AGRONOMIC AND ENVIRONMENTAL IMPLICATION OF PHOSPHORUS MANAGEMENT PRACTICES

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Introduction

Phosphorus (P) is an essential nutrient for growth of plants and aquatic organisms. Fertilizer or manure P application to land often is necessary to achieve or maintain optimal levels of crop production. However, P applications seldom are needed in high-testing soils and excessive applications can result in increased P delivery to water resources. Excessive nutrient levels can result in eutrophication of surface freshwater resources. The movement of P from agricultural land to water bodies is a complex process involving several source factors, transport factors, and multiple delivery pathways. Phosphorus moves into surface water attached to particulate matter eroded from the land and as dissolved P in surface runoff or subsurface tile drainage. It can also move into groundwater mainly as dissolved P.

Widespread animal production in the upper Mississippi River watershed, mainly in the Corn-Belt region, results in significant manure application to many agricultural fields. Applications of fertilizer or manure P in excess of P removal with crop harvest have resulted in sharp soil-test P (STP) increases in many areas of the region during the last few decades (PPI, 2001). Recently applied P is particularly prone to loss and the loss is affected by factors such as the form of P applied, the time since application, the placement method, and precipitation events soon after application. The factors contributing to P loss from agricultural land to surface waters are commonly grouped as source factors (site and management) and transport factors. This presentation focuses on selected source factors related to fertilizer and manure P management relevant to both crop production and risk of increased P delivery from fields to water resources.

Phosphorus in Soils

Soils of the North Central Region typically contain 300 to 1000 ppm of total P. This range results from differences in long-term soil forming processes and management practices. Only a small portion of the total P is readily available to plants. A small fraction of soil P is dissolved in the soil solution in the orthophosphate form, which is the form taken up by plants. As the plant depletes orthophosphate in the soil solution, dissolved P is replenished from P in a soil pool (sometimes referred to as labile P) in which P is held by a variety of relatively weak bonds to mineral particles and organic matter. The majority of soil P is in a stable pool (sometimes referred to as non-labile P) in which it is strongly held to mineral particles or is combined in mineral compounds of low solubility, mainly iron (Fe) and aluminum (Al) phosphates in acid or weathered soils and calcium (Ca) phosphates in calcareous soils, and in recalcitrant organic compounds. Stable P is considered unavailable to plants in the short term, although it becomes available over time at a very slow rate. The degree and strength to which P is bound in soils are largely determined by the amount and types of Al, Ca, and Fe compounds present and by other soil properties such as pH, organic matter, clay mineralogy, and the amount of P currently present in the soil.

Most P fertilizers used in crop production are composed of water-soluble P compounds. The most commonly used granulated fertilizers are ammonium phosphates while fluid P fertilizers may include ammonium phosphates, potassium phosphate, and ammonium polyphosphates. There is little use of acidulated calcium phosphates (superphosphates), which once were the most common sources of commercial P fertilizers. The total P content and P forms in manure applied to fields vary greatly with the species, animal age, diet, and storage method. Some manures may have up to 80 to 100 lb P_2O_5 per ton (some poultry manures, for example) whereas others may contain 5 to 10 lb P_2O_5 per ton or less (such liquid swine manure from lagoons or solid cattle manure). The proportion of organic, inorganic, and immediately soluble P in manure also varies greatly. For example, more than 80% of the P of liquid swine manure is in inorganic and soluble forms while the rest is present as organic P. Therefore, liquid swine manure P reactions and availability to plants in soils is near to that of fertilizer P. On the other hand, solid manure from beef and dairy cattle can have less than 50% inorganic P with the rest in relatively more stable organic forms. Estimates of manure P that becomes available to the first crop after application range from 60 to 100% in the North Central Region (J. Peters et al., 2004. Unpublished. NCR-13 Regional Soil Testing and Plant Analysis Committee).

Application of P fertilizer and some manures (mainly poultry and liquid swine manures) causes a fast and sharp increase in soluble P in the soil at the point of application. Chemical equilibrium is rapidly reestablished as much of the added P is adsorbed to soil particles or precipitates as compounds of lower water solubility. The increase in soil soluble P is less evident and more gradual over time for other manures. Over time some of the P in the weakly retained soil P pools is converted into more stable mineral and organic forms. Therefore, the immediate result of fertilization and manure P applications is to increase the capacity of the labile P pool to replenish solution and stable soil P pools. The net long-term result depends on several soil chemical and mineralogical properties, P removal by crops, P movement to deeper soil layers, and P loss with soil erosion, surface runoff, or subsurface drainage.

While water-soluble manure P may be a good indicator of short-term P loss potential when manure is applied to the soil surface, it is not a good indicator of P available to a crop or long-term loss. The more labile inorganic and organic P forms can become readily available for crops or algae shortly after being in contact with soil or surface runoff and the soluble P may be retained to a different degree by soil constituents. Reducing the total P concentration of animal manures would effectively reduce the amount of P applied to fields and should reduce the risk of P loss. Use of phytase, a group of enzymes used to increase the digestibility of phytate P in swine and poultry rations, is becoming common in large feeding operations. This practice can reduce total P in manure about 25 to 35% when mineral P supplementation is reduced accordingly. Recent research does not confirm early reports suggesting that its use significantly increases the proportion of soluble P in manure.

Soil-Test Phosphorus Levels for Crop Production

Soil P tests have been developed based on knowledge of the chemical forms in which P exists in soils and empirical work to assess how the tests correlate with crop growth and P uptake. Interpreting a soil-test value requires an understanding of the impacts of the extractant, method of soil sampling, and sample handling on the test result and also of the intended use for the result. Accurate interpretations of soil-test results and appropriate fertilizer recommendations require that the relationship between the amount of a nutrient measured by a given soil test and the crop response to the added nutrient be known through field calibrations for different crops, soils, and growing conditions.

Soil P tests for agronomic use employ dilute strong or weak acids, complexing ions, and (or) buffered alkaline solutions. The Bray P-1 and Mehlich-3 tests, and the Olsen test in a lesser degree, are routinely used in the North Central Region. The Bray P-1 test was developed for use in the acid to neutral soils of the region and the Olsen (or sodium bicarbonate) test was developed primarily for use on calcareous soils. Regional research has shown that the Bray P-1 test is not reliable in many calcareous soils. The Mehlich-3 extractant is being rapidly adopted in the region because it is suitable for a wider range of pH and soil properties than the other tests and also can be used for extraction of other nutrients. With the exception of calcareous soils these tests are highly correlated, but the actual quantities measured can differ greatly. For example, in acid or near neutral soils the Olsen test usually measures 50 to 70% of the P measured by the Bray P-1 and the colorimetric version of the Mehlich-3 test (Mallarino, 1997). The inductively coupled (ICP) method of determining extracted P results in more measured P than the traditional colorimetric method, and different interpretations are needed for the Mehlich-3 extractant when these two determination methods are used (Mallarino, 2003a). As an example, Fig. 1 shows relationships between the relative yield increase of corn and STP measured by various soil tests across several Iowa soils. The response curve is used to divide STP levels into categories very low, low, medium or optimum, high, and very high or excessive. In general, there are only small differences across states of the region regarding recommended optimal STP levels for similar crops grown on relatively similar soils of Illinois (Hoeft and Peck, 2001), Iowa (Sawyer et al., 2002), Minnesota (Rehm et al., 2001), and Wisconsin (Kelling et al., 1998).

