# NUTRIENT MANAGEMENT FOR INCREASED CROP PRODUCTIVITY AND REDUCED ENVIRONMENTAL IMPACTS †

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## Abstract

Careful management of plant nutrients is more important than ever because of volatile grain/fertilizer price ratios and public concerns about water quality impairment due to excess nutrient loss from fields. The management concepts most relevant to increase the efficacy of crop production while limiting water quality impairment are different for nitrogen (N) than for less mobile nutrients such as phosphorus (P) and potassium (K). This article highlights considerations for P and K but with emphasis on P because deficiencies are more widespread and excess P loss results in serious water quality impairment. Soil testing, nutrient removal with crop harvest, and soil chemical/mineralogical properties are important pieces of information that must be used together with price ratios when deciding P and K application rates. Soils of some regions can retain or transform significant amounts of applied P and K in forms of low availability for crops. In most regions, however, P or K retention by soil does not mean much "fixation", which allows for management of fertilization over time. For example, an excess P or K applied for a first crop in a rotation does not necessarily imply a yield or economic loss because it will be crop-available next year. The possibility for long-term management and consideration of the probability of a crop response for different soil-test values result in several options concerning soil-test interpretations and fertilizer application rates and timing. Other considerations should include land tenure and producers' attitude concerning economic risk, and potential impacts on water quality, which expand the realm of management options. These issues must be considered when making fertilization decisions because they result in different "best management practices". Many prefer simple science-based recommendations, but an over-simplification of recommendations will not result in better nutrient management, more profitable crop production, or improved water quality. This presentation will address some of these issues based on the Iowa experience in a way that may be useful to scientists, crop consultants, and producers in regions where production conditions may be similar or different.

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## Introduction

Careful management of plant nutrients is very important these days because of volatile grain/fertilizer price ratios and public concerns about water quality impairment due to excess nutrient losses from fields. Largely unpredictable crop and fertilizer price fluctuations and actual or perceived government regulations complicate fertilization decisions, however. The uninformed public and many regulatory government agencies see reducing fertilization rates as an effective way of reducing nutrient loss from fields and improving water quality, especially when animal manure is applied. Reducing nutrient application rates across all conditions is not a good management decision, however, because it may reduce producers' economic returns to crop production and may not necessarily reduce nutrient loss from fields significantly.

The basic nutrient management concepts most relevant to increase the efficacy of crop production while maintaining or reducing water quality impairment are different for nutrients of high mobility in soils such as N (mainly the nitrate form) and the less mobile ones (such as P and K). This article highlights considerations for the less mobile nutrients, and examples focus mainly on P because excess K loss does not result in water quality problems but eutrophication of freshwater resources due to excess P is a serious problem in developed countries and some areas of developing countries. Therefore, producers and crop advisors should know fundamental concepts of soil testing use and application practices, and need to understand that there is no single best way for interpreting soil-test values and deciding nutrient application rates. Agencies in charge of nutrient management regulations also should understand the importance of flexible regulations because there is no single and best set of best nutrient management practices.

## Soil testing: A Useful but Imperfect Diagnostic Tool

Soil testing for P and K is a useful diagnostic tool and should be used to decide fertilization rates. Compared to high crop and fertilizer prices during the last decade, soil sampling and testing have become less expensive and their use is even more justified. Soil-test methods attempt to measure an amount of nutrient that is proportional to the amount of nutrient available for crops, and the amount measured may differ across soils with contrasting properties. Also, different tests for one nutrient often provide different results that can be expressed in a variety of ways. Therefore, soil-test methods need to be calibrated to be used in a specific region. The calibration process includes determining the soil-test level or range that separates responsive from not responsive soils (the critical level or range) and the fertilization rate appropriate for each soil-test value or range (Dahnke and Olson, 1990). Most countries and states of the U.S.A. establish soil-test interpretation categories that encompass very low to very high or excessive nutrient levels. Determining the critical level or range is not a clear-cut process and a variety of mathematical equations can be used to determine critical levels. All equations include some bias and a significant level of uncertainty, and calculations may target maximum yield or maximum economic yield. Widely different critical levels can be established depending on many assumptions and considerations (Mallarino and Blackmer, 1992). Also, whether it is explicitly recognized or not, scientists introduce their own bias concerning the most important considerations and most appropriate management philosophy. Fig. 1 shows, as an example, correlation of soil-test P with corn and soybean response to P application in Iowa and the current interpretation classes.

