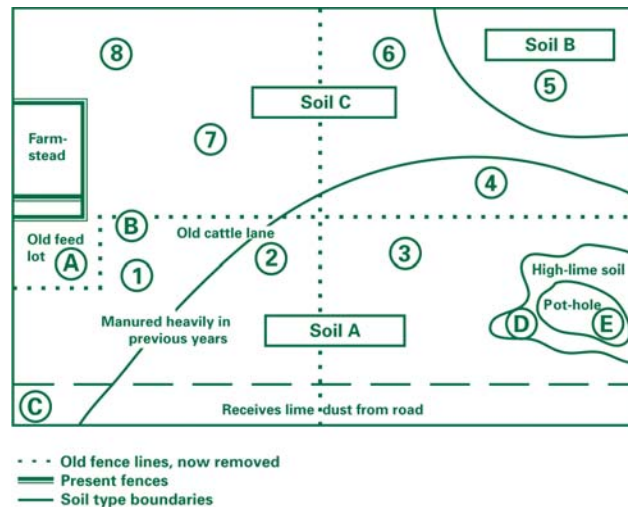
Figure 3. Example of sampling map for an 80-acre tract, which is now farmed as one field. Numbers designate soil sample areas and letters designate areas either not sampled or sampled separately. Adapted from Take a Good Soil Sample to Help Make Good Decisions, 2003, PM 287, Iowa State University.
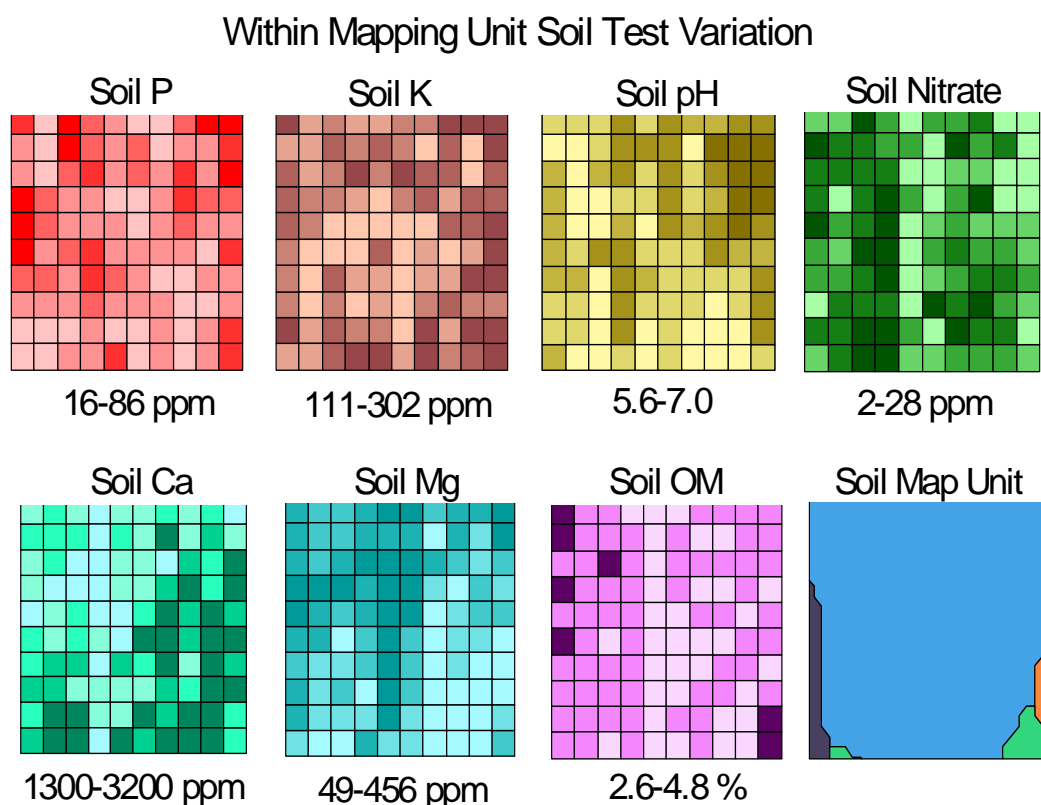
The main assumption supporting this "soil type" approach are that soil factors indeed result in different nutrient levels, nutrient removal, or nutrient use efficiency; and that the nutrient variation is lower within these sampling units than across units. Obviously, these assumptions may, or may not, be true for all fields. For example, differences in soil formation factors or previous management practices may not be sufficiently different to result in relevant average differences between units. Also, long histories of nutrient application and soil or crop management may have over-ridden any natural variation between soils, or may have introduced very high variation within each soil unit. Research and surveys have shown that today this is the case in many fields. This is the reason that alternative soil sampling approaches began to be used and recommended since the mid-1990s.

Grid Sampling

Grid sampling uses a systematic approach that divides fields into squares or rectangles of equal size (usually referred to as "cells"). The location of each grid cell usually is geo-referenced using GPS devices. The cell size varies greatly depending on subjective factors, which among others include sampling and testing costs. In the mid-1990s cell sizes were 4 to 10 acres, but recently a 2.5-acre size is the most commonly used. Several studies have suggested that for grid sampling to be effective, the cell size should be smaller than about 5 acres. Soil samples are collected from within each of these grid cells following "grid point" or "grid cell" approaches. The grid point approach involves collecting one composite sample made up of a number of soil cores (generally 5 to 15) from a small

central area of each cell or from the intersection of the grid lines. This approach emphasizes a good representation of a small area each time samples are taking over time over trying to represent well the entire area of a cell. The size of the "point" sampled varies greatly, but usually ranges from 1,000 to 10,000 square feet, and research has suggested should not be larger so the method is distinct from the "cell" approach. The grid cell approach involves collecting a set of cores randomly from the cell trying to represent its entire area as much as possible. Neither approach is better across all conditions but the grid point sampling usually is preferred because it is faster. The results of analyses of the soil samples collected with either grid sampling approach may be used directly for fertilizer or lime recommendations (in effect, treating each grid as a small field) or they may be entered into a computer mapping program that uses different interpolation procedures to assign values to non-sampled areas to produce a continuous map of soil test results and eventually a nutrient application map. Sampling at high densities allows for more accurate, but more expensive soil-test and nutrient application maps.