A thorough understanding of crop response to P and factors such as sampling date, sampling depth, and both method and time of nutrient application is needed to interpret STP results correctly and to provide P application recommendations. Other factors (such as climate, plant population, levels of other nutrients, and crop cultivars among others) often influence crop growth, P uptake and removal with harvest, and the P application rate needed to maintain optimal crop production. However, these factors usually have little impact on the optimal STP levels for crops. The influence of these factors often is very important for nutrients that are highly mobile in the soil (such as the nitrate form of N) but less important for nutrients such as P with stronger retention by the soil.

Soil Sampling for Phosphorus

For a soil testing program to be effective, besides proper soil-test calibration and laboratory quality control, soil samples should be collected in a cost-effective manner, should accurately represent the nutrient level in the area of interest, and the sampling depth should be the same as the depth used for developing soil-test calibrations. Sampling is a critical component of the soil-testing process because it usually represents the largest single source of error in soil testing. Many factors that vary both spatially and temporally influence nutrient concentrations in soils.

Soil-test P variation with depth results from a combination of soil-forming and management factors and from the differential mobility of nutrients in soils. Nutrients such as P with relatively low mobility tend to accumulate near the application point. The tillage system and the application method greatly influence vertical and lateral P stratification. The significant vertical stratification of P in pastures and no-tilled soils is well known. However, as shown in Fig. 2, vertical and lateral stratification also exists in fields managed with chisel-plow tillage and subsurface banding can significantly reduce STP concentration near the soil surface. Therefore, the proper depth for soil sampling and its consistency are important considerations. Soil samples should be collected from the soil depth that results in the soil-test values best correlated with nutrient sufficiency for crops, which can be known only through soil-test field calibration research. Soil samples for P and other nutrients with relatively low mobility in soil often are collected from the top 6 to 8 inches of soil. Although a shallower soil sampling for P sometimes is recommended in some parts of the country for soils managed with no-tillage or pastures, the available field calibration research (or the lack of it) in the northern region does not justify establishing differential sampling depth recommendations at this time.

Variation in landscape position and soil parent material can cause large changes in soil texture, organic matter, drainage, and other properties over a field and can result in large spatial (lateral) STP variability. These properties may affect STP directly through their influence on the amount of plant-available P or indirectly through crop yield and P removal with harvest. Variability caused by long-term history of manure or fertilizer application and other soil or crop management practices overlays the variability associated with soil-formation factors. Proximity to livestock confinement areas, feed storage areas, and field boundaries are additional examples of historical factors causing large variability in many fields. Small-scale variability usually predominates in fields with long histories of cropping and fertilizer or manure applications, especially when nutrients are applied using band methods. The challenge in these situations is to determine cost-effective methods to delineate sampling areas within a field and the number of cores needed for each composite sample to account for small-scale variability.

A variety of systematic and zone sampling approaches have been developed to measure STP. The development of affordable global positioning technology, geographic information systems, and variable-rate application equipment has led to widespread use of site-specific soil sampling approaches in the region. These approaches typically are used to generate a soil fertility map to serve as an input to computer-controlled equipment for applying varying rates of one or more materials. One such approach is zone sampling, by which field areas with more homogeneous properties than the field as a whole are delineated. Differences in landscape position, soil mapping unit, remotely sensed soil and crop canopy properties (such as soil color and electrical conductivity and canopy color and growth patterns), and grain yield measured with yield monitors are examples of factors often used to define management zones. Another approach involves systematic grid sampling, where soil-test patterns in a field are determined by means of a dense and systematic sample collection. A grid size of approximately 2.5 acres is common in the region. Small-scale variability of P is so high in some fields that accurate within-field soil fertility mapping is practically and economically impossible. Many producers and crop consultants believe that the cost of dense grid sampling can be reduced by taking only a few cores for each composite sample, and often take as few as four to five cores per sample.

However, research in the region demonstrates that at least 10 to 15 cores per sample should be collected from most fields to have reasonable confidence on soil-test results. Much uncertainty still exists regarding how to best perform site-specific soil sampling and generate accurate soil fertility maps.

Phosphorus Application and Placement Methods

Phosphorus applications can be tailored to match crop needs and minimize excessive soil P accumulation by use of soil testing and estimates of P removal with harvest. Phosphorus removal by crops varies greatly among species and with plant part harvested, and Extension services of most states provide tables with average values. Soils with naturally high STP levels are scarce in the North Central Region, and most high-testing soils result from historical P applications in excess of crop removal. Several long-term experiments have been used to provide recommendations. For example, Iowa (Mallarino et al., 1991; Webb et al., 1992; Dodd and Mallarino, 2005) and Minnesota (Randall et al., 1997) long-term research showed that annual fertilizer P rates of 30 to 50 lb P_2O_5/acre/year maintained near-optimum STP levels (16 to 20 ppm as Bray P-1) and corn - soybean grain yields. This long-term research also shows that additional P application for row-crop production may not be needed for 10 to 15 years in soils with STP four to five times higher than optimal levels for crops, except for small starter fertilizer rates in some conditions.

The time of P application before planting a crop is not a critical issue for the predominant crops and soils of the region. This is because P has relatively low mobility in soils and the soils of the region have low to moderate capacity for retaining added P in unavailable forms. Therefore, P can be applied at planting time or in advance of planting without a significant loss of efficiency. Several studies in Iowa (J.R. Webb and A.P. Mallarino, unpublished) and Minnesota (Randall et al., 1997) have shown that annual or bi-annual P applications for corn-soybean rotations have approximately similar efficiency. Moreover, similar efficiency of broadcast and band fertilizer P for no-till crops in Iowa has been partly explained by broadcast P application several months (in the fall) before planting (Bordoli and Mallarino, 1998; Borges and Mallarino, 2000). Also, manure P application in advance of planting time may increase the efficiency of applied P with any tillage system because of usually slow P release from organic P forms.

Fertilizer placement options for crops have been evaluated for many years in the North Central Region. Theoretical reasons suggest increased efficiency of banded P in some conditions compared with the ubiquitous broadcast application. These include reduced P retention by soil constituents in forms unavailable to plants (which involve processes independent of plants or plant growth) and increased plant P uptake through a variety of processes as a result of placing a fertilizer band in the root zone. Reviews by Randall and Hoeft (1988) and Bundy et al. (2005) provide excellent summaries of published research. Much effort has focused on corn. Although placement options exist for other crops, the area planted is smaller, banding generally is not used or recommended (such as for soybean), or surface broadcast application the only practical approach (such as for forages) for applying P unless fertilizer is incorporated into the soil before crop establishment. Reviews of early work indicate that grain crop responses to P placement are less frequent at high STP levels than at low STP levels. At low STP levels and low P application rates, planter-band applications (mainly applied 2 inches beside and 2 inches below the seeds) usually maximize corn response to P compared to the broadcast placement method when the rates are similar. Research since the early1990s has placed more emphasis on deep banding, in-furrow starter N-P-K or N-P fertilization, and surface-band fertilizer applications.