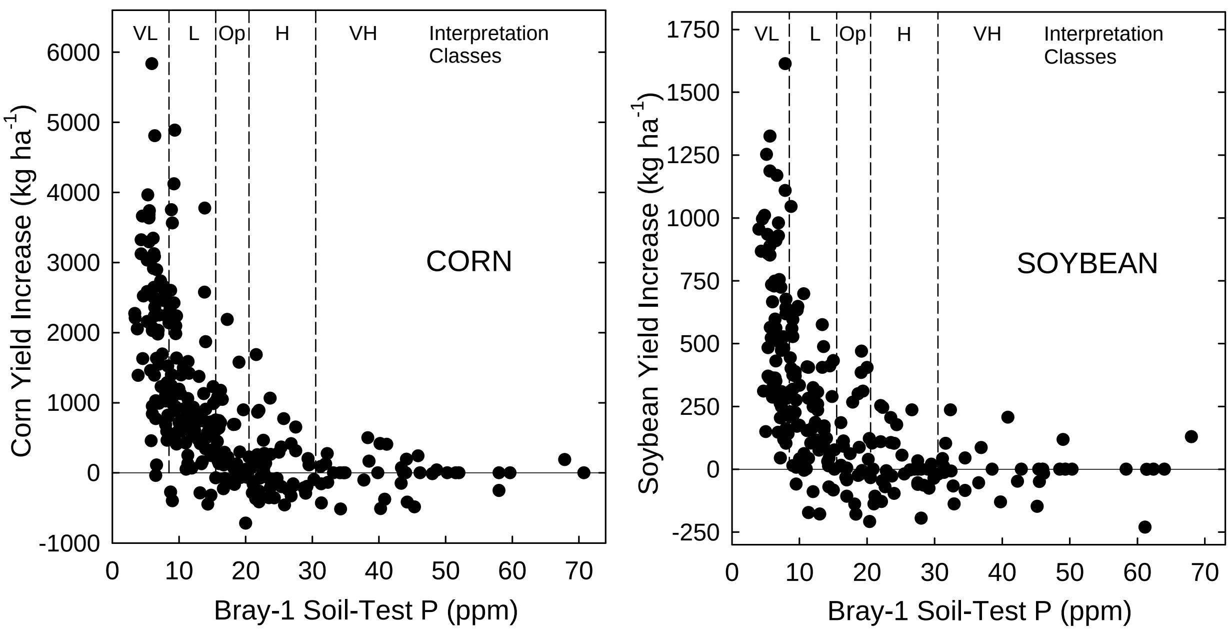


Fig. 1. Relationship between grain yield increase from fertilization and soil-test P values. Data points adapted from Dodd and Mallarino (2005) and Iowa soil-test P interpretation classes from Sawyer et al. (2002).

## Concepts for Soil-Test Interpretation and Fertilizer Recommendations

Concepts and philosophies for soil-test interpretations and fertilizer recommendations vary across states of the U.S. and countries. Some emphasize short-term profitability from applied nutrients, high returns per unit of nutrient applied, and reduced risk of fertilizer over-application by accepting a moderate risk of yield loss. This concept is sometimes referred to as the sufficiency level philosophy. It requires precise and frequent use of soil-testing and in general is more suitable for soils with large capacity to retain applied P or K in forms that are not available to crops (high “fixing” capacity). Others emphasize long-term profitability from fertilization, maximum returns over a long term, maintenance of optimum or slightly higher than optimum soil-test levels, and reduced risk of yield loss due to insufficient fertility. This concept is often referred to as the buildup and maintenance philosophy. It may not require frequent soil testing, in general is suitable for soils that retain but do not necessarily “fix” much of the applied P or K, and requires knowledge of fertilizer rates needed to maintain soil-test values, which usually is based on P or K removal with or without adjustments based on empirical data.

Most soil-test interpretations often combine aspects of both interpretation philosophies. The interpretations and nutrient recommendations often differ even with approximately similar crop response and soil-test calibration data, however, because the philosophy and assumptions of those making the recommendations also differ. The P and K application rates for low-testing soils recommended in Iowa (Sawyer et al., 2002) are based on crop response data, and are designed to be profitable and to minimize risk of yield loss for a soil-test range where the probability of a large crop response is very high. These rates will gradually increase soil-test values to the Optimum category, for which the fertilizer recommendation is designed to maintain an Optimum level based on estimates of P or K removal by crops. Moderate soil-test buildup happens even with economically optimum rates applied to low-testing soils. This is explained by partial plant uptake, recycling to the soil with residues, and soil properties that keep applied P and K in crop-available forms over time.