As a general rule, grid sampling should be considered if the previous management practices have significantly altered soil nutrient levels across the field and nutrient variability no longer follows the distribution of soil map units or topography. Figures 4 and 5 show the results of using a grid sampling approach for several soil properties in an Iowa field with a long history of fertilizer application. The field almost completely encompassed one dominant soil map unit (soil series, erosion and slope phase), but dense grid sampling revealed very high variability for almost all properties sampled.

Within Mapping Unit Soil Test Variation

Soil P
16-86 ppm

Soil K
111-302 ppm

Soil pH
5.6-7.0

Soil Nitrate
2-28 ppm

Soil Ca
1300-3200 ppm

Soil Mg
49-456 ppm

Soil OM
2.6-4.8 %

Soil Map Unit

Figure 4. Example of a grid sampling for soil P, K, pH, nitrate-N, Ca, Mg, and OM (OM) in an Iowa field with mainly one dominant soil map unit.

Figure 5 is another example that shows how a tenfold range in sampling density at a research site near Lincoln, Nebraska, resulted in significantly different patterns. In this case, the coarser sampling grid missed a systematic variation pattern in soil nitrate, probably related to livestock fencing. The average recommended N rate for the field at the higher grid density was 148 lb N/acre. The average recommended N rate was 162 lb N/acre at the lower grid density; where 45 percent of the field received a different N recommendation with the coarser grid. The coarse grid was denser than most commercial grid sampling practiced by fertilizer dealers and crop consultants.
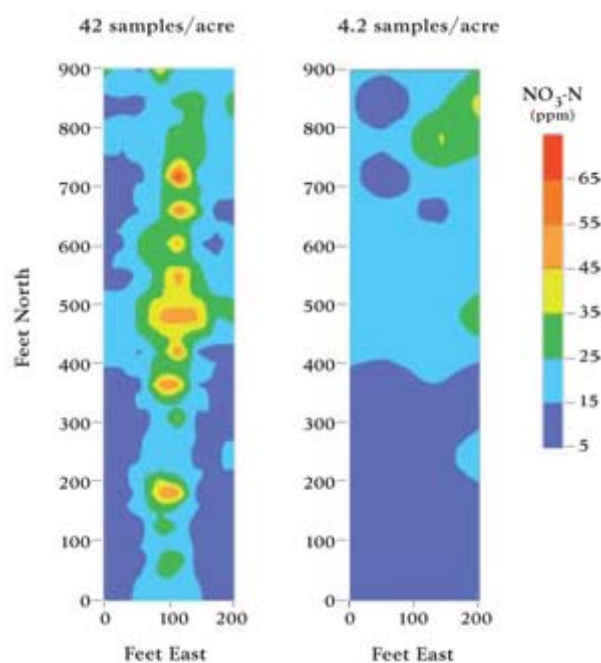
Figure 5. Interpolated nitrate-N map from a field sampled with different grid sampling density. Adapted from Ferguson and Hergert (2009), "Soil Sampling for Precision Agriculture" (EC154), University of Nebraska-Lincoln.

The very high within-field variability in these and many other fields (even within one soil map unit) clearly justifies dense grid soil sampling for nutrient application using variable rate technology. In other situations, however, accurate soil test maps can be generated at much lower sampling densities. The issue is to know how densely a field should be sampled so that the increased accuracy and precision of soil test results and crop response offsets increased costs. No general rule is possible, however, because the optimum grid density obviously depends on the field, what soil properties are being assessed, the costs of soil sampling, testing, and VRT application; and the nutrient/crop price ratios. These issues, plus the increased availability and decreasing costs of several precision agriculture technologies, have encouraged crop consultants and researchers to consider a third soil sampling approach.

Zone Sampling

Zone sampling is the most recently suggested sampling approach, and attempts to improve the traditional approach of sampling by soil map units while providing an alternative to the usually denser and costly grid sampling approach. The basic assumption is that maps of soil or crop canopy

characteristics provide additional useful information to delineate sampling zones that may differ in nutrient availability. Soil cores are collected at random from within each zone and are bulked together to provide one composite sample per zone and one soil-test value for each unit. Several information "layers" can be used to delineate sampling zones. For example, aerial or satellite images could distinguish between soils with different percentages of OM, crop canopy that reveal nutrient deficiencies and even areas with different growth patterns. Yield monitor maps and apparent electrical conductivity maps also may be helpful in identifying zones that could be sampled separately. This approach assumes that the soil or crop characteristics used to delineate zones result in relatively homogenous nutrient availability within each zone compared with the entire field area. A downside to zone sampling may be that the management of the field over time for crop production, such as crop harvest, fertilizer application, manure application and liming, may have over-ridden any natural nutrient variation related to soil or crop canopy characteristics used to delineate zones. If the variation within a zone is as large as between zones, then this sampling approach will not be effective. For example, if soil map units and images of bare soil to reveal OM variation are part of the zone delineation decision, but after many years of fertilization or liming, patterns of soil-test P, K, or pH variation may not follow soil or OM variation.