The placement of P or K fertilizer below the depth typically achieved with broadcast or planter-band application has been evaluated as a method of avoiding reduced nutrient availability due to stratification, particularly in no-till and ridge-till systems. While substantial evidence of nutrient stratification exists (e.g., Randall et al, 1985; Robbins and Voss, 1991; Rehm et al., 1995), reports of significant detrimental effects on crop yield are few. Early work by Farber and Fixen (1986) compared broadcast, deep band, fall-applied surface strip, and planter-band P applications for late-planted corn and found that the "2 by 2 inch" planter-band application was superior to the other placement options across three tillage systems. Work in Iowa has shown no advantage of deep P placement. A comparison of deep-band P (5 to 7 inches deep) with broadcast and planter-band P (placed 2 inches besides and below the seed) placements for corn and soybean managed with no-till (Bordoli and Mallarino, 1998; Borges and Mallarino, 2000) and ridge-till (Borges and Mallarino, 2001; Borges and Mallarino, 2003) tillage systems showed no differences among the placement alternatives for various soils and STP ranges, although deep-band K often was better for both crops. However, deep P banding reduces P accumulation at or near the soil surface (Fig. 2) and similar results have been observed for injected liquid swine manure.

Starter fertilization involves low rates of nutrient mixtures placed near or in the seed furrow with the planters and is commonly used in corn production. Most starter fertilizers contain N, P, and K, and mechanisms of crop response to starter are not always clear. Research in the North Central Region has shown frequent corn response to starter N, P, and K (Ritchie et al., 1996; Scharf, 1999; Lamond et al., 2001; Bermudez and Mallarino, 2002; Mallarino, 2003b; Niehues et al., 2004). Many, such as Vetsch and Randall (2002), concluded that responses to N-P-K starter mixtures were not due to a consistent response to a single nutrient. Iowa work with no-till corn after soybean in high-testing soils (Mallarino, 2003b) showed that N explained the response to starter fertilizer in the three responsive sites of a total of eight fields. In the responsive fields, the primary N rate (110 to 160 lb N/acre) was injected across all treatments at the V5-V6 corn growth stage. Recent research (Niehues et al., 2004) suggests that response to sulfur (S) may also partly explain response to S containing starter mixtures in the region.

Starter fertilization often increases corn yield in low-testing soils because crops respond to nutrient addition regardless the placement method. At higher soil fertility levels, the response to starter is less frequent, however, and probably due to a placement effect that enhances early plant growth or helps overcome occasional limitations to early nutrient uptake imposed by the management system or climate. Table 1 shows a summary of results of experiments in the region. Some of these experiments and others (Lamond, et al., 2001; Niehues et al., 2004) reported responses to starter mixtures in soils testing low to high in P and (or) K. However, Bermudez and Mallarino (2002), Mallarino (2003b), and Kaiser et al. (2005) found no significant response to starter P or K in Iowa high-soils when the starter was applied in addition to recommended broadcast P-K rates for corn-soybean rotations. Research indicates a greater likelihood of response to starter for continuous corn than for corn after soybean in environments with a short growing period where an acceleration of plant growth can translate into higher yield

(Farber and Fixen, 1986; Bundy and Widen, 1992; Bundy and Andraski, 1999) and for some corn hybrids than for others.

The rate and placement of starter fertilizers can influence their performance. Higher starter rates are needed to optimize production in low-testing soils than in other soils when the starter is the sole nutrient source (Kaiser et al., 2005). Work with seed-placed starter indicates that application rates must be limited to avoid seedling damage and reduced plant populations. Nitrogen and K rather than P are the rate limiting factors, and recommendations for seed placement typically indicate that the N plus K_2O in the fertilizer should not exceed 10 lb/acre of these nutrients. However, the safe application rate is highly affected by soil moisture content and the source of N and K. Because of these limitations, use of in-furrow N-P-K or N-P fertilizers often does not provide enough P to maximize crop response in low-testing soils.

Studies in the region suggest that manure application does not influence corn response to starter fertilizer strongly or consistently. Factors such as the importance of rapid early season growth in realizing yield potential, soil drainage, and possibly soil test level may influence response in manured systems. Motavalli et al. (1993) evaluated starter fertilization for corn silage on a soil with excessively high STP in northern Wisconsin. The starter increased yield in 1 of 3 years, but there was no interaction between manure and starter fertilization. Bundy and Andraski (1999) found that manure application did not significantly influence starter response on high-testing Wisconsin soils.

Surface-band P fertilizer applications usually have been evaluated as a starter fertilizer placement option. Teare and Wright (1990) found that a surface band of an N-P fertilizer increased yield across a range of corn hybrids. Surface band or dribble starter treatments were not as effective as seed or side-placed placements in Illinois studies (Ritchie et al, 1996). However, Lamond et al. (2001) and Niehues et al. (2004) found that surface dribble treatments produced similar yield response to banded starter or differences were small and inconsistent. Little is known about potential implications of applying these small fertilizer rates to the soil surface at or near planting time for P loss with surface runoff.

Available precision agriculture technologies to producers or custom fertilizer and manure applicators facilitate application of P at rates adequate for different parts of a field. Dense grid soil sampling from many fields of the Midwest has shown very large within-field spatial variability of STP. Variable-rate application of fertilizer P is common, and some custom applicators are beginning to apply manure at variable rates. Research in Illinois (Anderson and Bullock, 1998) and Iowa (Wittry and Mallarino, 2004) has shown that grid or zone soil sampling methods combined with variable-rate application based on STP often do not increase crop yield compared with traditional methods. Mallarino and Schepers (2005) suggested that use of current P fertilizer recommendations that encourage STP build-up in low-testing soils combined with very high small-scale STP variation may explain the lack of yield response differences between uniform- and variable-rate fertilization methods. However, Iowa research showed that application according to spatial variability minimizes P application to high-testing areas and reduces STP variability within fields (Fig. 3).

Environmental Implications of Phosphorus Management for Crop Production

Most P management practices discussed above have implications in relation to risk of P delivery from agricultural fields to water resources and environmental P management. Phosphorus delivery from fields depends on complex interactions between source and transport factors. In this section we briefly discuss the most relevant issues of source factors. Source factors that affect P delivery to surface waters include soil P level and management practices such as the time and method of P application, although tillage practice and cropping system often also are considered as source factors.