Most soils of Iowa and the U.S. Corn Belt have no chemical and mineralogical properties that result in significant transformation of applied P or K into unavailable forms (Dodd and Mallarino, 2005) as may happen in other regions. Most soils retain P and K, but this does not mean retention (or fixation) in forms unavailable to plants. Although studies suggest that 20 to 30% of the applied P or K is absorbed by a first crop, the rest becomes part of a soil pool that is or becomes available to following crops and can be measured by soil testing. This has two very important consequences. One is that much of the applied nutrient can be “banked” in the soil, and this allows for long-term soil-test and fertilizer management. This is not possible for N, and may not be efficient for P or K in regions where a major proportion of the applied nutrient is retained by soil in forms of little availability for crops. The other consequence is that in soils with little "fixation" capacity, methods of fertilizer application or products that enhance fertilizer P use efficiency do not have the value they may have in soils having significant fixing capacity. This is the reason that management guidelines in the Corn Belt seldom suggest use of P or K placement methods or products that theoretically increase nutrient use efficiency by reducing the reaction of soluble P or K sources in soils. Hundreds of field trials conducted in Iowa and similar soils of neighboring states have shown little or no differences between broadcast, shallow banding with the planter, and deep-banding P placement methods for yield of corn (other than starter effects on some conditions) or soybean managed with tillage, no-tillage, strip-tillage, or ridge-tillage. However, banding may have an advantage when low rates that limit yield are applied and in other regions with drier climate or soil that actually fixes applied P.

## Considering Crop/Fertilizer Price Ratios and Uncertainty

As the soil-test levels increase, the probability of a yield increase from fertilization and the size of the yield or economic response decrease. Price ratios influence the fertilizer rate that should be applied in order to optimize the profitability of fertilizer application and crop production. No matter the philosophy supporting interpretations, the net returns to investment in fertilizer are high in low-testing soils, decrease as soil-test levels increase, and usually become negative for the High and Very High test categories. Fertilization of low-testing soils usually results in significant returns because the probability of a large yield increase is high. Iowa experimental results in Fig. 2 show how net returns to fertilization with a certain rate change according to soil-test values and price ratios.

Relationships for yield response (Fig. 1) or economic returns (Fig. 2) show well the degree of uncertainty that always exists when relating soil-test values with crop response to fertilization. Soil testing is not free of error or uncertainty, and test results can be interpreted in very different ways depending on many factors. Sampling error due to large spatial variability and laboratory bias are large and should be recognized as a source of uncertainty. Uncertainty also arises from difficulties in accurately predicting conditions that limit response to fertilization or induce a higher than expected response. Therefore, it is very important that recommendations provide an idea of the probability of response for the different soil-test categories. Iowa field research has shown that the percentage of P or K applications expected on average to produce a yield response within each soil-test category shown in Fig. 1 is approximately 80% for Very Low, 65% for Low, 25% for Optimum, 5% for High, and <1% for Very High. These estimates are provided in the recommendations publication (Sawyer et al., 2002).

Applying fertilizer rates lower than needed to achieve the maximum net return will result in higher return per unit of nutrient applied. This is because of the usual curvilinear toward a plateau shape of the crop response to fertilization or soil-test values.