5. Frequency of Sampling

Typically suggestions are to collect samples every three to four years for most nutrients, except the most mobile ones. More frequent (every 2 years) or annual sampling is recommended in fields where rapid changes in soil-test levels are expected (such as in sandy soils) or for high value crops. Sampling for mobile nutrients, like nitrate, usually needs to be done yearly. To optimize nutrient use efficiency and economic benefits from fertilization for the more immobile nutrients (P, K, and several secondary and micronutrients), a more frequent sampling may be justified in low-testing soils than in soils where nutrient levels are adequate and the main benefit of sampling and fertilization is to maintain soil test levels over time. Regardless of the sampling frequency, records of changes in soil-test values over time should be kept for each location sampled. This record may be required in nutrient management plans and allows for comparison of test results over time, which helps understand effects of nutrient management practices on soil-test levels. Also, frequent sampling will provide trends of soil test trends over time, which together with records of nutrient application and yield can help when test results are odd or unexpected. Decisions about the frequency of sampling also should consider the sampling approach in relation to number of samples collected from each field, because of the cost/benefit of denser and more frequent sampling. No general rule is possible to follow because the optimum frequency and density of

sampling varies greatly with the nutrient, the within-field nutrient variability, temporal nutrient variability, and crop/nutrient price ratio.

Sample Handling and Testing Procedures

After the sample has been collected, contamination must be avoided. Common sources of contamination include dirty sampling tools, cross-contamination from containers or tools and storage containers. Contamination for N, P, or K testing seldom is a serious problem because the obvious importance of keeping tools or samples away from fertilizers usually is recognized. Contamination is more frequent and serious for micronutrients, however, mainly for copper (Cu), iron (Fe), and Zn from galvanized or steel buckets, probes and grinders. Even ash from cigarettes or sweat from hands can be a source of contamination. Soils should be shipped to the testing laboratory only in suitable containers and the best is to use plastic lined sample bags that often are provided at no charge by soil testing laboratories.

Collected cores should be mixed thoroughly to form a composite sample. Moist cores should be crushed and mixed to provide a homogenous sample so error when subsampling in the laboratory is minimized. If more cores are collected than can fit into the sample container, adequate mixing is essential so a representative sample of one to two pounds is sent to the laboratory. If the samples are not shipped immediately to the laboratory, they should be kept in a cool place or in a refrigerator if stored more than 2-3 days. This is not important for all nutrients, but is for nitrate and S, for example. If the mixed sample is to be dried before delivery to the laboratory, the drying should be done at temperatures no greater than 104 degrees F (40 degrees C).

Several soil test methods are available to measure the availability of individual nutrients in collected soil samples. Issues related to testing procedures are not addressed in this article. Different methods are often recommended for different regions or states of the U.S. because different tests are more appropriate for some soils than others and because of tradition or availability of research data. Producers and crop advisers should always be certain that soil test interpretations used to develop fertilizer recommendations are based on research using the same laboratory analysis procedures that are used to generate soil test results. The specific procedures recommended for testing soils in each state or region are often described in regional publications prepared by regional soil testing and plant analysis committees. For example, these include the NCR Publication 221, "Recommended Chemical Soil Test Procedures for the North Central Region" prepared by the North Central Research and Extension Committee on Soil Testing and Plant Analysis (NCERA-13) and Bulletin 409 "Procedures Used by State Soil Testing Laboratories in the Southern Region of the United States" prepared by the Southern Extension and Research Activities

committee Methodology, Interpretation, and Implementation of Soil, Plant, Byproduct and Water Analyses (SERA-6). Specific soil-test interpretations for several soil test methods and nutrient recommendations for crops are prepared and published by most states.

Summary

The application of appropriate rates of fertilizer and manure nutrients for crop production with minimal impact on the environment is highly dependent on the information derived from soil samples collected and analyzed to estimate levels of crop-available nutrients in soils. Therefore, samples collected should provide the best representation of the field or sub-field area sampled. Important issues to be considered include the sampling depth, time of year when samples are taken, number of soil cores per composite sample, number and distribution of samples across a field and sampling frequency. Seldom does one single composite soil sample adequately represent an entire field and sampling approaches can be implemented that are useful for precision nutrient management using precision agriculture technologies such as variable-rate application. To guide more precise fertilizer applications to optimize the profitability of nutrient management or to address environmental concerns, entire fields can be divided into smaller areas and sampled accordingly. Regardless of the method used for collecting multiple samples or dividing fields into smaller areas, a sufficient number of soil cores should be collected for each composite sample so that the sample adequately represents the area sampled. Without representative samples, recommendations based on test results will not be accurate.

Chapter 10:
Economics of Nutrient Management and Environmental Issues

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Introduction

The objective of nutrient management is to apply the proper nutrients and rates, and place them correctly and at the right time to best supply crop needs for profitable crop or animal production. Properly managed nutrients can also help protect the environment. Nitrogen (N), phosphorus (P) and potassium (K) are typically the largest fertilization expenses in crop production. The application of these nutrients is critical because it can significantly improve crop yield in many crop rotations. However, unneeded application or poor efficiency results in increased production cost and lost potential economic return. In addition, N and P management has environmental importance since their losses from agricultural systems have been identified as likely contributors to elevated surface or groundwater nitrate (NO_3^-) concentrations, impairment of freshwater bodies, and also hypoxia of coastal waters (such as the Chesapeake Bay and the Gulf of Mexico). Therefore, when choosing N and P applications, rate, timing, source and placement, producers need to carefully consider options to achieve the most profitable economic return while minimizing impacts on water quality.

Despite the progress that has been achieved in reducing water pollution from point and non-point sources, assessments indicate that almost 40% of U.S. waters have not met water quality standards. When N or P is present in lakes or rivers at a high concentration, a condition called "eutrophication" or biological enrichment can occur. High N and P from the Mississippi River has been blamed for a low oxygen hypoxic zone in the Gulf of Mexico. Excess algae growth occurs in response to the enriched nutrient concentrations. When the algae die, their decomposition consumes dissolved oxygen that suffocates fish, increases toxin-producing microorganisms, and reduces the aesthetic value of water. Also, excessive NO_3^- in drinking water systems can present a health hazard to very young infants (methemoglobinemia) and sometimes requires expensive treatment for nitrate removal. Sources of N and P contributing to environmental problems include agricultural surface runoff, soil erosion (mainly for P), leaching to

subsurface drainage tile lines and groundwater (mainly for NO_3^--N), sewage treatment plants, atmospheric N and other sources.