<u>Soil-Test P Level and Sampling Depth</u>
The potential for dissolved and particulate P loss through soil erosion, surface runoff, and subsurface drainage increase as soil P increases. Soil P is one of the factors useful to assess risk of P delivery to surface water. It may be measured by agronomic soil tests such as Bray P-1, Olsen, and colorimetric or ICP versions of the Mehlich-3 and also by environmental soil P tests that measure water-extractable P or presumed algal-available P (such as the Fe-oxide impregnated filter paper test, or estimated soil P saturation). The results of the agronomic and environmental P tests are generally well correlated in the North Central Region (Attia and Mallarino, 2002; Andraski and Bundy, 2003). Many studies have found that concentrations of dissolved, bioavailable, and particulate P in runoff increase linearly as STP increases. In some cases, P concentration in runoff may increase more rapidly at very high STP levels compared with lower levels. Another consideration is that the total P concentration in sediment is higher than in the eroded soil; this P enrichment occurs due to removal of organic material and fine soil particles that are higher in P than the average for the soil. Studies of relationships between various STP and P loss with subsurface drainage show little P increase in water until a certain STP value (usually referred to as change point), after which P loss usually increases linearly. A study with subsurface tile drainage systems at three Iowa locations (Klatt and Mallarino, 2002) indicated a change point of approximately 60 ppm by the Olsen test or 100 ppm by the Bray P-1 test, which is four to five times larger than optimal levels for most crops of the region.

Ideally, soil samples collected for environmental purposes should reflect the depth of the soil-water mixing zone that contributes to P loss. Phosphorus accumulation at or near the application point is well known, and unless the P is incorporated into the soil fertilization or manure application results in high P levels in the mixing zone of soil and runoff especially for no-till and forage fields. This affects soil-test results and has implications for P loss in runoff. Tillage and deep P banding reduces STP stratification, but significant stratification exists with use of implements such as chisel plows and field cultivators (Fig. 2). Interpretation of agronomic soil tests is generally based on a sampling depth of 6 to 8 inches. Research in the region has shown inconsistent results concerning the benefit of a shallower sampling depth for prediction of both crop yield response to P and dissolved P loss with surface runoff in stratified no-till and pasture fields. Although a shallow sampling depth sometimes improves relationships between STP and runoff P, often differences are very small (Andraski and Bundy, 2003; Vadas et al., 2005). These results together with practical complications of implementing different sampling depths in production agriculture have resulted in the use of agronomic tests and sampling depths for P loss assessments. Furthermore, Wisconsin research is showing that reasonable predictions of STP stratification are possible for the purpose of assessing risk of P loss.

Soil-Test P Spatial Distribution

Spatial variability of soil P within a field needs to be considered in assessing risk of P loss. High concentrations of P in some field areas, mainly because of uneven manure application, can strongly affect soil test results. Sites of old farmsteads often have high STP as well. In pastures, grazing animals tend to deposit more manure near feeding areas, shaded areas, water sources, and fences and gates resulting in relatively high soil P levels in these areas. Global position systems and variable-rate fertilization provide an opportunity to apply P only where it is needed within a field and to reduce STP variation. Although use of this technology usually does not increase yield significantly or consistently, Iowa research showed that application according to STP minimizes P application to high-testing areas and reduces STP variability within fields. Moreover, Mallarino (2003c) showed that variable-rate P application could be practically implemented based on P index ratings for field zones, not just based on STP.

Phosphorus Application and Source

An increase of the P application rate often increases risk of P loss independently of the STP level. In fact, research based on simulated rainfall shows no relationship between runoff P and STP for runoff events immediately after P application. Water passing over the soil surface interacting with recently applied manure or fertilizer P is highly concentrated in P, much of it as dissolved P. The concentration of runoff P shortly after application usually increases linearly as the rate of P application increases, although exponential increases are possible, and incorporation of the P into the soil tend to reduce P concentrations (Figs. 4 and 5). Although the timing of P application may not have a major impact for crop production in the region, it can greatly impact P loss from fields in various ways. The risk of recently applied P loss is higher when the application is made in periods of high probability of intense rainfall, to water-saturated or snow-covered soil, to sloping ground, and to flood-prone areas. Time also influences risk of P loss in another way. Iowa research shows that a runoff event 10 to 15 days after fertilizer or manure application can reduce total and dissolved P concentrations in runoff by over 50% as compared to rain within 24 hours when manure was applied to soil having corn or soybean harvest residues and was not incorporated (Fig. 4). Data in process indicate that this effect varies for different manures and is higher for liquid swine manure. Added P that reacts with the soil is less prone to losses with surface runoff. Therefore, when the P is not injected or incorporated, applying P with anticipation of runoff events can substantially reduce the risk of P loss. The probability of runoff in this region is typically greatest in late winter and spring, a period that includes snowmelt, high rainfall, and little soil cover.

Research is showing inconsistent differences between fertilizer and liquid swine manure sources concerning P loss with surface runoff after surface applications. For example, Daverede et al. (2004) showed slightly larger runoff P concentrations for liquid swine manure than fertilizer (Fig. 5) while Iowa research (M.U. Haq and A.P. Mallarino, unpublished) is finding slightly higher runoff P for fertilizer. However, P losses after applying other manure types tend to be lower than for fertilizer at similar total P application rates (M.U. Haq and A.P. Mallarino, Iowa State University, unpublished). Several factors not well identified at this time can explain this result. Manure typically has less soluble P than fertilizer P, adds organic matter (sometimes it includes bedding), and often increases water infiltration all of which can result in less runoff P immediately after applying manure than fertilizer. Ginting et al. (1998) showed that total P loss from plots receiving beef manure was either similar or lower than from plots receiving no manure. Also, Bundy et al. (2001) showed that total P load in runoff from simulated rainfall was significantly lower where dairy manure was surface applied than in a control treatment where manure was not applied.

We mentioned above that annual or biannual P applications are similarly effective for most crops of the region as long as the application rates are similar. However, a biannual application system increases the instantaneous application rate. Because research usually shows a linear relationship between P rate and P loss with runoff, high, more spaced P application strategies may increase P loss. However, there is little evidence that applying the same amount of P in infrequent applications at higher rates with care and appropriate methods results in more long-term potential for P runoff loss than annual applications with proportionally lower rates of application. Also, infrequent N-based applications of manure benefit farmers as it allows them to meet the full N need of crops such as corn grown in rotation and reduce the need for supplemental N fertilization.

Incorporation of applied P, deep banding of P fertilizer, or injection of liquid manure generally reduce the rate of P build-up near the soil surface and both short-term and long-term risk of P loss with surface runoff. However, runoff P loss may not be reduced when the P incorporation into the soil involves tillage or the aggressive injectors often used to apply liquid manure. The increased soil erosion risk associated with the incorporation or injection of manure or fertilizer needs to be considered. On highly erodible land, the P rate and the degree of soil and crop residue disturbance by application or tillage equipment largely determines the option of least risk. These concerns emphasize the need of a comprehensive tool, such as the P index, that considers both source and transports factors to assess risk of P loss from fields.