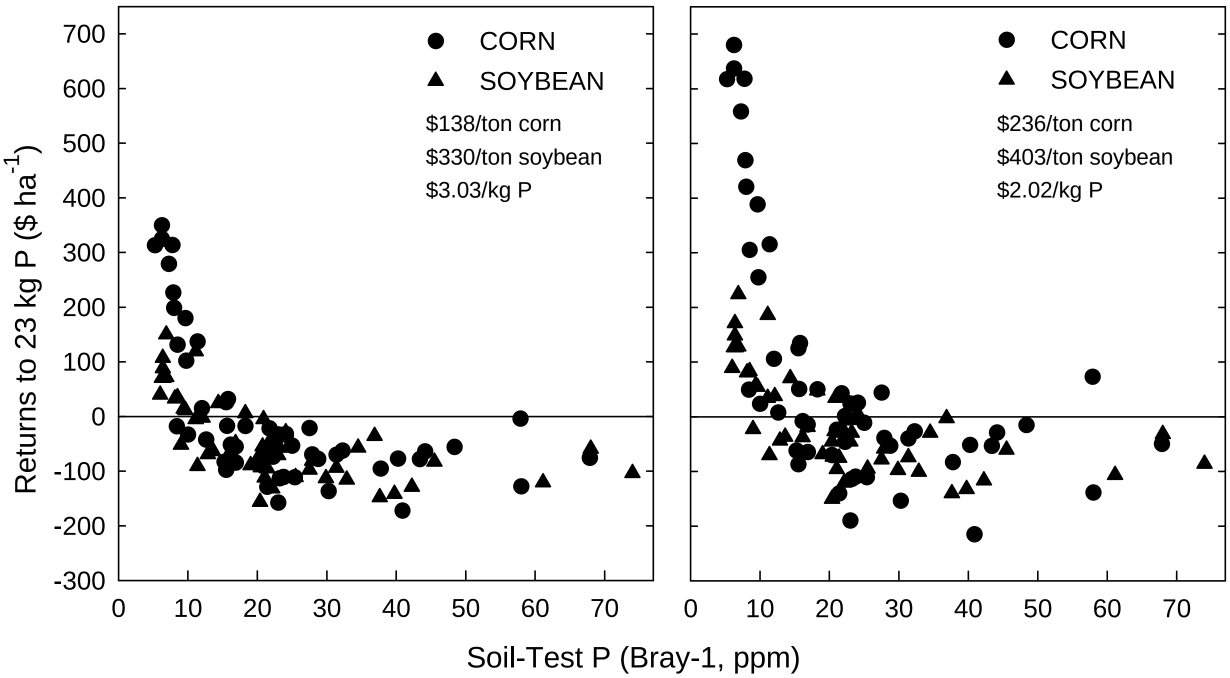


Fig. 2. Net returns to P application for different soil-test P levels and assumed prices (adapted from Mallarino, 2009).

Figure 3 shows an example of grain yield increases and net returns from P fertilization in a low-testing soil. Maximum total return is achieved at a rate lower than the rate that maximizes yield (how much lower depends on price ratios), higher rates decrease total return, and excessively high rates may even result in negative returns. Therefore, producers should carefully study if and when application rates to low-testing soils can be reduced. A sound decision requires consideration of many factors, which include the producer business management philosophy. A low application rate may increase the return per unit of fertilizer applied but may limit yield, total return to investment in fertilizer, and total return to the production system. With a small magnitude or probability of crop response, the risk of over-applying fertilizer is much higher (Fig. 3). In some regions, similar yield levels can be achieved in low-testing soils by using reduced planter-band P fertilizer rates compared with broadcast fertilization. Research in many fields has shown that this is seldom the case in soils of Iowa and the humid Corn Belt, however, (Bordoli and Mallarino, 1998; Borges and Mallarino, 2000; Kaiser et al., 2005). Yet, subsurface banding can be a good method to apply P uniformly and precisely, and can be used together with other management practices that benefit yield (such as strip tillage or row-placed insecticide).

In high-testing soils, the likelihood of a loss to investment in fertilization for one crop is high because the probability of a yield response is low and any response usually is small. Allowing a soil-test decline to occur in high-testing soils also may reduce the risk of water quality impairment. Therefore, avoiding unnecessary fertilization of high-testing soils is the most profitable change a producer can use in times of high or uncertain prices. Some believe that allowing high-testing values to decline may not be a good business decision because fertilizer prices may be even higher in the future. This is an issue that each producer should consider, but this may not be a good nutrient management decision. Making decisions for intermediate soil-test values is not simple, however, and there is no single best answer valid for all conditions.