Since N and P are very different in terms of their dynamic interactions in soil, fertilization practices and management influence on potential losses, the economic and environmental aspects related to management will be discussed separately.

Nitrogen Management Considerations for High Profitability and Low Environmental Risk

Proper N management for crop production involves the integration among adequate rate, source, timing and placement. When managing N, interactions among these four factors are perhaps more important than for any other nutrient. However, rate often has the greatest influence on leaching losses of NO_3^--N.

Nitrogen Rate

Crop response to applied N varies among crops. It is very important from the management point of view to have an approximate idea of the shape of the yield-N fertilization response curve for each crop and specific conditions affecting response to applied N before deciding an N rate to apply. Figure 1 shows the quadratic-plateau shaped N response curve for yield response in a crop like corn, where over applying N beyond the rate at which the maximum agronomic yield is reached (within a certain range) usually does not cause a yield decrease or quality issues. For small grain crops, like wheat, barley and others, however, over-application of N may cause yield decreases due to plant lodging and harvesting problems and in some cases too high grain N or poor grain quality for end uses. Not only is fertilization rate important, but also consideration of other N inputs that may result in too-high crop available N in the soil, such as carry-over NO_3^-, residual manure N, and previous legume crops.
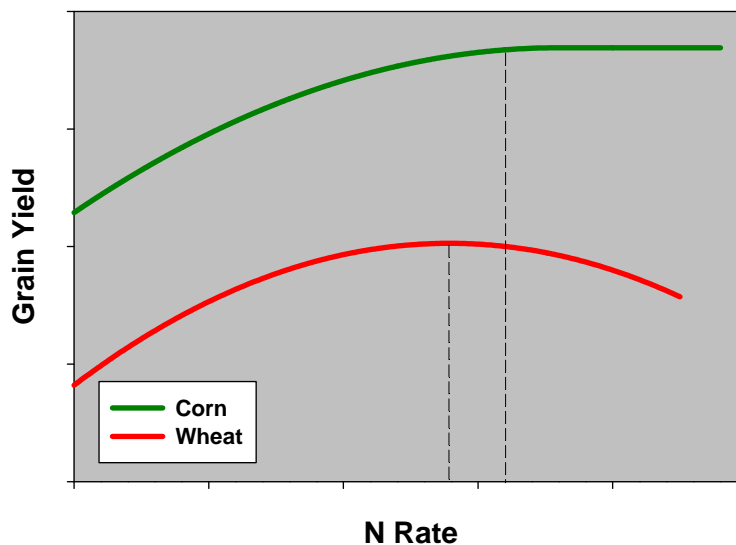
Figure 1. Schematic representation of typical N response curves for corn and wheat. The vertical dashed lines indicate the N rate at which the maximum agronomic crop yield is reached.

From an economical point of view, rather than applying N to produce maximum yield, producers should apply N rates that return the most profitable yield, where the yield gain from N application will more than pay for the invested N. Applying N at rates that produces maximum yield always causes lower net return, although the return loss can vary from small to large depending on crop/nutrient price ratios, crops and the shape of the response curve for specific conditions. From an environmental point of view, applying N to produce maximum yield will result in greater N loss (NO_3^--N) than application at the most profitable rate. Therefore, both economic and environmental perspectives need to be considered together when making N management decisions.

Applying more N than needed by crops to assure maximum yield is not considered an acceptable management practice. The current N fertilizer cost situation is neither cheap production insurance nor environmentally benign. High N fertilizer costs, uncertainty about crop prices and environmental effects should encourage growers to critically consider application rates. Figure 2 shows how NO_3^--N loss via tile lines increases rapidly as fertilizer N rate increases beyond the economic optimum N rate (EONR). This concept applies for all crops fertilized with N and most production scenarios, which highlights the importance of accurately determining the optimum N rate to maximize profitability and minimize environmental impacts within specific crops and production systems. In spite of much research, this is

much easier to say than actually achieved in production fields due to the numerous and unpredictable factors that affect the optimum N rate and the crop response to applied N.

Since NO_3^--N in subsurface drainage increases with increasing N application rate, there is potential to affect NO_3^--N losses through change in N rate. However, the level of change will be related to the rate comparison and starting rate. In addition, and as mentioned above, the success relative to water quality goals is not likely to be achieved solely through rate adjustment. For instance, at EONR for corn production, NO_3^--N in tile flow typically exceeds the maximum contaminant level (MCL) of 10 mg N L^{-1} drinking water standard. Moreover, even if no N is applied, NO_3^--N will exceed the proposed EPA nutrient criteria for total N in surface waters. There are also questions regarding costs associated with reducing NO_3^- losses, and how those costs are to be paid. If N application rates being used are above the EONR, then producers can gain economically by reducing rates to those levels. They will achieve a net economic positive due to reduced N input and no associated loss in yield. However, if producers are already applying N at the EONR, then reduction below those rates will impose an economic penalty through yield loss.