Interpretive Summary

<u>Practices Recommended</u>
- Apply P fertilizer rates that optimize crop yield based on soil testing and crop P removal.
- When applying N-based manure, use P index ratings as a planning tool to avoid excessive soil P build-up and choose methods and timing of application that reduce the risk of P loss with surface runoff and subsurface drainage.

<u>Important Considerations</u>
- Soil P testing is an imperfect tool but is very useful to guide P application for crop production. The soil sampling and testing methods recommended in the region for crop production generally are adequate for environmental P management. However, soil-test P classes used for crop production are not appropriate for environmental P management.
- Optimization of manure nutrients use and farm profitability may result in soil-test P build-up in production systems that include animal and corn production. Use of the P index is a valuable tool to avoid excessive soil P build-up and risk of P loss.
- Subsurface P placement methods reduce P accumulation at or near the soil surface and have potential to reduce P loss in sites with high risk of erosion and surface runoff compared with surface application methods. However, they are more costly and seldom increase crop yield further than other methods, and their impact on reducing P loss is dependant on their effect on increasing risk of erosion and the probability of a runoff event shortly after application.

Therefore, guidelines for their use should be flexible to avoid economic penalties to producers.

<u>Limitations</u>
- Even with P application rates according to soil-testing and crop removal and without exceeding optimal soil-test P levels for crops, rates of P delivery to surface water resources may be unacceptably high in conditions with very high erosion and surface runoff.
- Cost-effective soil sampling methods for crop production may not appropriately describe spatial soil-test P variability to reduce P loss in critical field areas.
- Limiting manure application to P-based rates limits manure N use and may reduce farm profitability.

<u>Potential</u>
- Fertilizer P rate reduction or elimination directly benefits crop producers when soil-test P values are above optimum levels for crops and reduces the potential for P loss.
- Elimination of fertilizer and manure P application during periods of snow-covered or frozen sloping soil reduces the potential for P loss.
- Application of N-based manure rates for crops in conjunction with the P index is a reasonable way of encouraging utilizing manure nutrients while reducing the risk of soil P build-up and P loss from fields.

<u>Additional Information Needed</u>
- More research to evaluate impacts of P placement methods on both short-term and long-term P loss from fields and on soil erosion rates.
- Better understanding of the impact on P loss of the time between surface P application and a runoff event and of the probability of a runoff event shortly after application.
- Research on the effect of the proportion of soluble P in animal manures and P loss with surface runoff shortly after a surface application.
- Research to further develop and learn use of cost-effective tools for assessing within-field variation of soil-test P and applying P more accurately to reduce risk of under- or over-fertilization.

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References

Anderson, L.L., and D.G. Bullock. 1998. Variable rate fertilizer application for corn and soybean. J. Plant Nutr. 21:1355-1361.
Andraski, T.W, and L.G. Bundy. 2003. Relationships between phosphorus levels in soil and in runoff from corn production systems. J. Environ. Qual. 2003 32:310-316.
Atia, A.M., and A.P. Mallarino. 2002. Agronomic and environmental phosphorus testing for soils receiving swine manure. Soil Sci. Soc. Am. J. 66:1696-1705.
Bermudez, M., and A.P. Mallarino. 2002. Yield and early growth responses to starter fertilizer in no-till corn. Agron. J. 94:1024-1033.

Bordoli, J.M., and A.P. Mallarino. 1998. Deep and shallow banding of phosphorus and potassium as alternatives to broadcast fertilization for no-till corn. Agron. J. 90:27-33.

Borges. R., and A.P Mallarino. 2000. Grain yield, early growth, and nutrient uptake of no-till soybean as affected by phosphorus and potassium placement. Agron. J. 92: 380-388.

Borges. R., and A.P. Mallarino. 2001. Deep banding phosphorus and potassium fertilizers for corn managed with ridge tillage. Soil Sci. Soc. Am. J. 65:376-384.

Borges, R., and A.P. Mallarino. 2003. Broadcast and deep-band placement of phosphorus and potassium for soybean managed with ridge tillage. Soil Sci. Soc. Am. J. 67:1920-1927.

Buah, S.S.J., T.A. Polito, and R. Killorn. 1999. No-tillage corn hybrids response to starter fertilizer. J. Prod. Agric. 12:676-680.

Bundy, L.G., and T.W. Andraski. 1999. Site-specific factors affecting corn response to starter fertilizer. J. Prod. Agric. 12:664-671.

Bundy. L.G., T.W. Andraski, and J.M. Powell. 2001. Management practice effects on phosphorus losses in runoff in corn production systems. J. Environ. Qual. 30:1822-1828.

Bundy. L.G., and P.C. Widen. 1992. Corn response to starter fertilizer: Planting date and tillage effects. Better Crops Plant Food 76:20-23.

Bundy, L.G., H. Tunney, and A.D. Halvorson. 2005. Agronomic aspects of phosphorus management. p. 685-727. *In* A. Sharpley and T. Sims (eds.). Phosphorus: Agriculture and the Environment. ASA Monograph Series No. 46. ASA-CSSA-SSSA, Madison, WI.

Daverede, I.C., A.N. Kravchenko, R.G. Hoeft, E.D. Nafziger, D.G. Bullock, J.J. Warren, and L.C. Gonzini. 2004. Phosphorus runoff from incorporated and surface-applied liquid swine manure and phosphorus fertilizer. J. Environ. Qual. 2004 33:1535-1544.

Dodd, J.R., and A.P. Mallarino. 2005. Soil-test phosphorus and crop grain yield responses to long-term phosphorus fertilization strategies for corn-soybean rotations. Soil Sci. Soc. Am. J. 69:1118-1128.

Farber, B.G., and P.E. Fixen. 1986. Phosphorus response of late planted corn in three tillage systems. J. Fert. Issues 3:46-51.

Ginting, D., J.F. Moncrief, S.C. Gupta, and S.D. Evans. 1998. Interaction between manure and tillage system on phosphorus uptake and runoff losses. J. Environ. Qual. 27:1403-1410.

Hoeft, R.G., and T.R. Peck. 2001. Soil testing and fertility. p. 78-116. *In* Illinois Agronomy Handbook 2001-2002. Circ. 1360. Coop. Ext. Serv., Univ. of Illinois. Urbana.

Kaiser, D.E., A.P. Mallarino, and M. Bermudez. 2005. Corn grain yield, early growth, and early nutrient uptake as affected by broadcast and in-furrow starter fertilization. Agron. J. 97:620-626.

Kelling, K.A, L.G. Bundy, S.M. Combs, and J.B Peters. 1998. Soil test recommendations for field, vegetable, and fruit crops. University of Wisconsin Extension Publ. A2809. Madison, WI.

Klatt, J.G., A.P. Mallarino, and B.L. Allen. 2002. Relationships between soil phosphorus and phosphorus in surface runoff and subsurface drainage. An overview of ongoing research. p. 183-189. *In* North-Central Extension-Industry Soil Fertility Conf. Proceedings. Vol. 18. Des Moines, IA.