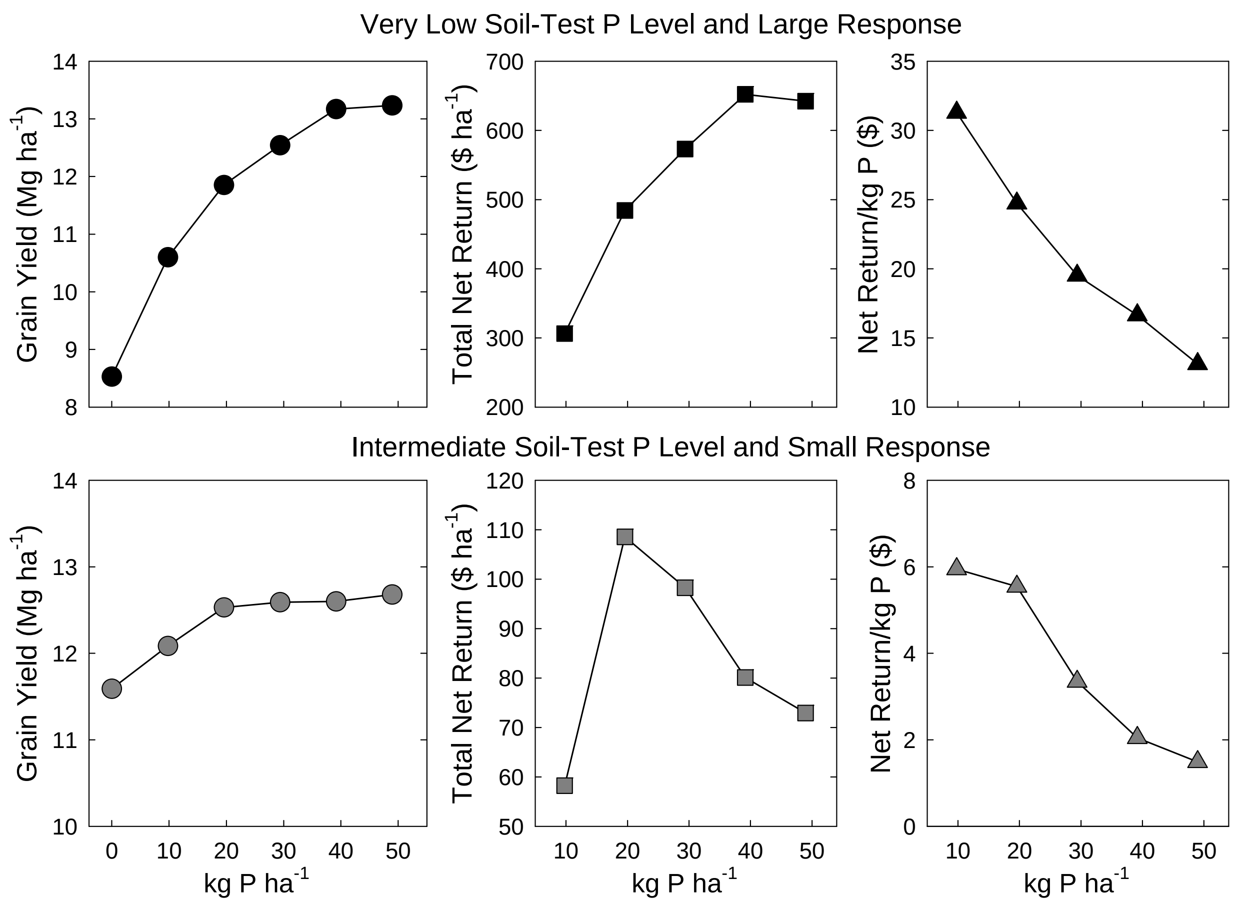


Fig. 3. Corn yield response to P fertilization in a soil testing very low in P, total net returns, and returns per lb of P applied (assumed $167/ton of corn grain and $3.03 per kg of P).

## What Soil-Test Level Should Be Maintained?

Fertilizer or manure application and P or K removal with crop harvest are the most important factors determining change in soil-test levels over time in soils of many regions. Yield levels vary significantly within and across fields and, therefore, greatly impact nutrient removal. Research has shown that an Optimum soil-test level can be approximately maintained by applying P or K rates equivalent to crop removal as long as assumed yield levels and nutrient concentrations of harvested products are appropriate (Mallarino et al., 2011). However, Fig. 4 demonstrates that the relationship between P removal and soil-test P is clear and consistent only over a period of years and can be very variable and inconsistent from year to year. Research has shown that variation in yield levels do not affect soil-test P and K critical levels or increase them by a very small magnitude, at least at the highest yield levels currently observed in Iowa. On the other hand, consideration of the yield level, especially rapidly increasing corn yields, is very important to increase soil-test P and K values to desirable levels and to maintain these levels in response to removal.

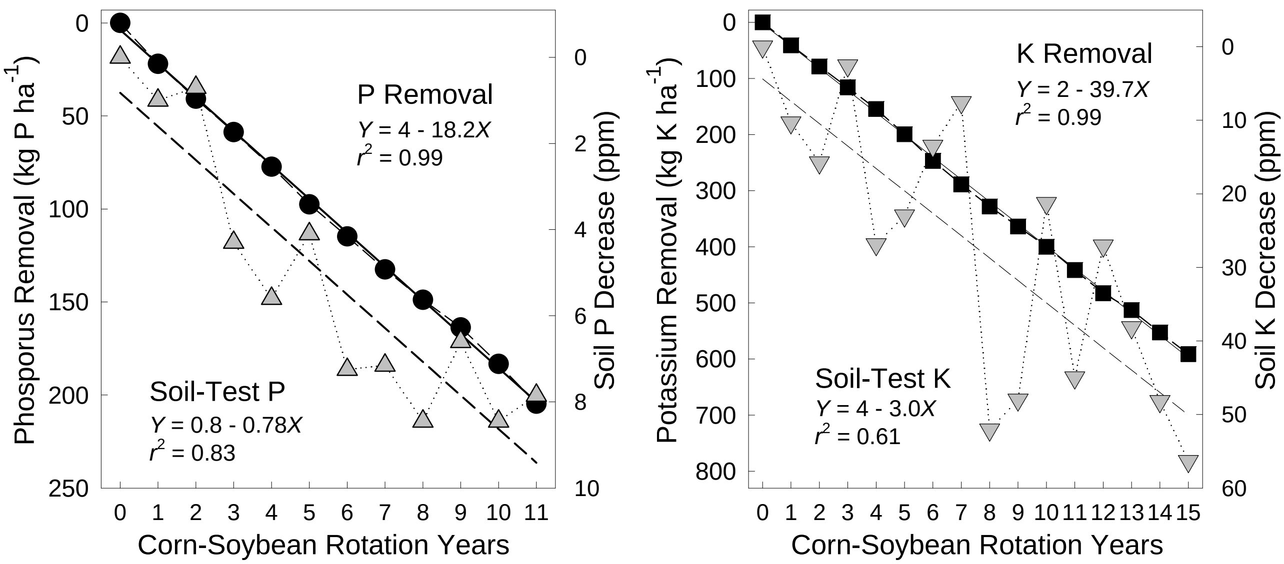


Fig. 4. Trends of soil-test values and P or K removal for corn-soybean rotations over time for plots that received no P or K fertilization (averages across five Iowa locations).