Since yield response decreases with increasing N rate, the cost in yield penalty for reduced N input is less near the EONR than at lower N rates. Therefore, cost per unit of NO_3^--N reduction in drainage water becomes much larger as N rate declines below the EONR and approaches zero. This illustrates the significant risk and economic constraints that producers face if they are asked to reduce N application to rates below maximum net return.
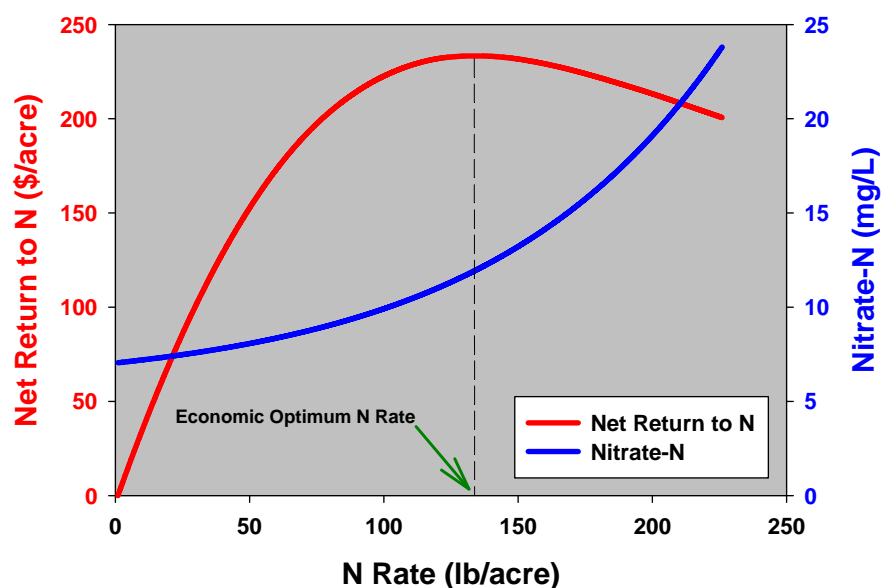
*Figure 2. Importance of using economic optimum N rates for greatest profit
and minimizing nitrate-N loss (via subsurface tile drainage).*

Nitrogen Timing and Placement

Many corn producers in the U.S. Corn Belt apply N in the fall. Reduction in NO_3^--N concentration in tile drainage water can be observed with use of a nitrification inhibitor or when moving from fall to spring applied N fertilizer, considering the same application rate. Any additional fertilizer application in the fall to compensate for anticipated losses would further increase NO_3^--N loss, therefore moving from fall to spring in conjunction with a rate reduction would be an even larger benefit.

Sidedressing N in corn can potentially increase N use efficiency and reduce losses. This can be done in different ways and with different sources of N. However, the concept of applying fertilizer after crop emergence is consistent.

In small grain crops, N sufficiency during tiller initiation is very important because potential head number is determined by tillering success. However, the N requirement when stem elongation begins is only about one third of the total season uptake. Thus, split N applications often produce better results due to avoidance of potential N loss conditions such as volatilization, denitrification and leaching. The initial topdress of a split application should be applied before or at planting. The purpose of this application is to provide adequate N to promote adequate tillering and head number. In-season applications or final topdress should be applied by the time the first node appears at the beginning of stem elongation.

The thought behind this timing strategy includes applying N during plant uptake as well as timing to reduce the risk of loss from early spring rainfall/leaching events. Research in general shows a reduction in NO_3^--N concentration in tile drainage water when moving from fall to spring/split applied N fertilizer. In season N applications also allows the N rate to be adjusted through either soil sampling or crop canopy sensing.

Nitrogen Source

Research suggests there is little, if any, difference in NO_3^--N leaching or crop yield when using different traditional sources of fertilizer or manure, provided similar plant available N application rates are used and management is appropriate for the source. Using slow or controlled release fertilizer sources may have an impact on improved crop efficiency and NO_3^--N leaching, similar as with sidedressing N, but little water quality data is available to quantify this. Besides potential impact on NO_3^--N leaching, some manure sources high in solids content may have a positive impact on soil organic carbon, soil structure and surface runoff.

Other Practices

Several in-field and edge-of-field practices besides direct N management (rate, time, placement and source) can significantly reduce NO_3^--N losses from production fields. These practices will likely need to be utilized in addition to traditional in-field N management in order to meet NO_3^--N reduction and water quality goals.

Cover crops have the potential to reduce NO_3^--N leaching in corn-soybean rotation by taking up water and NO_3^--N during the time between corn and soybean maturity and planting the next crop. However, effect on NO_3^--N leaching is greater in areas with potential for more fall and wintertime cover crop growth, and less in northern climates where the period for cover crop growth is more limited.

Crop rotation changes can help in reducing NO_3^--N losses by including perennial crops or crops that require minimal or no N fertilization. For example, perennial crops such as forage grasses, alfalfa, energy crops, or annual crops less N fertilization demanding would decrease the needed rotation N application and thus the amount of NO_3^--N loss. Even though this alternative does not seem possible at a large scale, it may be an option for specific areas where N contamination of water sources is severe. In extreme cases, land may need to be taken out of crop production, retired, or converted to permanent pastures in sensitive areas. The establishment of buffers at the edge of the fields, wetlands, or bioreactors to treat tile-flow

water could also be complementary strategies to help reduce NO_3^--N loss to surface waters and help with Gulf hypoxia and local water quality concerns.

Phosphorus Management for High Profitability and Low Environmental Risk

Proper management of P applications is a key for optimizing yield, profitability and water quality. In most regions, key P management issues for crops involve knowing the optimum soil-test P level, applying fertilizer to avoid deficiencies and achieving the optimum soil-test level over time by using various strategies considering fertilization rates and the frequency of application. Therefore, in the vast majority of fields, the fertilizer P application rates being used are the rates that maintain desirable soil-test P values based on removal or empirical information. In practice then, the historical P application rates and current soil-test P level a farmer maintains is the most important and widespread issue for the economics of P management and water quality. Nevertheless, in some conditions, the P rate, source, time of application and placement method should be considered to maximize P use efficiency and profitability while minimizing the risk of water quality impairment. The rate of P application is of great concern with excessive application that often occurs mainly when manure is applied as a waste, when any manure is applied at N-based rate to continuous grain crops and even when poultry manure (which often has a lower N/P ratio) is applied at N-based rates for corn in rotation with soybean. Subsurface banding or injecting of P could be a best management practice in soils with very high retention capacity that transforms applied P to forms of low availability to crops or with high risk of erosion and surface runoff.