Lamond, R.E., W.B. Gordon, B.J. Niehues, and C.J. Olsen. 2001. Evaluation of starter fertilizer formulations and placements for conservation tillage production systems. p. 137-143. *In* Proc. North Central Ext. Industry Soil Fert. Conf. Vol. 17. 14-15 November. Des Moines. IA. Potash and Phosphate Inst., Brookings, SD.

Mallarino, A.P., and R. Borges. 2006. Phosphorus and potassium distribution in soil following

long-term deep-band fertilization in different tillage systems. Soil Sci. Soc. Am. J. 70:702-707.
Mallarino, A.P. 1997. Interpretation of soil phosphorus tests for corn in soils with varying pH and calcium carbonate content. J. Prod. Agric. 10:163-167.
Mallarino, AP., J.R. Webb, and A.M. Blackmer. 1991. Corn and soybean yields during 11 years of phosphorus and potassium fertilization on a high-testing soil. J. Prod. Agric. 4:312-317.
Mallarino, A.P. 2003a. Field calibration for corn of the Mehlich-3 soil phosphorus test with colorimetric and inductively-coupled plasma emission spectroscopy determination methods. Soil Sci. Soc. Am. J. 67:1928-1934.
Mallarino, A.P. 2003b. Foliar and starter fertilization. Are they needed to supplement primary fertilization? p. 113-120. *In* The Integrated Crop Management Conf. Proceedings. Dec. 3-4, Ames, IA. Iowa State Univ. Extension.
Mallarino, A.P. 2003c. Using the Iowa phosphorus index for agronomic and environmental management of fertilizer and manure phosphorus. p. 121-126. *In* The Integrated Crop Management Conf. Proc. Dec. 3-4, Ames, IA. Iowa State Univ. Extension.
Mallarino, A.P., and J.S. Schepers. 2005. Role of precision agriculture in phosphorus management practices. *In* A. Sharpley and T. Sims (eds.). Phosphorus: Agriculture and the Environment. American Society of Agronomy Monograph Series No. 46. Madison, WI.
Motavalli, P.P., K.A. Kelling, and J.C. Converse. 1989. First-year nutrient availability from injected dairy manure. J. Environ. Qual. 18:180-185.
Niehues, B.J., R.E. Lamond, C.B. Godsey, and C.J. Olsen. 2004. Starter nitrogen fertilizer management for continuous no-till corn production. Agron. J. 96:1412-1418.
Potash and Phosphate Institute (PPI). 2001. Soil test levels in North America. Summary update. Tech. Bull. 2001-1. PPI/PPIC/FAR. Norcross, GA.
Randall. G.W., and E.G. Hoeft. 1988. Placement methods for improved efficiency of P and K fertilizers: A review. J. Prod. Agric. 1:70-79.
Randall. G.W., T.K. Iragavarapu, and S.D. Evans. 1997. Long-term P and K applications: I. Effect on soil test incline and decline rates and critical soil test levels. J. Prod. Agric. 10:565-571.
Randall. G.W., J.A. Vetsch, and T.S. Murrell. 2001. Soybean response to residual phosphorus for various placements and tillage practices. Better Crops Plant Food 85:12-15.
Rehm, G.W., G.W. Randall, A.J. Scobbie, and J.A. Vetsch. 1995. Impact of fertilizer placement and tillage system on phosphorus distribution in soil. Soil Sci. Soc. Am. J. 59:1661-1665.
Rehm, G., M. Schmidt, J. Lamb, and R. Elliason. 2001. Fertilizer recommendations for agronomic crops in Minnesota. Publ. BU-6240-S. Univ. Minn. Ext., St. Paul.
Ritchie, K.B., E.G. Hoeft, E.D. Nafziger, L.C. Gonzini, JI. Warren, and W.L. Banwart. 1996. Starter fertilizers for no-till corn. Better Crops Plant Food 80:6-9.
Robbins, S.G., and R.D. Voss. 1991. Phosphorus and potassium stratification in conservation tillage systems. J. Soil Water Conserv. 46:298-300.
Sawyer, J.E., A.P. Mallarino, R. Killorn, and S.K. Barnhart. 2002. General guide for crop nutrient recommendations in Iowa. Publ. Pm-1688 (Rev.). Iowa State Univ. Extension.
Scharf, P.C. 1999. On-farm starter fertilizer response in no-till corn. J. Prod. Agric. 12:692-695.
Teare, J.D., and D.L. Wright. 1990. Corn hybrid-starter fertilizer interaction for yield and lodging. Crop Sci. 30:1298-1303.

Vadas, P.A., A.P. Mallarino, and A. McFarland. 2005. The importance of sampling depth when testing soils for their potential to supply phosphorus to surface runoff. Position paper. Minimizing Phosphorus Losses from Agriculture / Information Exchange Group (SERA-17/IEG) committee. Available at www.sera17.ext.vt.edu.

Vetsch, J.A., and G.W. Randall. 2002. Corn production as affected by tillage system and starter fertilizer. Agron. J. 94:532-540.

Webb, J.R., A.P. Mallarino, and A.M. Blackmer. 1992. Effects of residual and annually applied phosphorus on soil test values and yields of corn and soybean. J. Prod. Agric. 5:148-152.

Wittry, D.J., and A.P. Mallarino. 2004. Comparison of uniform- and variable-rate phosphorus fertilization for corn-soybean rotations. Agron. J. 96:26-33.

Table 1. Frequency and size of no-till corn yield response to N-P-K or N-P starter fertilizer in several states of the Upper Mississippi River region (adapted and update from Bundy et al., 2005).†

Location	Reference	Response frequency	Response
Illinois	Ritchie et al. (1996)	8 of 9 trials	14 bu/acre average
Iowa	Buah et al. (1999)	7 of 9 trials	4 to 18 bu/acre
Iowa	Bermudez & Mallarino (2002)	5 of 7 trials ‡	2 to 8 bu/acre ‡
Iowa	Mallarino (2003)	3 of 8 trials	5 bu/acre average
Iowa	Kaiser et al. (2005)	1 of 2 ‡	15 bu/acre ‡
Missouri	Scharf (1999)	6 of 6 trials	13 bu/acre average
Wisconsin	Bundy & Widen (1992)	8 of 12 trials	15 bu/acre average

† Soils tested medium, optimum, or higher in P and K according to local interpretations