Although the concept of maintenance P and K fertilization is well established in the U.S., it is still poorly understood by some producers and crop consultants in the U.S. and other countries. Use of this concept is one of the clearest evidences for the philosophy underlying fertility management. For example, soil-test maintenance is not considered by a strict sufficiency level philosophy. Recommendations often fail to specify the criterion used to establish the soil-test range to be maintained and the expected economic return to maintenance fertilization. The Iowa recommendations clearly indicate that the objective of fertilization based on removal is to maintain a soil-test range (Optimum) that results in a 25% probability of a small yield response. Therefore, such application rates are designed to maintain soil-test values and eliminate nutrient deficiency, but not necessarily to maximize profit from fertilization of one crop. The soil-test decline without sufficient P or K application is small in one year and gradual over time (Fig. 4). Therefore, a producer could reduce or withheld fertilizer application for this soil-test category depending on various factors. Applying a lower rate may be reasonable when the fertilizer/grain price ratio is higher than usual, fertilizer supply is scarce, or limited funds are needed for more critical production inputs. On the other hand, some producers may believe that a 25% probability of a yield loss, even when small, is not acceptable given high costs of other production inputs or fixed costs. Furthermore, perceptions about next year crop and fertilizer prices may encourage producers to apply no maintenance fertilization or a buildup rate.

## Land Tenure and Risk Considerations

Land tenure and the producer business management approach strongly influence the amount of P and K to be applied, mainly with soil-test values near optimum levels. The land tenure is not a consideration for the economics of N fertilizer management but should be a clear consideration for P and K management due to residual effects of application and the possibility of long-term management discussed above. Many years ago Fixen (1992) demonstrated that interest rates and land tenure can have a large impact on the soil-test level considered optimum for crops.

Reducing the P and K fertilizer rates in low-testing soils with safe land tenure is not a good business decision because there is a high probability of a large crop response, increases the risk of yield loss and of limiting returns to the production system, and an excess application for one crop does not mean an excess for the crop rotation. Even with uncertain land tenure I do not recommend a reduction in the P and K rate for low-testing soils because there is a large probability of a large crop response. With uncertain land tenure and optimum soil-test levels, however, the maintenance fertilization rate may be reduced or withheld because there is a low probability of crop response. If the reduction in the nutrient application rate is prolonged over time, however, total net returns to fertilization and future productivity may be limited. Therefore, with uncertain land tenure and high risk, decisions concerning maintaining a desirable soil-test range depend mainly on the probability of response for that range and the producer's attitude towards risk.

## Soil-Test Phosphorus and Application Rate Effects on Water Quality

Beliefs and regulations concerning protection of water quality from excessive P loss from fields also may affect decisions about fertilizer or manure P application. Sustained high application rates that increase soil P concentration to levels much higher than optimum levels for crops increase the risk of P loss and eutrophication of surface water bodies. Phosphorus usually is the nutrient that limits and controls algae growth in freshwater bodies. Eutrophication occurs when excessive algae growth and reduced water oxygen levels due to high nutrient levels result in imbalances in water ecosystems, fish kills, increase in toxin-producing microorganisms, and reduced aesthetic value of lakes or streams. Livestock production results in large quantities of manure that is a valuable nutrient source for producing high crop yield, and can be used to minimize use of inorganic fertilizers and conserve nonrenewable nutrient sources. Soil-test P values often are very high in fields where manure is applied without consideration of crop nutrient needs or is based on N needs of cereals. This is especially the case for poultry manure (lower N:P ratio) and for any manure applied to continuous corn or wheat.

The concept of soil-test calibration for crop production also applies to interpretation 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. Relationships between P concentration in surface runoff and soil-test P show that runoff P usually increases linearly with increasing soil-test P. Figure 5 shows how the soil-test P level, soil type, and sampling depth affect the concentration of dissolved P in surface runoff. Sampling a shallow soil depth greatly improves the relationships compared with the common 15-cm sampling depths, and this was observed for both tilled and no-tilled fields (not shown). The increasing risk of P loss becomes clear and consistent for soil-test values higher than about 30 to 40 ppm (15-cm depth), however, which is the boundary between the High and Very High Iowa soil-test interpretation classes. Experiments looking at P loss through subsurface drainage indicate that significant loss begins to occur at soil P levels four to five times higher than optimum levels for crops (not shown). Therefore, both the economics of crop production and environmental concerns should discourage fertilizer P application strategies that increase soil-test P to levels much higher than optimum levels for crops.