Soil-Test Phosphorus Level, Crop Yield, and Profitability

Figure 3 shows the general relationship between soil-test P level and crop yield. Soil test levels are generally distributed into interpretation categories referred to as very low, low, medium (or optimum), high and very high (or excessive). The critical level or range separates soil-test values for which there is a high probability of large to moderate crop response to fertilization (very low and low) from values for which there are small and infrequent responses (high and very high). The critical level will vary with the test method, crop, soils, climate, and fertilizer/grain price ratio; and sometimes even with the philosophy of researchers that establish interpretations and recommendations. For example, the Bray-1 P level considered adequate for crops, and at which no fertilization is recommended, vary from about 12 to 30 ppm for forages or grain crops across the U.S.
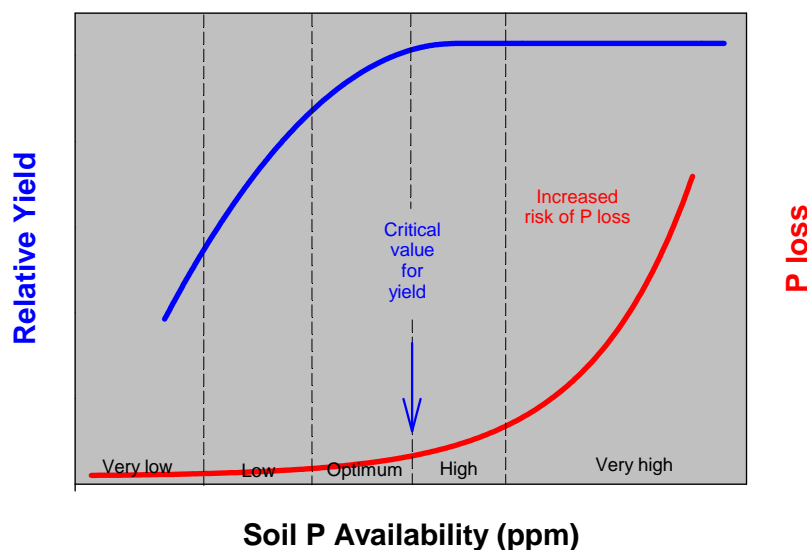
Figure 3. Schematic representation of the general relationship between relative crop yield and P loss with runoff.

In addition, because nutrient and crop prices influence the profitability of nutrient application and crop production, economic considerations together with producers' management and business philosophies further influence the optimum soil-test levels for crops. The optimal soil-test P level from an economic perspective will depend largely on the nutrient and fertilizer price ratios, producer management and other enterprise decisions. Figure 4 shows, as an example, how different crop/fertilizer price ratios influence the corn and soybean response to P fertilization and how prices may influence the optimum soil test level to maintain.
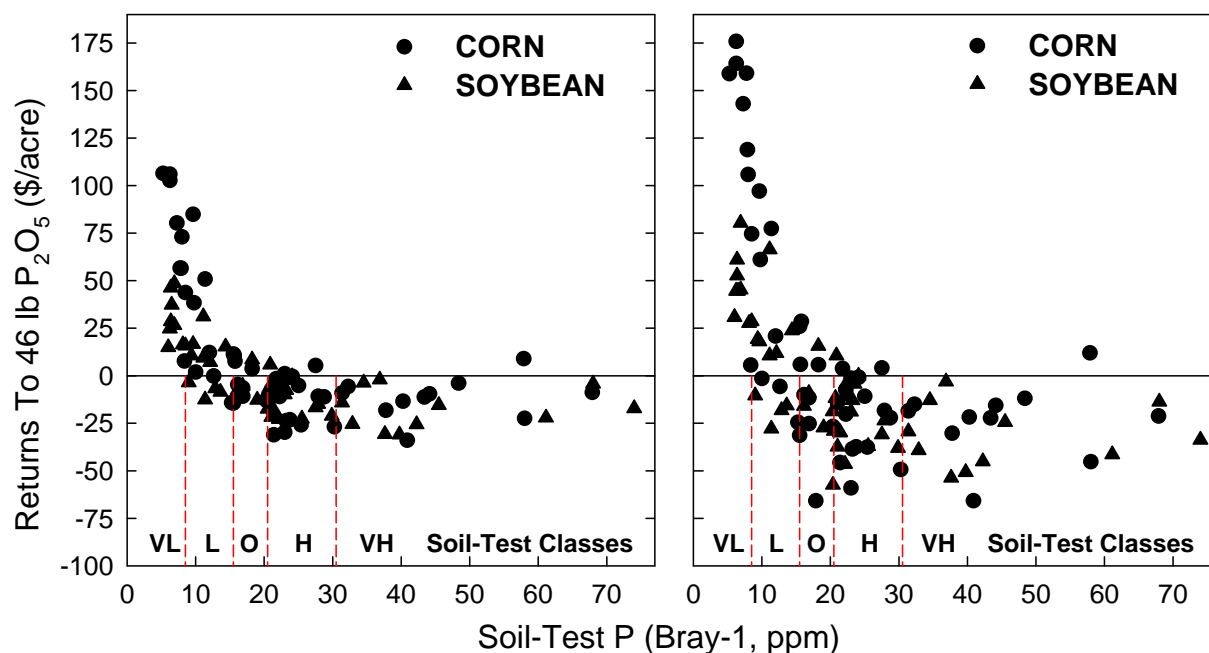
Figure 4. Net returns to P for different soil-test P levels and crop/fertilizer prices.
Left graph: Corn and soybean grain at $2.00/bu and $5.50/bu, and P at $0.32/lb P₂O₅.
Right graph: Corn and soybean at $4.00/bu and $10.00/bu, and P at $0.40/lb. VL, very low; L, low, O, optimum; H, high; VH, very high (from Mallarino, A.P. 2009. Long term phosphorus studies and how they affect recommendation philosophies. p. 6-12. North-Central Extension-Industry Soil Fertility Conf. Proceedings. Nov. 14-15. Vol. 25. Des Moines, IA).