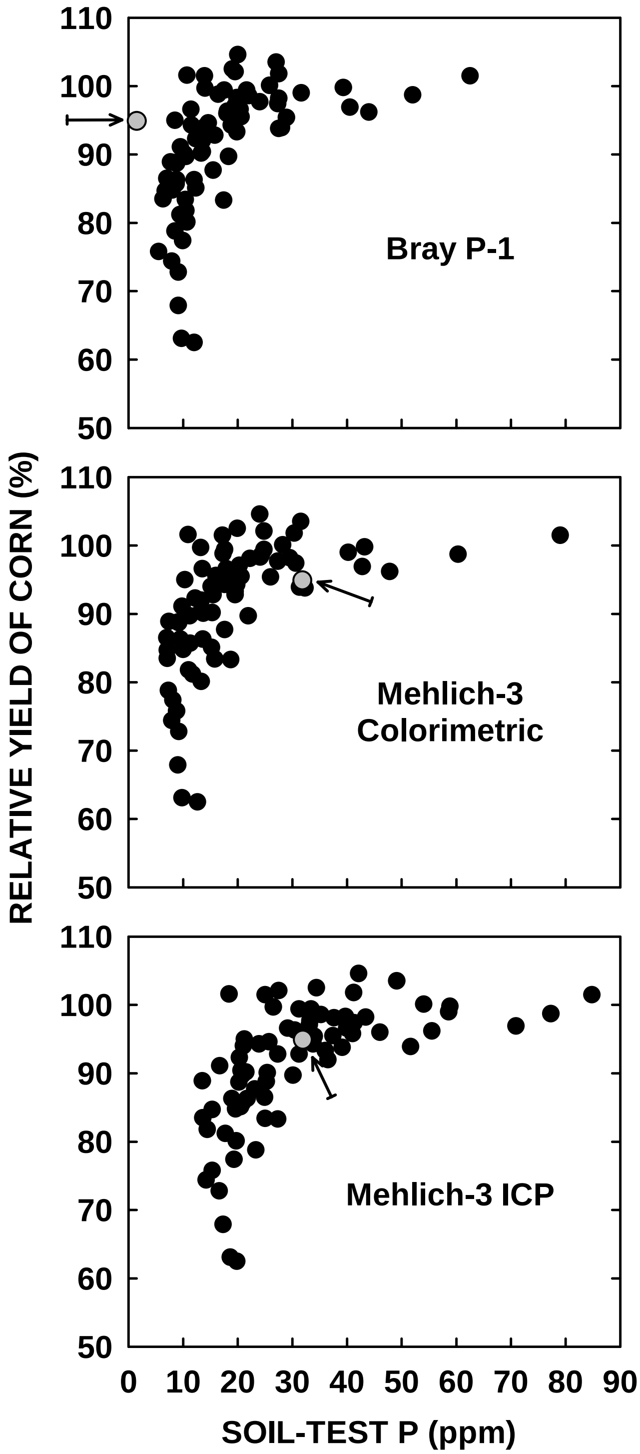

Fig. 1. Example of the relationship between corn yield and soil-test P measured by three P tests commonly used in the Upper Mississippi River region (adapted from Mallarino, 2003a). The gray point and arrow indicate results for a highly calcareous soil.

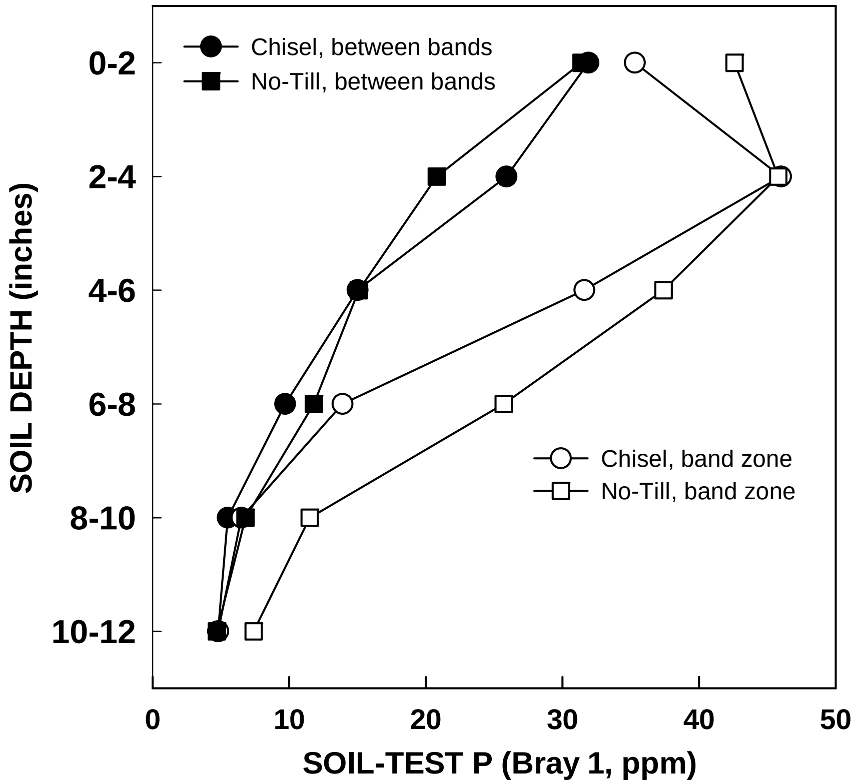

Fig. 2. Mean soil-test P across five sites after several years of no-till or chisel-plow tillage and deep-band P fertilization for band and inter-band zones (adapted form Mallarino and Borges, 2006).

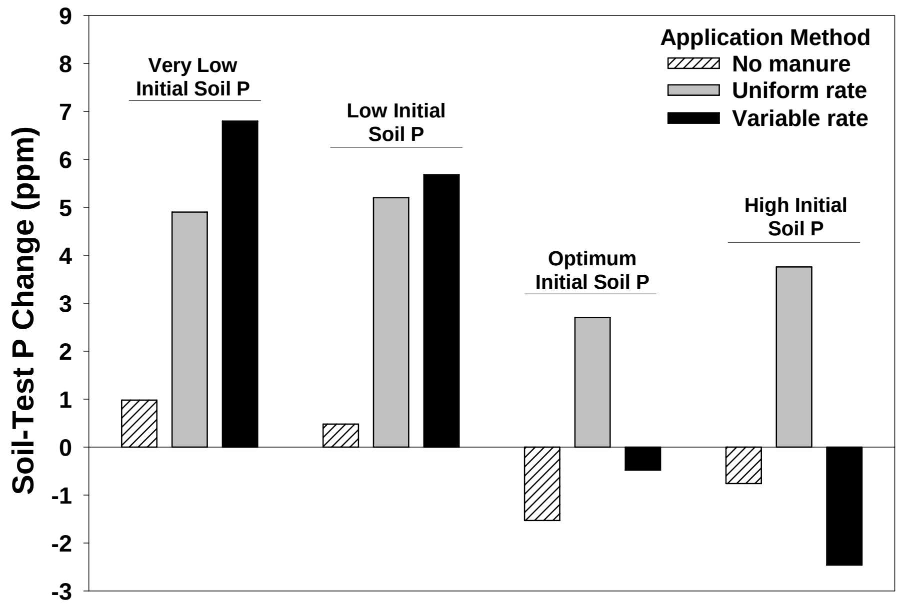

Fig. 3. Effect of uniform application and soil-test P based variable-rate application of liquid swine manure on soil test P change within a field for various initial soil-test P interpretation classes. Adapted from Mallarino and Schepers (2005).