A frequent question is how commonly used soil-test P methods relate to methods designed to measure P forms most relevant to algae growth instead of forms relevant to crop growth. Research in Iowa has shown good correlation between routine soil-test P methods and several so-called "environmental" soil P test methods (Atia and Mallarino, 2002; Klatt et al., 2003; Allen and Mallarino, 2006; Allen et al., 2006). Similar results were found in other states of the U.S.

and, therefore, routine soil-test methods used for crop production also are used for assessments of risk of water quality impairment. In some conditions environmental soil P tests (saturation indices, for example) predict better P impacts on water quality, however. These conditions include soils with extreme properties and soil P levels several times higher than optimum levels for crops.

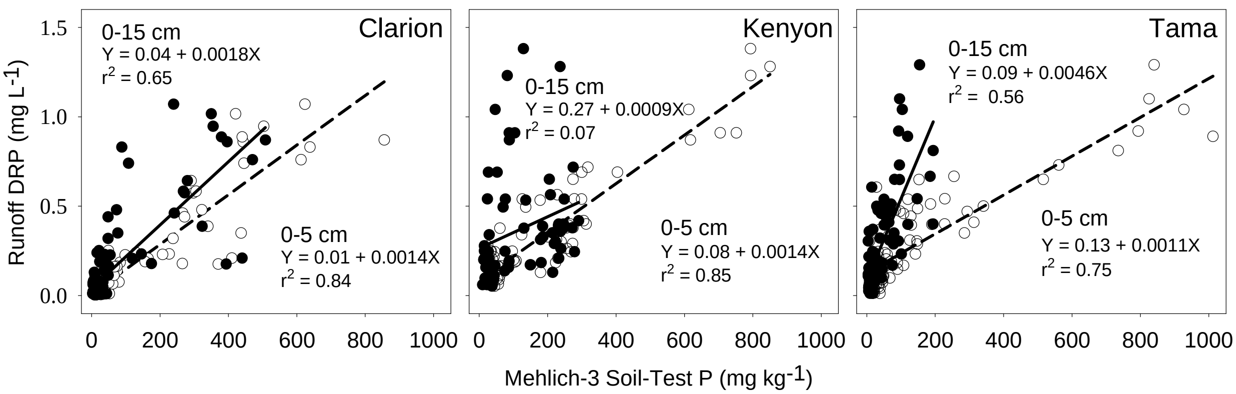


Fig. 5. Relationship between dissolved reactive P (DRP) in runoff P and soil-test P measured at 0-5 cm and 0-15 cm depths for Iowa soils managed with corn-soybean rotations and tillage or no-tillage.

Incorporating P into the soil without significantly increasing soil erosion reduces P concentration at or near the soil surface and may reduce runoff P loss. Field research in Iowa during the last two decades has shown that incorporation into the soil or subsurface banding and injection of fertilizer or manure P into the soil does not improve crop yield compared with broadcast application but significantly reduce P loss for runoff events shortly after application to sloping ground. This is not necessarily the case for delayed runoff events, however, or when the tillage or the incorporation operation results in increased soil erosion. Figure 6 shows that incorporation of P into the soil (by disking in this case) greatly reduces the P loss with runoff for runoff events occurring shortly after applications. However, even with a few days delay in the runoff event the effect of incorporation is much less or does not exist or increases P loss at low application rates. Similar results were observed in research with fewer application rates using inorganic fertilizer and other manure types. Therefore, incorporation or banding of the P into the soil can reduce the risk of P loss with erosion and surface runoff when the operation does not increase soil erosion or water loss and mainly in seasons with likely runoff events. This is important because no-till has many advantages, and consideration of the probability of runoff events for the timing of P application could alleviate potential P loss due to a lack of P incorporation.

## Comprehensive Phosphorus Risk Assessment Tools

Economic considerations do not justify fertilizer P application rates higher than needed to optimize crop yield. Utilizing manure N and consideration of the cost of transporting manure long distances may justify applying manure to high-testing soils, however, when site factors determine a low risk of P loss. This is the case because transport factors affecting soil and water loss from fields often are more important than the soil-test P level and the application rate at determining P delivery to water resources though erosion, surface runoff, or subsurface drainage. This is the reason that P risk assessment tools or P indices were developed. In the Unites States, the P index is 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.