Phosphorus Management and Water Quality

Phosphorus is lost from fields as dissolved forms in surface runoff or subsurface drainage and as P bound to soil particles, which is usually referred to as particulate P. The dissolved P runoff fraction is readily available to algae growth, while the particulate P fraction becomes available over time at a rate that depends mainly on the chemistry and depth of the receiving waters. With few exceptions, such as in areas with sandy soil or subsoil and level landscape, the particulate P loss is several times greater than the dissolved P loss. Therefore, soil and water conservation practices are as important, and often more important, than P management practices concerning P loss from fields. This is the reason that in most states P risk assessment tools or P indices have been developed that consider all these factors to classify fields or field areas according to risk of P loss. The P index or related risk assessment tools are being required as part of the nutrient management planning process by regulatory federal or state agencies when manure is applied or when any P source is applied within watersheds with impaired water quality.

Different types of P indices have been developed regionally or by the states. No P index is a complete P source and transport model, although some have been validated with water quality data. It is a practical quantitative tool that provides reasonable estimates of P loss risk while they can be used by advanced farmers, crop consultants and nutrient management planners. It uses an integrated approach to consider soil and landscape features as well as soil conservation and P management practices in individual fields or different areas within fields. These characteristics include P source factors such as soil test P, total soil P and the rate, method and timing of P application using commercial fertilizer, manure and other organic sources. Transport factors include precipitation, erosion and sediment delivery, surface runoff, distance from the field to the nearest stream, a variety of soil conservation practices and subsurface drainage. Components of all current P indices are erosion (particulate P lost with sediment loss) and surface runoff (dissolved P loss). A subsurface drainage component (dissolved P loss) also is included in regions where leaching through the soil profile or subsurface tile drainage are important. Most states have publications in which each state P index is explained with detail. Understanding how the different factors influence the risk of P loss helps agricultural producers, conservation planners and others by determining the causes of high risk loss. This allows for the identification of the most effective P management practices and soil or water conservation practices to reduce the P loss for different fields and conditions.

Phosphorus Management Practices

There are considerations regarding P source, timing, placement and rate that producers that are included in P indices and should be considered in order to maximize P use efficiency and minimize P loss from fields.

Phosphorus soil-test level: Interpretation of soil-test P values for water quality issues must be different than for crop production. There is general agreement that soil-test levels higher than adequate for crops may significantly increase the risk of P loss and water quality impairment, which was indicated in Figure 3. The concept of soil-test calibration used for crop production also applies to interpretations for risk of water quality impairment. The meaning of a certain soil-test value in terms of nutrient loss and impact on algae growth may vary greatly across sampling depths, soil-test methods, soil properties, soil and water transport to water resources and the properties of the receiving water body. Although the hypothetical example in Figure 3 indicates an exponential relationship between soil-test P level and P loss, the relationship found can be linear when values are not extremely low or high. Sampling a shallow soil depth, which seldom improves the value of soil testing for crops, greatly improves the relationship between soil-test P and P loss compared with the common 6 or 8-inch sampling depth for all fields but mainly for no-till, hay, or pastures. In general,

the increasing risk of P loss becomes consistent for soil-test values higher than about 30 to 50 ppm (Bray-1 or Mehlich-3 tests, 6 to 8 inch sampling depth), which is at the optimum or slightly higher levels for most crops. Therefore, the economics of crop production and environmental concerns should discourage management strategies that increase soil-test P to levels much higher than optimum levels for crops. Scientists agree that the soil-test P level is only one of several factors that affect P loss and transport from agricultural fields, so the risk of loss from elevated soil-test P levels should be considered in a comprehensive P risk assessment tool, such as a P index.

Phosphorus timing: In general, the P application timing does not have a significant effect on crop yield where the soil properties do not result in extensive conversion of applied P to crop unavailable forms. This means that in most soils of the U.S., P application can be made at varying times before planting of crops However, the time of P application during the year and also the time between the application and a runoff event can significantly influence P loss with surface runoff. For example, research in Iowa and other states has indicated that total and dissolved P concentrations were over 60% less when a runoff event occurred after 10 to 15 days compared with events immediately after surface application. As added P reacts with the soil, it enters the labile soil P pool and is less prone to losses in runoff. Therefore, the risk of P runoff can be substantially reduced by applying P when runoff events are unlikely for one to three weeks after P application. The probability of runoff P loss in the Midwest is typically greatest in late winter and spring due to increased frequency and intensity of rainfall for already wet soils, and in northern areas also due to snowmelt runoff events.

Phosphorus source: Research has shown reduced P losses with runoff with manure compared to fertilizer, especially with runoff events soon after application. Manure P typically is less soluble in water than fertilizer P due to organic P fractions, and that results in less dissolved P in runoff occurring immediately after surface application. Also, manure application can result in reduced erosion and surface runoff due to increased water infiltration when manure contains considerable bedding, with reductions in sediment and runoff volume that can be greater than 2.5% per ton of surface applied manure (dry matter basis) per acre. The effect of such manure application on runoff and erosion can extend for multiple years after manure application.

Phosphorus placement: Research has shown little to no differential response to P placement methods for most crops in soils with low P-fixing capacity and where initial soil-test P levels are not very low. In severe P-deficient conditions, high clay soils and high fixing soils such as those with high content of aluminum and iron oxides or reactive calcium carbonate, P banding is generally recommended over broadcast application to increase plant availability of applied P and to obtain

higher P use efficiency and economic return. From a water quality perspective, however, P banding or injection always reduces particulate or dissolved P loss with erosion or surface runoff compared to surface application unless the operation increases soil erosion significantly. This is because surface application of P increases soil P levels at the soil surface (in the soil-runoff water mixing zone). Runoff P loss may or may not be reduced with incorporation of manure or fertilizer with tillage because of usually increased soil erosion rates. Precipitation, slope, infiltration rate, application rate, distance to stream and many other factors influence the benefit of incorporating P with tillage at reducing P loss with runoff. Dissolved P in runoff is generally higher with surface application if a runoff event occurs shortly after application. The risk decreases with time after application before a runoff event occurs and can decrease further when rainfall that do not cause runoff occurs before a runoff event.