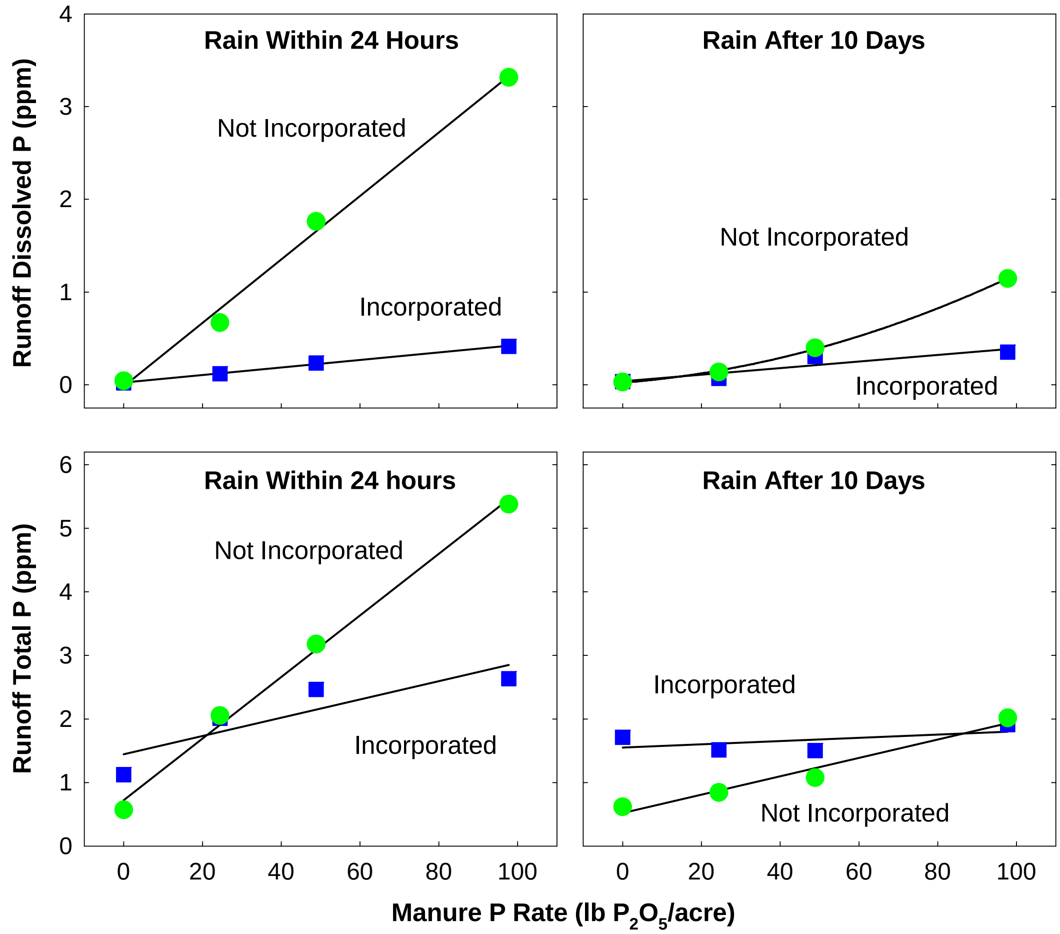

Fig. 4. Effect of liquid swine manure incorporation into the soil and time of simulated rainfall on dissolved and total P concentrations in runoff (unpublished, B.L. Allen, A.P. Mallarino, and J.L. Baker, Iowa State University).

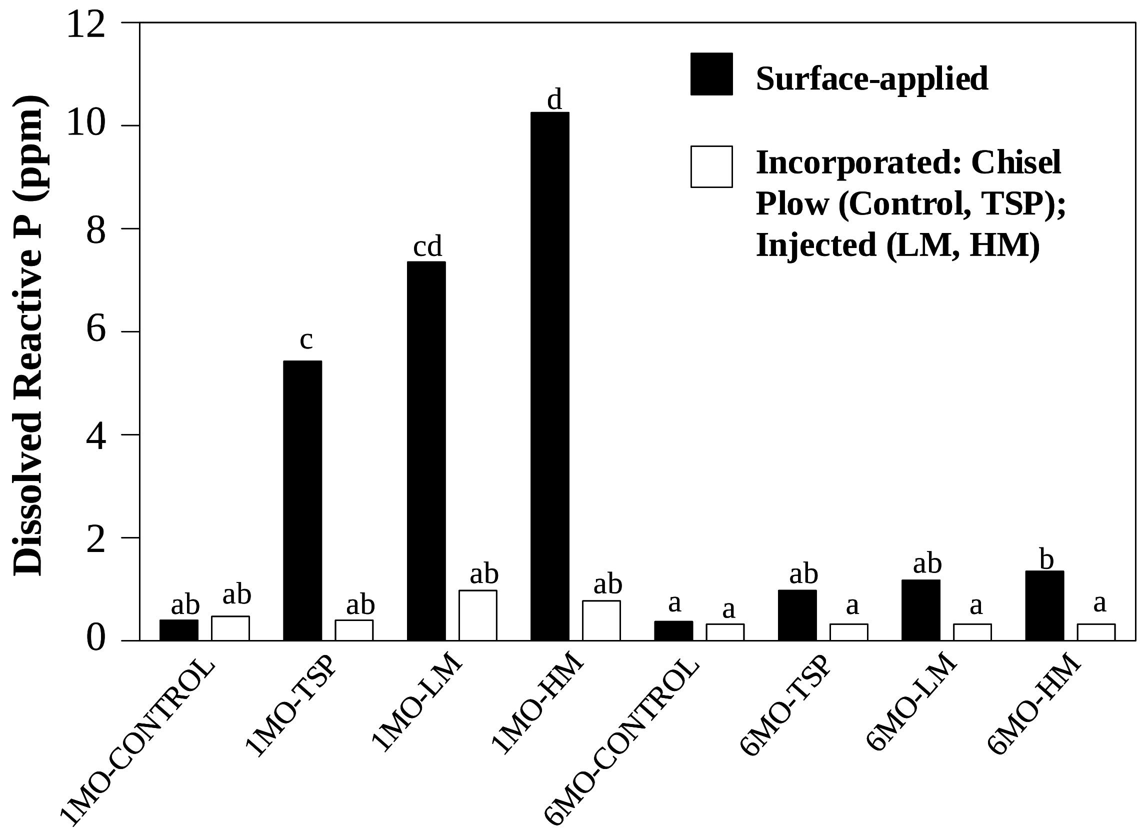

Fig. 5. Mean dissolved reactive phosphorus (DRP) concentration in runoff as affected by time of rainfall simulation one (1MO) and six months (6MO) after P application; P source (control, TSP = triple superphosphate, LM = low swine manure rate, and HM = high swine manure rate); and application method (surface-applied and incorporated, where the control and TSP were chisel-plowed and LM and HM were injected). The P rates applied were 110 lb P_2O_5/acre for TSP, 68 to 80 lb P_2O_5/acre for LM, and 135 to 161 lb P_2O_5/acre for HM. Values that have the same letters are not significantly different (P < 0.1). Adapted from Davedere et al. (2004).