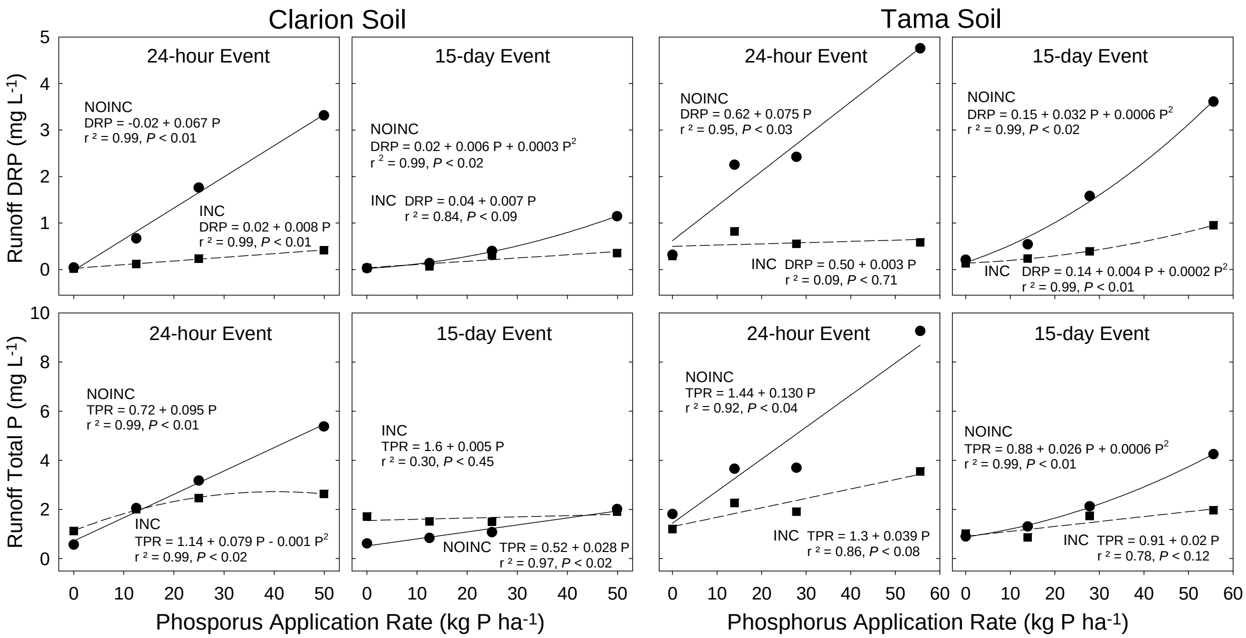


Fig. 6. Effect of P application rate, incorporation, and time of simulated rainfall on runoff P concentrations for two Iowa fields. INC, swine manure incorporated; NOINC, swine manure not incorporated. Adapted from Allen and Mallarino (2008).

The P indices developed in Iowa and most states of the U.S. are not complete P transport models, but are practical quantitative tools that provide reasonably good estimates of loss risk while can be used by advanced farmers and crop consultants. Most P indices that have been implemented include a number of site characteristics related to the source, transport, and management of P. These characteristics (or factors) may include soil erosion potential, water runoff class, soil-test P, fertilizer or organic P application rate and placement method, as well as others. Early P indices were qualitative, and different factors were considered additive. Each factor was assigned a relative potential P loss rating with a corresponding numerical value, and a weighting coefficient was assigned to each factor to reflect its relative importance in contributing to P loss. The P index was calculated by multiplying each potential P loss rating by its corresponding weighting factor and summing the results. The index value for an individual field was placed into a category (for example, very low to very high) with associated interpretations and recommendations for nutrient management. Recent index versions developed for specific regions or states include other factors and changed how potential P loss ratings were calculated to obtain a P index. Additional factors in some P indices include distance to water body; tillage, vegetation, or grazing management; site hydrology (for example, slope gradient and length, flooding frequency, drainage class, subsurface drainage, etc.); and estimates of the degree of soil P saturation.

The Iowa P index uses a multiplicative approach to combine source and transport factors within three major components based on the major P transport mechanisms. These components are erosion (sediment and particulate P loss), runoff (water and dissolved P loss), and subsurface drainage (water and dissolved P loss. Each component provides an approximate (or proportional) estimate of the amount of P delivered from fields through each transport mechanism that would be biologically available for aquatic ecosystems. The outputs from the three components are summed to get an overall approximation of the total biologically available P delivered. The resulting number (one per field or per each conservation management unit within a field) is placed into one of five risk classes (very low to very high). These classes are based on current knowledge concerning the impact of P loads on eutrophication of water resources. For details of the Iowa P index see Mallarino et al. (2002) and USDA-NRCS (2004).

Therefore, the P index approach is more comprehensive than relying only on soil-test P or P application rate thresholds since these will not provide reasonable estimates of potential for P delivery to surface water resources and the reasons for high potential loss. The P index is a more rational assessment tool, and can be used to identify nutrient, soil, and water management practices that can reduce high P loss and water quality impairment.

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