Variable rate phosphorus application: Dense within-field soil sampling has shown very large spatial variability of soil test P. Precision agriculture technologies available to producers or custom applicators facilitate application of fertilizer and manure at rates adequate for different parts of a field. Research has shown that grid or zone soil sampling methods combined with variable rate application based on soil-test P may not increase crop yield compared with traditional methods but always reduces spatial variability by minimizing P application to high-testing areas within fields. Variable rate application of fertilizer P is common, and some custom applicators are beginning to apply manure using variable-rate technology. Therefore, dense soil sampling and this technology can be implemented to addressing environmental as well as economic concerns.

Soil and Water Conservation Practices

The risk of runoff P loss is affected by many soil and water conservation practices that in spite of their potential importance and effectiveness to reduce P loss form fields can only briefly addressed here. These practices are especially effective in fields with grain crops, since soil and water losses are much less with well managed permanent hay or pastures. The different practices typically reduce total P loss by affecting differently the loss of particulate P and dissolved P.

Tillage and phosphorus incorporation into the soil: Tillage practices generally have an impact on soil erosion, which is the primary source of P delivery with sloping ground. Although the results of P loss with different tillage systems is site specific, research suggests less P loss generally occurs with minimum tillage than conventional tillage systems. Systems such as no-till, for example, decrease significantly the particulate P loss but usually increase the proportion of dissolved P lost.

Cover crops: Cover crops reduce P loss mainly by reducing soil erosion, and the effect of P uptake varies widely with the amount of growth allowed and the cover species. A cover crop increases soil stability from root growth in addition to providing a physical barrier between rainfall and the soil surface. Cover crops can be seeded in the fall using a variety of methods including drilling the seed after crop harvest, broadcasting the seed after crop harvest, or aerially broadcasting the seed before harvest. In northern regions the efficacy of cover crops is diminished because there is no winter growth, and growth in the fall and early spring (before optimum crop planting dates) is limited. Research suggests that when using a cereal rye cover before corn, the cover should be terminated about 2 weeks before corn planting in order to limit negative impact on corn growth and yield. On the other hand, there is no effect on soybean yield, so rye growth can continue longer in the spring and potentially provide more benefit in reducing erosion and P loss during a period with high rainfall intensity.

Sediment control structures, contour or strip cropping, buffers, and wetlands: Terraces and ponds are well known practices that result in significant reduction of soil and P loss from fields, although their efficacy is highly dependent on the landscape and maintenance. Contour cropping and strip cropping that alternate summer and winter grain crops or grain crops with hay can significantly reduce soil erosion, surface runoff, and mainly particulate P loss. Buffers come in many sizes and shapes, and may involve diverse plant species. Buffers reduce sediment transport from fields and stabilize stream banks, and physically remove particulate P from runoff water. The impact on dissolved P loss usually is minor, and is more effective when will enters the soil under the buffer with infiltrating water. The performance of installed wetlands is very dependent on the wetland-to-watershed ratio (how large the wetland is compared to the watershed). The larger the wetland-to-watershed ratio, the greater will be the percentage of P removal. Many factors affect the efficacy of wetlands at reducing P loss, including how much land is available and the sediment influent concentration. Over the long term, wetlands may not effectively remove P due to P saturation of the system, and research has shown that some old wetlands are actually sources of dissolved P.

Summary

Adequate nutrient management permits efficient crop production while reducing water quality degradation from nutrient pollution. A nutrient management plan is a site-specific decision process that integrates appropriate rate, source, timing and placement. This permits efficient nutrient use by crops and helps reduce nutrient losses to the environment. The issues associated with development and

implementation of nutrient management plans are many and complex. Some amount of nutrient loss will occur even when the best nutrient management practices are employed, but these losses should be lower than would occur without nutrient management.

For N management, of greatest importance is for crop producers to carefully consider the rate of application, and apply rates that provide maximum return to the N investment. Any N application will increase soil NO_3^--N and thus potential for greater NO_3^--N concentrations moving to water systems. However, applying economic optimal rates maximizes return and reduces N effects on water quality. Because N of most environmental concern is NO_3^-, other management practices need to focus on improving crop N use, that is high yield production, and limiting NO_3^- accumulation or keeping NO_3^- in the soil system. These practices, such as overall optimal crop production practices, time of application, nitrification inhibitors, slow-release products, cover crops and in-season tools such as soil NO_3^- testing and crop sensing, will help with improving use efficiency and lower chance of N loss.

Phosphorus management is somewhat simpler than for N in humid regions, due to differences in the type of chemical transformations, no gaseous phase or volatilization risk, and less influence of environmental factors on processes that control crop-available forms and losses. Also, although the vast majority of P in soils is unavailable to plants because it is bound in insoluble P minerals or sorbed strongly to soil particles, soil sampling and testing is more reliable and useful than testing for N in humid regions. The goal of sound P management in most regions of the U.S. should be to keep the soil-test P level at optimal ranges for maximum economic crop yield, and utilize application methods and timing that optimize P use efficiency and economic profitability, while minimizing the risk of excess P loss from fields that can impair water resources. Due to the strong dependence of P loss on soil and water losses from fields, crop, soil and P management systems should avoid or minimize practices that increase soil erosion and surface runoff. Therefore, P management planning must consider practices that influence erosion and water loss from fields, and cannot simply address soil-test P and P application. Use of the P index or similar P risk assessment tool that estimates in a comprehensive way impacts of the risk of P loss for P, soil, and water management practices the best way by which producers can evaluate how economically optimum P management practices interact with soil conservation practices so that they can minimize water quality impairment.